Geophysical Monograph Series
American Geophysical Union

Geophysical Monograph Series

A. F. SPILHAUS, JR., *managing editor*

1 Antarctica in the International Geophysical Year
A. P. CRARY, L. M. GOULD, E. O. HULBURT, HUGH ODISHAW, AND WALDO E. SMITH, *editors*

2 Geophysics and the IGY
HUGH ODISHAW AND STANLEY RUTTENBERG, *editors*

3 Atmospheric Chemistry of Chlorine and Sulfur Compounds
JAMES P. LODGE, JR., *editor*

4 Contemporary Geodesy
CHARLES A. WHITTEN AND KENNETH H. DRUMMOND, *editors*

5 Physics of Precipitation
HELMUT WIECKMANN, *editor*

6 The Crust of the Pacific Basin
GORDON A. MACDONALD AND HISASHI KUNO, *editors*

7 Antarctic Research: The Matthew Fontaine Maury Memorial Symposium
H. WEXLER, M. J. RUBIN, AND J. E. CASKEY, JR., *editors*

8 Terrestrial Heat Flow
WILLIAM H. K. LEE, *editor*

9 Gravity Anomalies: Unsurveyed Areas
HYMAN ORLIN, *editor*

10 The Earth beneath the Continents: A Volume in Honor of Merle A. Tuve
JOHN S. STEINHART AND T. JEFFERSON SMITH, *editors*

11 Isotope Techniques in the Hydrologic Cycle
GLENN E. STOUT, *editor*

12 The Crust and Upper Mantle of the Pacific Area
LEON KNOPOFF, CHARLES L. DRAKE, AND PEMBROKE J. HART, *editors*

13 The Earth's Crust and Upper Mantle
PEMBROKE J. HART, *editor*

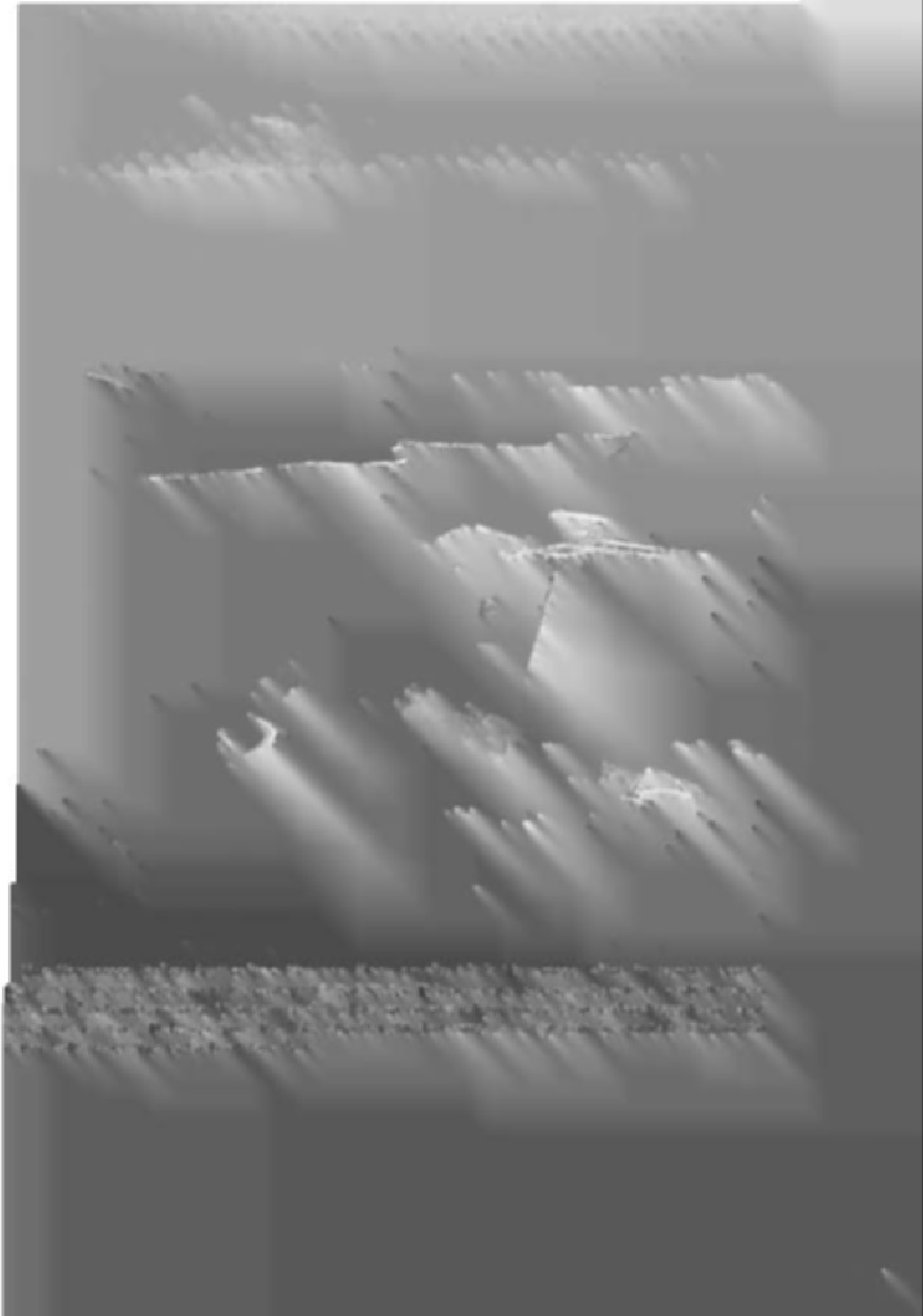
14 The Structure and Physical Properties of the Earth's Crust
JOHN G. HEACOCK, *editor*

15 The Use of Artificial Satellites for Geodesy
SOREN W. HENRIKSEN, ARMANDO MANCINI, AND BERNARD H. CHOVITZ, *editors*

16 Flow and Fracture of Rocks
H. C. HEARD, I. Y. BORG, N. L. CARTER, AND C. B. RALEIGH, *editors*

17 Man-Made Lakes: Their Problems and Environmental Effects
WILLIAM C. ACKERMANN, GILBERT F. WHITE, AND E. B. WORTHINGTON, *editors*

Man-Made Lakes:
Their Problems and
Environmental Effects



geophysical monograph 17

Man-Made Lakes: Their Problems and Environmental Effects

WILLIAM C. ACKERMANN
GILBERT F. WHITE
E. B. WORTHINGTON
editors
J. LOREENA IVENS
associate editor

American Geophysical Union
Washington, D.C.
1973

Published with the aid of a grant
from the Charles F. Kettering Foundation

International Standard Book Number 87590-017-8

1707 L Street, N. W.
Washington, D. C. 20036

Library of Congress Catalog Card Number 73-86486

WILLIAM BYRD PRESS, RICHMOND, VIRGINIA

Foreword

This volume is based on the papers that were presented or summarized at the International Symposium on Man-Made Lakes, Their Problems and Environmental Effects. The symposium was organized by the Scientific Committee on Water Research (Cowar) on behalf of the International Council of Scientific Unions (ICSU).

The symposium was held in Knoxville, Tennessee, in the United States during May 3–7, 1971, in the facilities of the University of Tennessee. Knoxville also is the headquarters of the Tennessee Valley Authority (TVA), and projects of the TVA were the center of interest during field trips that immediately preceded and followed the meeting.

The various unions of ICSU that are concerned with water actively cooperated in the planning of the symposium. The United Nations and numerous of its specialized agencies supported the symposium in the preparation of papers and in bringing leading specialists of the world to the meeting. These agencies are the Food and Agriculture Organization (FAO), the United Nations Development Program (UNDP), the United Nations Educational, Scientific and Cultural Organization (Unesco), the World Meteorological Organization (WMO), and the World Health Organization (WHO).

Special acknowledgment is accorded the Ford Foundation, which provided financial support for the attendance of numerous scientists from abroad and also supported the preparation of this volume. The National Academy of Sciences was the United States host and assisted the symposium in many ways.

The organizing committee consisted of Dr. William C. Ackermann, Chairman, Urbana, Illinois; Dr. E. B. Worthington, London, England; Dr. Gilbert F. White, Boulder, Colorado; Mr. Reed A. Elliot, Knoxville, Tennessee; and Professor Floyd C. Larson, Knoxville, Tennessee. Leading roles in organizing and conducting the symposium were performed by the distinguished session chairmen. Since they are not otherwise identified in this volume, they are mentioned here:

Session 1. Opportunities and Environmental Effects, Dr. William C. Ackermann, President of Cowar and Chief of the Illinois Water Survey, Urbana, Illinois, United States.

Session 2. Man-Made Lakes of the World, Dr. W. Manshard, Director of the Department of Environmental Sciences and Natural Resources Research, Unesco, Paris, France.

Session 3. Case Studies, Major Lakes, Mr. Louis Serra, General Secretary of Cowar and advisor to L'Electricité de France, Rueil Malmaison, France.

Session 4. Reservoirs as Physical Systems, Mr. James P. Bruce, Director of the Canada Centre for Inland Waters, Burlington, Ontario, Canada.

Session 5. Limnology and Biological Systems, Professor Karl Lagler, Consultant to FAO and School of Natural Resources, University of Michigan, Ann Arbor, Michigan, United States.

Session 6. Reservoirs in Relation to Man, part 1, Professor Alfred W. Booth, Department of Geography, University of Illinois, Urbana, Illinois, United States.

Session 7. Reservoirs in Relation to Man, part 2, Mr. C. H. Clay, Coordinator of Lake Projects, FAO, Rome, Italy.

Session 8. Management for Multiple Use, Mr. R. H. Hayes, Chief of the Engineering Division, U. S. Army Corps of Engineers, Louisville, Kentucky, United States.

This volume generally follows the order of the symposium. Opening remarks that set the tone for the symposium included greetings from Professor V. A. Ambartsumian, President of ICSU; Mr. H. N. Stroud, Assistant to the

General Manager of TVA; Dr. Charles H. Weaver, Chancellor of the University of Tennessee; and Mr. Louis Serra, General Secretary of Cowar.

Major addresses were given at the opening session by Mr. Ralph Townley of UNDP and by Dr. Thomas F. Malone, Vice President of ICSU. At the banquet later in the week addresses were given by Commander Sir Robert Jackson of UNDP and by Mr. Aubrey J. Wagner, Chairman of the Board of TVA.

Because of the large number of papers offered and accepted, each topic was summarized by a principal speaker on sessions 2–7 inclusively. The final session of the symposium was devoted to a discussion of management for multiple use and an attempt at synthesis of the entire topic. Introductory statements were offered by E. B. Worthington and Gilbert F. White. Substantial contributions were also made by S. El-Zarka, B. R. Allanson, Arthur D. Hasler, Stanley Frost, A. W. A. Brown, Jerome K. Fulton, Paul Simeon, James A. W. McCulloch, Karl F. Lagler, Thayer Scudder, and William C. Ackermann.

Actual summary and partial synthesis came later through the efforts of the Scientific Committee on Problems of the Environment (Scope) and its Commission on the Problems of Man-Modified Ecosystems. This commission, under the chairmanship of Gilbert F. White, reviewed all the symposium papers along with other material and prepared a report that, with minor changes, is chapter 1 of this volume.

The Knoxville meeting was the third international symposium devoted to the consideration of man-made lakes. The first was held in London in 1964. The papers presented at the London symposium appeared in *Man-Made Lakes,* published in 1966 by Academic Press and edited by R. H. Lowe-McConnell. The second international symposium was held in Ghana in 1966. These papers appeared in the volume *Man-Made Lakes, The Accra Symposium,* published in 1969 by Ghana Universities Press and edited by L. E. Obeng.

The Symposium on Man-Made Lakes at Knoxville was attended by 550 scientists, engineers, and managers. Some 175 papers were presented or summarized at the meeting, which was conducted entirely in plenary session. This formal organization and the many informal arrangements provided excellent opportunities for exchanges across normal disciplinary boundaries. The papers selected from the symposium for inclusion in this volume further extend the opportunities for broad communication of ideas and progress on the problems and environmental effects of man-made lakes.

WILLIAM C. ACKERMANN

Preface

This volume presents 113 technical papers drawn from the International Symposium on Man-Made Lakes, Their Problems and Environmental Effects, Knoxville, Tennessee, May 3–7, 1971. Some excellent papers were omitted in order to present in the space of one volume those papers most directly concerned with the man-made water body as opposed either to more remote upstream and downstream relationships or to topics equally applicable to natural water bodies. The multidisciplinary character of the symposium also was a guide to selection. The summary papers presented by principal speakers at the plenary sessions are included, but these have been abbreviated to avoid repetition of factual material in the papers that follow.

Although the arrangement of papers generally follows that of the conference sessions, the volume begins with a summary chapter prepared after the symposium. Also, because of the variety of topics, the order of the presentations from the sessions on reservoirs in relation to man and on management has been changed somewhat in chapter 5.

There is some overlapping of topics from one section to another, which to some extent is a reflection of the interrelationships of systems within the environment of a man-made lake. The case studies in chapter 2, in particular, include multiple topics, which are treated separately in succeeding chapters. Sections 2 and 3 of chapter 2 are aggregates of papers making up two major case studies: Volta Lake and Lake Kariba, respectively. The other case studies are single in-depth papers on specified man-made lakes and are presented here in alphabetical order. The editors found that the balance of papers among the various topics was uneven.

The organizing committee and the editors are especially pleased to have these papers published in the Geophysical Monograph Series of the American Geophysical Union.

WILLIAM C. ACKERMANN

Contents

CHAPTER 2: Case Studies of Major Man-Made Lakes

Section: World and National Registers

Section: Volta Lake, Ghana

Section: Lake Kariba, Zambia and Southern Rhodesia

CHAPTER 3: Physical Systems

Section: Hydrology and Hydraulics

Section: Sedimentation

Section: Meteorology and Hydrometeorology

Section: Seismic Effects

CHAPTER 4: Biological Systems

Section: Physical Limnology

Section: Aquatic Ecosystems

CHAPTER 5: Man-Made Lakes in Relation to Man

Section: Fisheries

Section: Resettlement

Section: Marginal Agriculture and Wildlife

Section: Health

Section: Tourism

Section: Shoreline and Terrestrial Features

Section: Engineering Techniques

Summary of Symposium and Recommendations

MAN-MADE LAKE ECOSYSTEM

Among the many ecosystems of which man is a part the man-made lake presents in sharp outline the difficulties and opportunities of tracing basic relationships and of shaping public policy to deal effectively with social goals and environmental change. When man throws a dam across a stream to create an impoundment, he generates a complex net of impacts. These spread through the human, biological, hydrologic, atmospheric, and earth crustal components of the environment.

The initial action of a dam usually is abrupt. The transformation from terrestrial and riverine to aquatic and lacustrine conditions is rapid and grossly evident. The full consequences, insofar as they are identified, reach not only far over the earth's surface but far after in time. Although much less than 1% of the continental land area is now covered by artificial lakes, they claim the attention of policy makers at national and international levels because of their strong ties to potential economic growth and because of their capacity for highly visible environmental and social disruption. Artificial lakes are symbols of economic advancement and also of dismay. They provoke issues of public judgment that are likely to appear wherever drastic changes are made in an ecosystem. Thus they embody the kind of complex relationships and choices that are involved when land and water are severely altered by drainage, cultivation, pesticides, or other massive human treatment.

In considering the significance of man-made lakes to society, we must ask why they are undertaken, whether they are the best methods for achieving the desired aims, and thereby what the alternatives are to building them. These questions lead to the questions of how man-made lakes differ from natural lakes and from place to place and how man functions as a part of the new ecosystem as it goes through its several stages of development.

Alternatives to man-made lakes. Man creates lakes to store water for power generation, flood control, irrigation, navigation, and urban water supply and waste disposal and for sport and commercial fishing, hunting, and recreational uses of the reservoir itself. A large experience documents the benefits that have accrued from building storage reservoirs of one kind or another, especially those benefits that help to improve the conditions of life in some areas. These benefits are an accepted part of man's technological arsenal for developing and controlling the natural world to his advantage. It could well be argued that some reservoirs are among our best examples of enlightened manipulation of the environment to enhance its quality. Unfortunately, with reservoirs as with most other major modifications, only a few careful assessments have been made of the full range of impacts of their construction.

For most efforts to enhance human welfare by building dams, there ordinarily are alternative ways of meeting the social need. Building an impoundment is not necessarily the most desirable alternative. Power may be generated from fuel sources; flood losses may be reduced by other means, such as channels or land use change; water may be transported directly by aqueducts from sources to places of demand instead of being stored until needed; and so on.

Sometimes, an impoundment is chosen because it seems the only physically feasible and

---

The papers of the Symposium on Man-Made Lakes, Their Problems and Environmental Effects were reviewed by the Working Group on Man-Made Lakes of the Special Committee on Problems of the Environment (Scope) of the International Council of Scientific Unions (ICSU). The personnel of the working group were Bernard H. Dussart, Karl F. Lagler, Peter A. Larkin, Thayer Scudder, Karoly Szesztay, and Gilbert F. White, Chairman, most of whom participated in the symposium. The resulting work group report, which was reviewed by a larger group of participants in the symposium, was published in 1972 by ICSU as *Man-Made Lakes as Modified Ecosystems, Scope Report 2.* With only minor changes the following chapter is wholly adapted from the report of the Scope working group and is an appropriate summary for the Symposium on Man-Made Lakes, Their Problems and Environmental Effects.

economical means of reaching a goal. Generally, an artificial lake is judged to be economically preferable to other alternatives. An artificial lake appears to accomplish a variety of benefits in a tidy way at low cost. However, many a dam is built without genuinely considering the other possibilities. It should not be assumed that a new dam, large or small, is necessarily desirable; however, it would be equally erroneous to assume that the appraisal of the alternatives is an easy task.

All such efforts logically hinge on the prior definition of social goals. These goals set the framework within which alternatives will be examined and impacts will be discovered and reconciled. Both goals and methods change over time and differ among nations. Whereas economic efficiency may be a primary goal in one place, regional development may predominate in planning water management in another area; in other places a large dam is partly a display of national autonomy and strength.

Projects as massive as many man-made lakes involve much more than efforts to increase real economic output. By design and by accident these lakes alter the relative abundance or power of different productive factors and thereby shift the range of economic opportunity in the area affected. In a developing country, man-made lakes may set in motion profound readjustments, such as the transition from subsistence to market-oriented economic life. In an industrial country, man-made lakes may shape the pattern of heavy manufacturing or of new recreation. The speed and direction of those changes may be critically important in determining the relative weight of economic gain against the disruptive social effects.

Any major environmental change is likely to produce substantial redistributions of wealth, income, and employment opportunities. The redistribution effects will hit different groups of people with different impacts. Even a project promising to be highly efficient in an economic sense may involve such gross inequities in distribution effects (as in the costs of relocation) that other measures may be required to compensate the losers.

Whatever the circumstances, reservoir construction is never warranted without prior examination of the other possibilities. An adequate comparison requires scientific knowledge to assess the likely effects. These are judged on social and economic grounds, and, man being man, the political factor ultimately will be decisive. The impacts stretch (1) downstream, (2) to distant consuming areas for water and power, (3) to upper parts of the watershed, (4) throughout the political and economic life of the nation, and (5) within the immediate area of the reservoir and the adjoining lands. The impacts on the last area, which may be defined as the biotic community and the nonliving environment as they function together, primarily create the man-made lake ecosystem. In dealing with this ecosystem, we thus examine only one sector of the impact of water management.

Response to uncertainty. Man has no early prospect of being able to judge accurately all the possible effects of a new lake. Whereas some of them (such as the influence of water depth on lake bed vegetation) may be predicted with confidence, many of the relationships are barely recognized, let alone sufficiently well understood to permit prediction. Moreover, the time dimensions of the processes at work differ greatly. The response of certain populations such as bacteria or phytoplankton to the new water body may be almost instantaneous, whereas the development of lake bottom soils or indeed of the whole lake system goes on over decades or centuries.

Faced with such uncertainties over a wide range of time horizons, the public agency responsible for new man-made lakes can take one of several postures. At one extreme the agency can push ahead with the primary purpose of construction (such as hydroelectric power), deal with actual side effects as they arise or are perceived, and hope that these side effects do not prove to be unduly serious or intractable. At the other extreme the agency can halt all new construction until long and painstaking research has established a sufficient knowledge of facts and a method to permit some minimum confidence of prediction. In between these extremes is a variety of positions involving efforts to make further studies, to prepare for certain contingencies, and to hedge against major disruptions.

Robert Bridges once remarked that 'conduct lies in masterful administration of the unforeseen.' In this sense, any thoughtful attempt to design and carry out the creation of a man-made lake is a search for wisdom. It is a search that requires large flexibility not only at the outset but throughout the entire life of the enterprise.

Natural and man-made lakes. A man-made lake is a combination of terrestrial and riverine ecosystems becoming a natural lake ecosystem. However, the man-made lake never arrives at that relative state because it is always subject to human manipulation of outflow and water levels. Likewise, a number of reservoirs are constructed by damming the outlets and raising the shoreline of natural lakes. For the purposes of this report we define man-made lakes as freshwater bodies created or enlarged by the building of dams, barriers, or excavations. They are subject to continuing human maintenance and operation. Where any of the factors comprising the water balance is significantly altered or controlled, the lake is counted as man made.

The resulting ecosystem is thereby different from that of a natural lake. Involved are the new physical environment, the aquatic and terrestrial communities, and the changing web of human interactions in those communities. It is easy to delimit the maximum lake level but difficult to draw a line around the areas affected by the organisms, especially man, that are related to the new habitat. Somewhat arbitrarily, we designate the following as parts of the lake basin ecosystem: the lake area, the immediately adjoining terrestrial communities, and the human communities within the upland areas (other than the main stem of the stream) draining directly into the lake. Difficulty is encountered in delimiting the boundaries of the physical and biological impact area, which varies according to the elements or species concerned. This definition excludes more distant communities influenced by the new habitat and its products, e.g., when land animals roam across a watershed, when electric power is transported to a city, or when political maneuvering for the dam affects the national political balance. This definition includes the populations directly affected by the artificial lake.

Recent widespread phenomenon. Although small lakes have been constructed over many centuries, as is recorded in the ancient tanks of Ceylon and the mill ponds of western Europe, the era of creating lakes of >100 km^2 in surface area did not begin until after 1915. Early in the 1900's the changes in earth moving and concrete technology made large and relatively inexpensive structures feasible. Since then, reservoirs of large size have been constructed in tropical and temperate zones on all the continents. Unlike some other products of modern technology, large reservoirs are as common per unit area in many developing countries as in high-income countries. At least 40 reservoirs with water surfaces of >1000 km^2 and 260 reservoirs with surfaces of 100–1000 km^2 are now in operation [*Fels,* 1970]. In volume the >4000 km^3 of water stored in those lakes would equal roughly one-third of the water in the atmosphere.

The largest number of big reservoirs (1000 km^2) is in the USSR, and Canada, China, India, and the United States all have major structures. In Ghana the Volta River reservoir inundates $>4\%$ of the total land area. Some of the countries with big reservoirs, as well as other countries, have built many small reservoirs of less than a few square kilometers. Thus Japan has 0.05% of its land area in such use, and Romania, which has 1200 small projects, has at least 0.2%. The Machakos area of Kenya is sprinkled with small dams. In North America, small reservoirs are widely used for regulated domestic water supply, flood control, waterfowl production, and recreational fishing. For these reasons, small reservoirs are widely recognized as a useful way of improving natural environments. In the western United States alone, at least 1000 small dams are being constructed each year.

Large versus small lakes. There is no obvious lower limit on the size of a man-made lake. Even in its hydrologic influence, as in its contribution to streamflow control, an aggregate of small lakes may be as important as a large lake. Indeed, in countries such as Bulgaria, Hungary, Japan, and Spain, water resource management and inland fishery development are based on hundreds of small reservoirs.

Although the same basic physical and biological processes are at work in large or small water bodies, there are profound differences in the limnology and management of ponds as opposed to small lakes and of small lakes as opposed to large lakes. The transition from ponds to small lakes is commonly associated with a mean depth of >3 meters or an area of >10 km^2; the transition from small lake to large lake is traditionally associated with a mean depth of >10 meters or an area of >100 km^2. With greater depth and area, there is characteristically a thermal stratification that is not so extreme as to severely deplete oxygen concentrations in deeper water and the development of a complex dynamic physical structure. There is also a rapid decline in natural productivity as depth and area decrease, as well as associated changes in ecosystem functioning. Large lakes or reservoirs are thus mostly separable from small lakes and reservoirs on biological bases.

From the viewpoint of power generation and large-scale water storage, only relatively large and deep reservoirs are economically attractive. One horsepower is generated by dropping 1 ft^3 of water per second through a height of 3.34 meters. Thus there are obvious advantages to constructing power dams with as much 'head' as possible. Similarly, for water storage the approximately parabolic shape of most lake basins ensures that each increase in the height of a dam progressively increases the storage benefits. In consequence, major reservoirs are usually made as extensive as possible, and thus they tend to be in the large-scale range. The social correlates of size are highly variable. A pattern of small reservoirs poses a quite different set of social considerations than a single large reservoir.

For these several reasons we direct attention in this review chiefly to the larger types of reservoirs with areas of >100 km^2. Although this designation may seem arbitrary, it is a useful line of demarcation between two quite different patterns of human ecosystem impacts.

In terms of the public responsibility for the disruptive effects the large reservoirs most often claim attention. However, aggregates of many small reservoirs may have profound environmental impacts.

Temperate versus tropical lakes. Western Europe has very few large lakes, and the larger ones are widely distributed over the land surface of the globe. Unlike certain other facets of modern technology, man-made lakes are numerous in developing countries. They are largely absent from polar areas. Although man-made lakes are relatively more numerous in semiarid zones, they have been built in humid zones such as the lower Ganges-Brahmaputra and in very arid areas traversed by exogenous streams such as the Nile.

The disparity in energy balance conditions for man-made lakes of the temperate and tropical climatic zones makes for some fundamental differences in water balance conditions, temperature regimes, and biological processes. Most of the serious human population dislocations have occurred in tropical situations, partly because large displacement would be political suicide in some temperate areas such as France. However, there are enough properties in common so that both zones may be treated as a group, the salient differences being recognized at critical points.

Why focus on man-made lakes? Large dams are hailed in many sectors as milestones of technological advancement of human welfare. In some other sectors they are lamented as ecological catastrophes. An examination of what is known and not known about reservoirs thus has significance as an inquiry into scientific and policy issues raised by massive human intervention in the environment and also as an aid to management of present and future reservoirs.

Major interdisciplinary investigations in cooperation with the United Nations Development Program (UNDP) on the Kainji, Kariba, Kossou, and Nasser lakes began essentially as salvage operations by the countries involved. These investigations have been interdisciplinary studies in which sociologists, aquatic biologists, fishery experts, economists, engineers, public health officials, and many other scientists have collaborated. They built on earlier studies preceding the dam construction, of which the Volta River investigations were perhaps the most searching. The UNDP activity led to the preparation by the Food and Agriculture Organization (FAO) of a general guide to the planning of man-made lakes [*Lagler,* 1969].

Symposiums in London [*Lowe-McConnell,* 1966], Accra [*Obeng,* 1969], and Knoxville [*Ackermann et al.,* this volume] have drawn together much of the international experience. At the Knoxville symposium in 1971, for example, members of the concerned disciplines joined in plenary discussion of the major scientific issues. Each of these symposiums has assembled a large part of the available information about the reservoirs of the world. The information so far collected has not been synthesized in such a way as to enable formulation without further analysis of a useful guide for setting policy for new reservoirs. Such a lack of synthesis is not a reflection on the symposiums or their participants. Rather, it mirrors the state of most reservoir investigations. With the exception of salvage studies the tradition is to examine small segments of the water impoundment experience. There have been only a few sustained investigations of such new water bodies in the USSR and in the United States national research program on the environmental factors relating to success or failure of major fish species.

If governments are troubled by the outcome of some reservoirs (and the research projects thereon), it is partly because the scientific waters are muddy. Mainly because of the educational and institutional barriers and the limitations in available training, much research remains to be done at both national and international levels in order to foster cooperative efforts among the physical, biological, and social disciplines concerned.

Man in the ecosystem. Basic to the choice of appropriate policy is the public view of the significance of man's act in building a dam. One widely held view is that man has the power and responsibility to manipulate natural systems to serve human ends and that the test of the wisdom of his action is in the short-term monetary returns. If a hydroelectric project returns the payments on the investment and stimulates regional growth, it is good.

A somewhat different view is that of man as intervening in a natural ecosystem. He disturbs existing systems and tries to balance the favorable and unfavorable effects. If a calculation in advance of construction shows that the total social benefits exceed the total social costs for specified groups of beneficiaries over a specified time period, the intervention in the ecosystem is judged to be warranted. The so-called natural system is viewed as somehow independent of but controlled by man.

A view that we find more suitable is that of man as the dominant species on the ecosystem earth. By building dams, man adds to his long demonstrated capacity for technological change, and he seeks to integrate that skill beneficially with an ongoing process of interaction among the human and other elements of the ecosystem. With inspiration and skill he may mold a better world for his descendents. Under this view the dam is only one among numerous and continuous interactions. A simple before and after model of change is not sufficient to describe the impacts. Long-term shifts in diversity and stability take on greater importance. Although some sort of assessment of the likely effects is essential at the stage when the feasibility of a new structure is being decided on, the process of assessment is a continuing part of human life in the system.

Because of the continuing interaction of the man-made lake with other systems, it is desirable that the management of a man-made lake be carried out in close association with activities upstream, downstream, and in areas that are linked by physical or social impacts. Reservoir management is part of a larger regional responsibility.

It is important here to state two theoretical problems. The first concerns the conceptualization of man as a part of an ecosystem; the second concerns the nature of the sociocultural system. Whereas it is relatively easy to analyze the lake basin human population as part of the man-made lake ecosystem, it is more difficult to include those government agencies that are responsible for planning and executing dam construction and lake basin development. In one sense they are external agents, although they are, of course, part of a wider ecosystem just as the human species is part of a global ecosystem.

The second problem relates to the nature of a sociocultural system. Certainly it is a system in that there is an interrelationship between component human actions and premises. However, social and behavioral scientists are finding that the analytical models that have been borrowed from the physical and biological sciences cannot be satisfactorily applied to human affairs. These analytical models include organismic models and equilibrium models, neither of which is particularly useful in dealing with the multidisciplinary features of man-made lakes. Yet one of the characteristics of man in society is a capacity to change the rules of the game radically through the generation of new ideologies and programs of social action. Examples include not only the appearance of worldwide religions like Buddhism, Christianity, and Islam but also the appearance of new political ideologies within the past 100 years.

We do not reject the utility of equilibrium analysis, for example, since in the hand of an ecologist or economist this analysis can be a powerful tool in dealing with certain limited types of problems and can be extended to deal in a broad way with survival strategies. Rather, the concept of equilibrium as developed by classical ecologists was not intended to come to grips with the complex interrelationships between man as a social, culture-bearing animal and other components of the ecosystem. Whereas it is not our task in this report to attempt to generate new theory or models, it is clear that there is as yet no unified theory that relates to social or ecological change in which man is viewed as an integral part of the ecosystem. It is obvious that detailed long-term studies of continuity and change within complex man-made ecosystems are essential if theoreticians are to have the data against which to generate and test increasingly complex models. Meanwhile, in this report, the model used is a rather simple one that views human societies primarily as coping systems.

Modes of social assessment. In theory, every public or private decision triggering a major change should follow on the heels of careful assessment of the full range of likely impacts, and the analysis should be repeated as conditions change. In practice, this sequence of events rarely happens. Indeed, the state of the art of defining and measuring impacts is so primitive and the object measured is so unstable that a firm appraisal at any one time would be impossible. Yet, some estimate must be made if only to provide a basis for comparing the tentative project with other alternatives.

One common mode of analysis is to make a cost-effectiveness analysis of a dam by a comparison with other possible measures. This analysis assumes that the primary aim is desirable and that the remaining question is whether a particular combination of engineering and auxiliary works would be the cheapest way of reaching the goal.

A more frequent mode of analysis is benefit-cost analysis. It attempts to place a value on each expected future stream of benefits and costs. The total benefits are then compared with total costs.

A third formulation is to ask what is socially the most desirable investment of the available capital. This inquiry would involve choice among sectors of investment, such as water control versus roads. It does not question the particular design of the water control works or the roads, although, like benefit-cost analysis, it involves assessment of their net social outcomes.

In both cost-effectiveness analysis and benefit-cost analysis a genuinely comprehensive evaluation would search out every possible impact and would try to attach a value to it. A series of troublesome issues inevitably arises in that effort. Many of the effects of a dam and reservoir (e.g., changes in gene stock or in species combinations of fish) cannot be readily identified. Even if these effects can be recognized, they may defy accurate monetary measurement. For those impacts that lend themselves to quantitative expression, there are the questions of what is a suitable time horizon and what is an appropriate rate for discounting the future. These decisions have a powerful influence on the feasibility calculation and rest finally on judgment in regard to the financial constraints for undertaking a project and in regard to the long-term role of the action in maintaining a viable world.

No thoughtful attempt to understand the consequences of setting in motion new ecosystems can ignore the complexities of making social and economic assessments of the foregoing sort. Considerations of the discount rate, multiplier effects, and the like cannot be dismissed, because, even if they are explicitly ignored, these factors enter inevitably into any estimate of prospective changes. The contrary also is evident; judgments on environmental aspects cannot be made casually just because solid grounds for quantitative measurement are lacking. Wise resource use is thus coincident with the best possible contemporary evaluation; it is neither superficial for reasons of expediency nor paralyzed by anxiety. Equally important are a clear-minded appreciation and statement of the inadequacies of current techniques of evaluation and a determination to improve them by learning from past experience. If the attempt is to produce constructive findings for the guidance of new research and public policy, a good deal of humility on the part of both natural and social scientists in regard to the limits of current knowledge and the difficulties of evaluating change must exist.

Four stages of creating the ecosystem. The making of the man-made lake ecosystem proceeds in four stages (Figure 1). Oftentimes the most crucial stage is the period of feasibility studies when the groundwork is laid for a decision on whether to build the structure. Second comes the period of final design and construction. Third, as soon as the dam is closed, a stage of reservoir filling and instability begins. Fourth, after the initial ecological instability, gradual adjustments take place during a more or less stabilized stage throughout the remainder of the reservoir's life.

In these circumstances, planning is not a single act of investment, however long and deliberate the studies leading to the construction decision may have been. Planning is a process that, if it is properly carried out, includes monitoring, mechanisms for preserving options, and alternatives for the timing, sequence, and scale of subprojects that may alter the direction of change in the last stage.

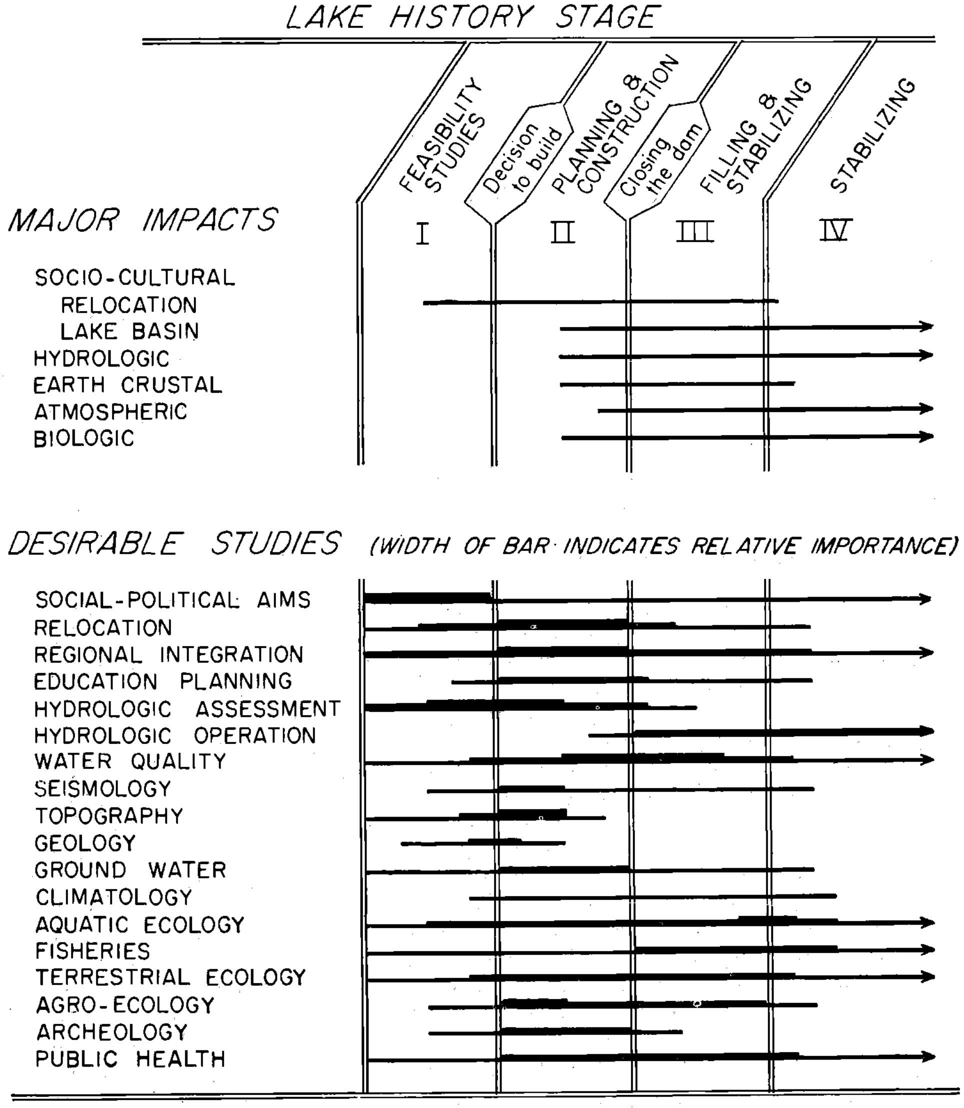


Fig. 1. Evolution of impacts of a man-made lake.

Reservoirs going through these four stages pose essentially the same problems of understanding that other ecosystems pose. They comprise an interacting entity of physical factors of environment, a complex web of biological production, and a skein of effects of human manipulation. They differ from many other ecosystems chiefly in the degree to which man causes a gross and sudden shaping of their physical structure and ensuing regime. In addition to having the usual dynamics of natural ecosystems, reservoirs have extremely unstable and transient initial conditions and a long-lasting, somewhat more predictable structure that is largely determined by initial design and by subsequent water discharge manipulations. For abruptness of initial transition in the third stage, there is no terrestrial counterpart except perhaps for the abrupt transition after such catastrophes as a forest fire or volcanic eruption. For human manipulation the character of structural design and regulation of water levels is a continuing element in ecosystem functioning.

One way of suggesting the character of the changes that take place is the evolution of impacts of a lake over time, different elements in the ecosystem taking on or losing importance as the development unfolds. In the stage of feasibility studies the definition of social aims and criteria for choosing among alternatives is crucial, although often this definition is treated only by unspoken assumption. At the same time the appraisal of whatever prior knowledge has accumulated about the physical, biological, and human characteristics of the area is essential to making estimates of impacts. In the planning and construction stage, much more detailed analysis and data collection are required within the agreed objectives of the project. The shape of the reservoir and all its auxiliary human activity are designed in this stage. In the filling stage the emphasis shifts to carrying out the plans and to observing change as a basis for later operations. In the lake management stage, there is continued interaction of reservoir discharge, biological systems, and human activity, and the ecosystem may be expected to change as social aims, management techniques, and scientific understanding evolve together.

Major components. In brief, the dam construction causes immediate relocation of people and creates a new water body. The artificial lake provokes seismic and microclimatic changes and becomes the habitat for aquatic and lacustrine populations. These populations interact in new production systems in which the sociocultural systems may be altered only slightly (when an impoundment covers and adjoins an unpopulated area) or profoundly (when new fishing, recreational, and agricultural activities are generated). The effects are not a single perturbation moving through the several systems; they change and continue through time.

In the creation of a man-made lake a previously riverine ecosystem is superimposed on a terrestrial one. The immediate result is an unsteady, not easily defined state, which with time becomes stabilized into a definable new ecosystem with limited characteristics similar to those of a natural lake. A man-made lake does not completely retain a riverine character; neither does it totally reflect the features characteristic of a natural lake. The new ecosystem is a complex hybrid that demonstrates a mixture of characters of the two parent ecosystems in physical terms as well as in behavior.

The terrestrial ecosystem contributes to the chemical character from its soils and geologic structure. It affects the physical character as a result of the mold of the flooded basin. Its flooded vegetation contributes to the early stages of the organic sediments and fertility of the new ecosystem.

The river provides the material structure for the new ecosystem: its water supplies the new environment, and its fauna and flora supply the new community. The result of the interaction of these two systems in the initial stage is an artificial lake ecosystem with its own unstable limnochemical and physical characters; its own diversified populations of benthos periphyton, plankton, large invertebrates, vertebrates, and plants; and its own energy transfer patterns at various trophic levels.

When the artificial impoundment becomes stabilized, it does not automatically take on the character of a natural lake, the features of which may be due to factors traceable into geologic times. Generally, a reservoir lacks the characteristic depth of natural lakes, and in tropical climates the stratification and profundal deposits that are so characteristic of natural lakes may be, respectively, temporary or absent. The reservoir may be deeper in parts than original maximum river depths, but even the limnetic zone may be virtually stationary and therefore may not support the biota normally associated with lenitic habitats. The resulting ecosystem produces far-reaching effects. Its conditions may, for instance, trigger an explosion growth of aquatic or semiaquatic shoreline vegetation, which in turn may have various effects on man and his actions in the vicinity of the created lake.

Thus the general question of what are desirable interventions in the environment has different points of emphasis for man-made lakes from those for numerous other ecosystems. These points change over time. The new lakes provide large and continuing opportunities for experimental manipulations of physical, biological, and sociocultural conditions. But this latitude for experiment is offset, since there is little opportunity for slow accumulation of experience. The reservoirs are not usually built by small increments to dam height, although to be sure the Aswan impoundment was constructed in three stages. Once the height is established, there is little freedom to rescind it. Whereas there may be opportunities for large-scale changes in discharge operation schedules after construction if economic constraints permit, the major structure is determined only once, usually at great expense; short of catastrophe, this structure will be on the scene for a long time.

In terms of total area transformed, man-made lakes do not bulk large. Their consequences loom higher on both the socioeconomic and environmental skyline than their combined surface does on the geosphere. Nevertheless, their symbolic importance is very great. Within their restricted areas, man-made lakes illustrate the immense difficulty of recognizing the ongoing transformation that is generated by a single technological change with all its auxiliary actions.

NEW WATER BODY

When the reservoir begins to fill, the physical structure of a new ecosystem begins to take form, and a new complex of relations between the lake and the adjoining area begins. A stage is set for biological and social transformations. This sequence has happened many thousands of times in the world, and man-made lakes now regulate to some degree about one-tenth of the total land runoff [*Lvovich,* 1969]. The physical impact of reservoirs not only is confined to the area that they cover but also extends far downstream; this impact creates major changes in hydrologic regimes. It is not within the scope of this review to describe this whole pattern of downstream change, but, where major effects substantially contribute to the judgment of feasibility of a reservoir scheme, these effects are discussed.

Inasmuch as the essential function of the reservoir is to store water, the basic questions in the feasibility stage (stage 1) of a man-made lake are whether there are better ways of impounding water and whether there are alternative ways of meeting social needs without water storage. In the planning stage (stage 2) the possible effects of the dam on sediment storage, earth stresses, and microclimate require exploration. The most crucial aspects of the new water body, however, are the patterns of water quality, density, and flow that develop in response to the local conditions and in relation to river inflow and outflow as regulated by man. These patterns may be predicted with considerable accuracy during stages 1 and 2, evolve in the filling stage (stage 3), and are the subject of continued study and manipulation thereafter. Even if the physical relationships were clear and stable, the manipulation of the new physical system is certain to change as the human values affecting demand for water shift in emphasis.

Water management alternatives. From the hydrologic and water management points of view, man-made lakes are storage elements of a local or regional water resource system built to control the flow regime of the system according to the requirements of the different water uses to be served. Water regulation by the reservoir operation is one physical means of advancing whatever social aims are defined by the government. If it is concluded that some type of water management is required, there are several alternative solutions to water resource development [*National Academy of Sciences,* 1968] that may serve partly or entirely as substitutes for man-made lakes in favorable circumstances. These options may include (1) extension of groundwater exploitation, (2) artificial recharge of groundwaters, (3) increase of streamflow by watershed management, (4) long-distance water transport, (5) decrease of demands for water by economic measures such as pricing or by technological changes (e.g., recycling of waste water), (6) desalination, and (7) cloud seeding.

Some of the above options (such as point 5 or 6) may have little or no environmental implication, but others (such as point 3 or 7) may have equal or even greater impact on the physical and biological environment than a man-made lake. It is a mistake to assume that any alternative may be an effective substitute for another in a given situation, but it is also an error to assume that water storage necessarily is socially the most desirable action.

Man-made lakes represent the creation of additional storage capacity in the hydrologic system. Always present is the natural storage capacity of the river basin itself, which transforms the precipitation regime into the streamflow regime of the river. This basin storage and its streamflow-regulating effect usually considerably surpass the storage and regulating effect of the reservoirs. On a global scale the total amount of the annual streamflow regulated by the natural basins (storage to produce base flow in dry weather) is estimated to be on the order of 12,000 km^3, i.e., about one-third of the total runoff from land areas [*Lvovich,* 1969; *Szesztay,* 1970]. Changes in land use or in soil cultivation practices may result in increased basin-regulated flow and may serve in some instances as a partial or alternative solution to constructing storage reservoirs. In other instances, such changes may decrease basin regulation and increase or create problems of floods and erosion.

Natural or artificial changes in the storage capacities of a river basin generally alter not only the streamflow regime but also the water balance. These effects may be of particular significance in arid and semiarid regions. Comparative studies have shown that the construction of several small and medium size storage reservoirs (with a total capacity of about 200×10^6 m^3) has reduced the annual flow by 10% in average years and by 25% during dry years in a 2000-km^2 semiarid river basin in northeast Brazil [*Dubreuil and Girard,* this volume].

This hydrologic side effect should not be overlooked in planning storage reservoirs and comparing them with other alternative solutions of water supply. In arid and semiarid basins such as the Colorado, increased storage reservoir development may reach a point beyond which the reduction of water yield by evaporation losses surpasses the possibilities of increasing low-flow discharges from reservoir storage [*Langbein,* 1959].

Storage of sediment. Although it is designed to store water, a new man-made lake immediately begins to store sediment carried by the stream. Storage reservoirs may lose a considerable part of their storage capacity due to silting, particularly in arid and semiarid regions. Erosion processes within the drainage area and the inflowing rivers are the principal sources of silting, but shoreline erosion in the lake itself, precipitation of a part of the dissolved materials of the inflowing waters due to changed chemical balances in the lake, nonreducible remainders of the biological processes, and wind-drifted materials may also contribute to the silting process. The range in observed rates is tremendous: in 1105 small reservoirs (storage capacity of <0.14 million m^3, or <100 acre-feet) in the United States, there was a loss of 54% of their storage capacity in 20 years under average conditions [*Dendy et al.,* this volume]. The corresponding value for big reservoirs (storage capacity of >1400 million m^3, or 1 million acre-feet) is 3%. Although many attempts have been made to develop theoretical schemes and regional empirical formulas for estimating sediment transport and rate of silting of rivers on the basis of basin characteristics, great uncertainties remain. The effects downstream on channel cutting and filling and on nutrition of estuaries and coastal beaches are, of course, linked to the volumes of silt remaining in the reservoir.

Earth stresses. The filling of a lake imposes new stresses on the earth's crust that, in turn, generate seismic movements and that, in some cases, generate earthquakes that are severe enough (6 on the Richter scale) to cause human losses. These seisms may vary in magnitude and time in accordance with a number of factors. Water height of ≥100 meters in a reservoir constitutes a factor that may be of major seismic importance in combination with geologic formation and structure. Generally, the seismic movements build up slowly to a peak several years after the reservoir begins to fill and then gradually decline [*Rothé,* 1970]. Moreover, the saturation of sedimentary formations by seepage from the reservoir may cause not only major losses of water but additional seismic movements.

Unless account is taken of these stresses by prior study and observations, both the dam and nearby areas may be subjected to unexpected damage. Anticipation of such effects becomes an essential part of feasibility investigations.

Microclimates. Relatively little is known about the precise influence of new reservoirs on weather and climate. At the microclimatic level, most of the evidence comes from comparison with natural lakes and their influence on precipitation, direction and frequency of wind, thunderstorms, hail, snow, and other phenomena. Further research will depend in large part on refinement of models of microscale atmospheric circulation [*Timofeev,* 1963]. The impact of the new lake on temperature, precipitation, and water balance in adjoining areas is related to both local conditions and mesoscale meteorological elements.

Transformation of water quality. The physical, chemical, biological, and radiological properties of the water leaving a lake may differ significantly from the waters entering the lake. A large number of factors affect this quality transformation process, and the water balance conditions of the lake are of basic importance in understanding, predicting, or influencing these changes. Four indices of the water balance regime play significant roles in setting the quality regime in a reservoir: (1) the renewal (exchange) process of the water stored in the lake, which depends on the ratio of fluxes to the 'participating' storage capacity (storage capacity participating in the renewal process is affected in the lake to a great extent by stratification conditions and internal flow regime); (2) the ratio of the amount of precipitation on the surface of the lake to the total amount of inflow; (3) the ratio of the groundwater inflow (including direct inflow and base flow of the entering rivers) to the total inflow; and (4) the ratio of the evaporation and evapotranspiration from the lake water to the total outflow fluxes.

When these indices are known, it becomes possible to anticipate gross changes in water quality, but the precise mix that will take place in the reservoir and thereby in the outflow is subject to other conditions as well. These are conditions that in conjunction with the climate govern density stratification and flow patterns within the water body.

Density and flow patterns. The possibility of a density stratification is the first question to be clarified if the flow regime of a reservoir is to be predicted. Seasonal temperature fluctuations governed by the energy regime are the most common causes of a density stratification, but other agents such as dissolved or suspended solids can also be influential. Beyond differences in densities (temperature) at different depths, the rate of flow through a given cross section is the principal factor determining the possibility of the formation of a stagnant layer or distinct water masses in the reservoir. A critical value of the densimetric Froude number (comparing the rate of flow to density gradient) has been derived theoretically for specifying conditions for the formation of a stagnant layer. However, laboratory and field data indicate that differences in morphometrics and flow characteristics cause significant deviations from this theoretical value [*Wunderlich and Elder,* this volume]. In the temperate zone, stratification in reservoirs having little inflow and outflow may be observed even where the reservoirs are shallow (10–12 meters). In contrast, strongly flushed reservoirs may be homogeneous down to several times those depths.

Where density stratification occurs, the inflow waters may move and be stored at the surface (overflow), at the bottom (underflow), or at an intermediate depth (interflow) according to how the conditions of their temperature (density) fit into the temperature profile of the reservoir. For similar reasons, flows caused by natural outflows or withdrawals develop also in specific layers of limited thickness. As a result, several distinct and independent internal currents may simultaneously exist within a density-stratified reservoir.

Wind drift is a major factor of the flow regime in shallow waters and in the surface layers of deep lakes [*Filatova and Kalejarv,* this volume]. Geometry of the shoreline and the lake basin plays an important role in the formation and development of the flow pattern corresponding to a wind of given direction, velocity, and duration. Because of changes in wind regime and the secondary flows generated by wind that cause changes in the water surface, the actual flow pattern reflects the residual effect of several preceding winds.

It thus becomes practicable to predict certain gross parameters of depth, area, water volume, sediment volume, and water quality in the new water body if there are data or estimations of the factors noted. Where these data are missing, the characteristics are much more conjectural. This doubt is increased by man's potential to manipulate inflow and outflow and thereby some aspects of temperature distribution in the reservoir. The totality of currents in a reservoir, whatever the causes for their generation, comprises a dynamic system for which relatively sophisticated model study is necessary as a basis for anticipating the consequences of altered schedules of manipulation.

Waste discharges into the lake. In many reservoirs the human discharge of waste has a significant effect on water quality, often as a result of measures not taken into account when the reservoir was planned. Thermal discharges may be highly significant, and flows of domestic and industrial effluents, of farm waste, and of excess fertilizers and pesticides may drastically modify the quality of stored water. In western Europe there are numerous reservoirs and some natural lakes that have experienced major changes in quality over recent decades as a result of these new wastes.

Heated waters are frequently released into man-made lakes by thermoelectric generating plants. Comprehensive evaluations of the applicability of the results of theoretical investigations lead to a few conclusions as to physical effects [*Benedict et al.,* this volume]. In conditions of stratified flows the wedge lengths of the heated waters may be predicted with considerable accuracy on the basis of theoretical solutions. Where there is no heat loss, which obtains close to the discharge point, the surface area within a specified temperature rise and the distance to complete mixing can be computed with reasonable accuracy on the basis of several diffusion models. Surface cooling usually has little effect in the initial regions, but it may become a significant factor if the influenced area increases in extent.

To maintain the required water quality conditions, it is important that waste discharges into the transient flows of man-made lakes be released in a prescribed proportion to the instantaneous flow passing the point of release. Thus a continuous forecasting service of the inflow and transient flow rates is a prerequisite for the effective solution of such problems [*Granju et al.*, this volume]. Such a service can be very important in evaluating the effects of thermal discharges on biological production.

Predictive capacity. A great part of the present knowledge on hydrology and hydraulics of reservoirs is based on the data of regular hydrologic observations and special field measurements. In addition, hydraulic models and laboratory tests are widely used tools in studying basic and applied problems of stratification conditions, flow regime, erosion, and sedimentation.

The development of a hydrologic model applicable to simulate the water balance and the related hydrologic events of a lake and its incorporating system is certainly the most promising basis for designing man-made lakes and evaluating their environmental aspects. For studying nutrient budget and aging processes of Lake Minnetonka in the United States, a three-subunit model was recently developed to simulate the water budget and lake level fluctuations on a monthly time scale.

A comprehensive model for lake studies is under development at the University of Texas for simulating long-term water quality changes [*Fruh and Clay*, this volume]. At its present phase the model is composed of four principal components: (1) inflow thermal and chemical routing, (2) atmospheric and radiation sources and sinks of heat, (3) vertical diffusion of heat and chemical concentrations, and (4) outflow routing (selective withdrawal).

In the course of further development it is intended to include additional components (such as chemical-biological changes of nonconservative chemicals within the impoundment) and to account for continuous changes in the water, heat, and chemical budgets of the impoundment.

Present investigations focus on the heat balance and temperature regime. In the computations concerning stratification conditions and flow regime the Koh and the Bohan-Grace solutions have been tested, and the latter has been applied. Heat balance components related to the water surface and those determined by the inflow and outflow were assessed separately but were combined in later phases of the procedure. Investigations involving temperature profiles, total heat content, and outflow temperatures as criteria for comparing computed and observed values are under way in several areas, including France, Romania, and the United States.

Theory and techniques of modeling and simulating large complex systems consisting of a hierarchy of models or submodels are rapidly developing, and it may be expected that evaluation of alternatives for man-made lakes will be assisted by this method with due regard to fairly wide ranges of their hydrologic, environmental, economic, and social aspects. By way of caution it should be noted that present predictive models for temperature regimes of reservoirs are still in the experimental stage, mainly owing to lack of precise input over time as well as to differences among reservoirs in morphologic, hydrologic, and atmospheric conditions. However, this problem exists in modeling biological systems as well. If and when predictive models can be brought to the point of practical use, then other water quality parameters such as dissolved oxygen may be introduced. Both density and chemical stratification are intimately related to fish production and harvest.

Process of creating a new water body. With regard to hydrologic and engineering activities the process of creating a new water body has four major phases that only slightly differ from those specified earlier from the broad ecological point of view.

1. Within the feasibility studies the water management options need to be specified with due regard to a tentative evaluation of all possible reservoir sites within the given region. These studies are principally based on available maps and data banks.

2. Engineering design may provide details of one or more of the accepted options and is usually based on extensive field surveys and observations. During this phase, social and environmental impacts should be identified and evaluated before final decisions are made as to design.

3. The phase of completing the project includes the construction of the dam and other engineering works (sluices, spillways, and channel improvements) and the filling of the reservoir, which is usually the responsibility of the constructors and may overlap with the construction period.

4. The operation and maintenance phase requires short-term and long-term forecasts of the hydrologic regime, as well as regular control of processes predicted or assumed in the design (rate of silting, temperature and ice regime, filtration under and across the dam, subsidence of the structures, and so on).

Regulation of lake level fluctuations. Short-term and long-term fluctuations in the lake levels reflect the nonequilibrium character of the water balance as governed by the meteorological events (primarily by the precipitation and temperature regime). Those fluctuations usually do not correspond, either singly or simultaneously, to the requirements for fish production, navigation, recreation, power production, or other water uses under natural conditions. In the tropics, mats of vegetation also affect the water balance and may hinder navigation, fisheries, and other uses. The construction of sluices to control the rate of outflow from the lake is the simplest and most widely applied way of intervening in the natural water balance and influencing the lake level fluctuations. Many attempts have been made to reduce evaporation rates by monomolecular layers or other surface covers on small reservoirs of the arid regions, but a complete control of lake level fluctuations usually requires diversions from neighboring river systems.

Such diversions, of course, impose changes on distant ecosystems. In mountainous regions, diversion by tunnel through a large vertical height with only modest lake storage may be attractive for power generation. The drawdown may thus be largely below the natural lake levels, and the natural lake bottom may thus be exposed. These kinds of reservoir projects pose many problems that are variations on the usual themes of reservoir impact. For example, natural river flows may be reduced in the drainage that was naturally receiving the diverted water, and problems of passage for anadromous fish may be created (the Nechako diversion in British Columbia is a good example).

Effects of withdrawal. Any withdrawal of water from the lake or from its inflowing rivers influences the water balance and stage regime. The result is a shift in the long-term equilibrium of the water balance and mean lake level. The direction and extent of the shift are determined by differences between long-term average precipitation and water surface evaporation. If evaporation exceeds precipitation, the result is a decrease in lake level and surface area, as in Lake Valencia, Venezuela. Quantitative estimates of the effects of withdrawals can be made on the basis of generalized water balance equations or diagrams specifying the long-term averages of the water balance components in relation to changes in the mean water level or surface area of the lake.

Hydrologic forecasting services. Safety and efficiency of riparian developments and water uses served by the lake may benefit from regular information about water levels and flows to be expected during operating periods. Short-term forecasts of flood flows of inflowing waters based on water stage and rainfall data at selected stations of the lake basin are essential to proper manipulation of spillways and sluices to avoid or decrease flood damages along the shoreline or at the damsite. Monthly and seasonal predictions of expected minimum and mean inflow may have great economic significance by making possible advance measures and regulations for water use. Predictions on water temperatures and ice regime are based on short-term and long-term meteorological forecasts and are facilitated by the great thermal inertia of the water body of the lake. The significance of such predictions of transient flow with regard to waste disposal has already been noted.

Hydrologic observations on man-made lakes. Regular and occasional hydrologic observations and field surveys are required for the following principal purposes: (1) to supply basic data for hydrologic information and forecasting services needed by the operation of the reservoir and the riparian water uses (possibly by telemetering systems in case of short-term warnings and forecasting), (2) to check the development of long-term hydrologic processes that may influence the safety and efficiency of reservoir operation (rate of silting, filtration below or across the dam, shoreline formation, effects on groundwaters, and so on), and (3) to supply data for further research on the processes involved.

National inventories of man-made lakes. With regard to both hydrologic observations and national inventories of characteristics of existing lakes, the opportunities for data collection are enormous, and national agencies must judge how much information is essential to ensure wise operating decisions. National registers may serve as a basis for selecting a few representative lakes and reservoirs for regular observation and detailed studies.

A register summarizing a few basic data (surface area, average and maximum depth, purposes and extent of use) would include all lakes, reservoirs, ponds, and dead river arms surpassing a reasonable lower limit. The significance of small size lakes and reservoirs is illustrated by the following example: in Hungary the total number of lakes and reservoirs of >100 ha is only 34, but this number increases to 300 and 1200 if 10 ha or 0.5 ha is selected as the lower limit of the register. Aerial photographs may supply all the data required for this kind of national register and, with appropriate dating, may provide a basis for evaluating seasonal and year by year changes.

Changing uses and values. Although it is true that most dams are built to endure over centuries, it is a grave mistake, often not accepted by the designer, that their uses likewise will remain unchanged. The record of the past 4 decades shows that the specific uses made of the water body may evolve rapidly after construction. However precise the allocation of water among expected uses may be, new technologies and new social values may alter the desired mix. Flood control storage may be claimed for low-water waste disposal as on the Ohio River. Recent experience in the Ruhr sector of the Rhine basin illustrates how increasing demands for recreation may inhibit fluctuations in water level on reservoirs first designed solely to serve navigation or electric power production. Such modifications in operating schedules in turn alter the hydrologic characteristics of the lake. The fourth stage is never completely uniform. And the accompanying biological transformations are never final, even though they may be more stable than they are during the filling stage.

The likely course of physical and chemical events in a man-made lake is more nearly predictable than the sociocultural events, but the two events are interlocked, for man continues to manipulate the basic inputs and outputs of water and chemicals. Thus the stage that is set for biological transformations is bound to remain unsteady.

SUMMARY AND RECOMMENDATIONS

TRANSFORMED BIOLOGICAL SYSTEMS

From the species point of view the greatest environmental impact of a man-made lake is on the natural systems of biological production, since there may be >1500 kinds of organisms alone on each square meter of land that is flooded. Inundation wipes out terrestrial production in the flooded area. Solar energy, once converted by green land plants and transferred through food chains mostly to land animals, comes to be harnessed by aquatic plants and phytoplankton and is transferred to aquatic animals, importantly to fish. In the process of environmental transformation by flooding, there is mass mortality and migration of terrestrial organisms and a virtual biological explosion of those riverine organisms, plant and animal, adaptable to life in the quiet waters of the new lake.

Process and understanding. Understanding the complex interlinked processes that lie between physical conditions on the one extreme and final production on the other is a central theme of aquatic ecosystem studies. If we fully understood the mechanics of production of undisturbed natural ecosystems, we would be better able to predict the effect of perturbations caused by man, or the effect of creating an 'instant lake' by building a dam. As it is, we have imperfect knowledge of aquatic ecosystem dynamics, and, consequently, we are imperfect in our interpretations of the transient initial conditions in reservoirs and of the relative stability that these conditions eventually assume. There is a growing body of observations that enables us to anticipate some of the biological features of reservoirs. For example, we know qualitatively that the flooding of vegetation may contribute to oxygen deficits as the plant material decays underwater, that floating aquatic vegetation may cause an array of inconveniences, and that an initial burst of productivity may be followed by less luxurious and more stable communities. But the scope of these and other effects is difficult to predict except in the most general way. These effects are events about which we can have concern on the basis of past experience rather than events that we can predict with confidence as consequences of particular projects or events for which we can prescribe solutions before they occur.

The level of scientific understanding of reservoir biology is relatively primitive because of the numbers of parameters and multidimensional aspects involved. Ecosystem modeling of biological production in reservoir situations may nevertheless be within the grasp of contemporary research. Within the next decade, several models will have been constructed for lakes.

With regard to fish production in reservoirs, empiricism is even more the prevailing level of the science. For single-species populations in virtually any environment, stock assessment techniques of varying degrees of sophistication are readily available and can be applied to management of the fishery. But, in the rapidly changing conditions following the filling of a reservoir, recruitment and growth are not stable, nor are the interspecific communities. The catch of fish is accordingly opportunistic, and it is potentially misleading before or during the stabilizing process of a man-made lake to suggest the size of sustainable yields. Once conditions are more stable, conventional techniques of stock assessment may be useful, especially if the fish community contains few species or is dominated by a few. For tropical reservoirs these assumptions may be as dubious as they are for large tropical lakes, and the best advice for the management of fisheries still is to document what is going on in hopes of gaining experience that will lead to new model systems on which to base predictions and harvesting practices.

Modern fishery resource management increasingly considers the social and economic factors involved. In many respects the maxim of maximum sustained yield is a myth because it can be uneconomic. More relevant to human affairs is maximum economic yield, and most relevant is some sort of management that optimizes social benefits for specified goals. This sort of optimum management, of course, brings in a multitude of considerations that transcend the narrow confines of a reservoir or watershed. In fact, reservoirs may provide a deceptively tidy focus for analysis of economic and social implications, and, more ideally, systems modeling should proceed from perception of social and economic goals through consideration of options to achievement, among which reservoir schemes are only one of many possible contributors.

The initial biological explosion in a new man-made lake is due both to the spatial expansion of the aquatic environment and to the release of nutrient materials from the bottom soils and submerged plant and animal remains. Normally, the lake evolves rapidly from artificially high productivity to the expected phase of relatively stable but lower productivity. Unless it is complicated by changes in water quality (e.g., from pollution), the future evolution will be reasonably predictable and generally slow, the actual rate depending on climate (latitude). The direction of this long-term evolution is much the same as that for natural lakes, i.e., ultimate filling and return to terrestrial production.

Altered land use in the basin inevitably accompanies creation of a man-made lake. In addition to gross elimination of terrestrial production from the flooded area, a number of biological interactions between uses of the land and water may develop. Hydrologically, a reservoir is a sink both for the sediments transported by and for the nutrients dissolved in tributary waters. Forestry and agricultural practices in the watershed thus affect aquatic production. Conversely, if chemicals are used to manage parts of the aquatic production (e.g., to control aquatic vectors of disease or nuisance aquatic plants), there may be impacts not only on fish but also on domestic consumption of the water and on the plants receiving downstream irrigation. Careless land management in the lake basin can accelerate erosion and thereby hasten filling of the lake and otherwise interfere with aquatic production through both siltation and turbidity.

Evaluation of the effects of a man-made lake on potential production in the land and water biological systems is based largely on predictions or on comparisons with natural or other man-made lakes. Although techniques for making predictions or comparisons are rough, they are improving. The requisite predictions can be posed as questions.

1. What is the actual and potential terrestrial production (crops, forest resources, and livestock production) that is lost by inundation? What are the short-term interactions of the modified production in the biological system with other components, especially with the sociocultural systems?

2. What is the actual and potential aquatic production (fish and other useful aquatic animals and plants) that is lost from the river, at the lake site, upstream, downstream, and from the adjacent sea? What aquatic production is gained in the reservoir, upstream, and downstream? What are the risks from changes in abundance and distribution of aquatic vectors of disease and nuisance animals and plants that may be favored by quiet waters? What rare or endangered plant and animal species and communities may be lost?

3. What are the agricultural and livestock production gains that may be derived in the

newly created habitat of the drawdown zone and adjoining lake-influenced land?

Biological system interactions. For simplicity in presenting the interrelationships of the systems that interact in the ecosystem of a man-made lake and also to emphasize the dynamic character of the mechanisms operative within each system, we have chosen to divide the life history of a new man-made lake into the four stages presented earlier. Stage 1 is the determination of the ecological, economic, social, and political feasibility of the project. If the project is determined to be feasible, stage 2 begins with the actual planning of construction and related social moves and includes the conduct of necessary studies. Stage 3 is the period during which the reservoir is filling for the first time, and this stage extends through the period after the first filling, during which the lake is biologically very unstable. Stage 4 is the period during which the lake can be considered stabilized and undergoing its more or less long-term evolution.

Within each stage we can identify the different analytical, investigational, and operational priorities that should be given to the disciplines involved in decision making. We apply two approaches at each stage: (1) identifying and defining the components of each of the systems involved and (2) determining the interrelationships and the mechanisms of all of the components (or at least of the key components) both within each system and between and among all the systems that make up the lake ecosystems. In the biological system, for example, components to be considered include not only the species and communities of living organisms but also the particular life history stages (ecophases) of each species.

Fortunately, in most ecological systems a large proportion of the energy flow takes place between a relatively small proportion of the total number of species of plants and animals. Moreover, these ecologically dominant forms are grouped into fairly separate communities. Thus, although the complexity of ecosystems is very great, the main features such as productivity and standing crops at different trophic levels can be assessed fairly simply. When they are augmented by studies of the dynamics of the dominant species, relatively superficial assessments can give a good guide to broad management practice. These techniques, of course, have been best developed for temperate aquatic ecosystems. The great diversity of species in tropical environments and the paucity of scientific workers continue to hamper the understanding of ecosystem functioning there.

Feasibility studies. At the feasibility analysis stage (stage 1) the basic parameters are much the same in evaluating both the short-term and the long-term benefits and costs for terrestrial and aquatic aspects of the proposed project. The challenge is to anticipate the effects of the proposed environmental manipulation on the four major kinds of terrestrial and aquatic organisms: (1) those of short life-span and frequent population turnover (e.g., nutrient-cycling bacteria and many algae), (2) those of intermediate life-span and turnover (e.g., cereal crop plants, some small fish, and such insects as mosquitoes), (3) those of long life-span and slow population turnover (e.g., perennial plants such as forest trees and large wild aquatic or terrestrial animals or domestic livestock), and (4) people.

To predict these effects, it is important to know the species and community composition of the terrestrial and aquatic environments affected. The plants and animals can then be analyzed for their uses, actual and potential. Judgments can be sought on which communities will contribute lasting elements to the biological system of the new lake. Some communities may become either beneficial or dominant in the new ecosystem; others will disappear. Those organisms that are or may become nuisances or threats to the health of man or his animals and crops can be especially appraised regarding whether their numbers or distribution will be altered. Where the lake site includes all or part of the range of a rare or endangered organism or community, judgment can be made on whether such an organism or community will have its survival favored or stressed by the habitat shift. If there is added danger, costs for offsetting this danger will enter feasibility decisions.

The foregoing assumes that biologists have a prior knowledge of the many species of organisms that are going to be influenced by the flooding, but, unfortunately, this is seldom the case. In general terms the vertebrates from fish to mammals and the higher groups of plants are well known or, if they are not well known, are rather readily surveyed. Microorganisms (whether plants such as algae, soil or mud organisms such as protozoans or nematodes, or plankton organisms such as copepods) are neither as well known nor as easily assigned to species rank as the higher organisms. Because these microorganisms may play important roles in ecosystem dynamics, a better knowledge of their systematics and biology is much needed. Meanwhile, they are treated as large groups that jointly perform ecologically wondrous things that we hope they will continue to perform.

Terrestrial production gains and losses by inundation. Attention is called here to one of the persistent shortcomings in benefit-cost analysis commonly applied to development schemes resulting in ecosystem modifications, i.e., the actual and potential benefits of not undertaking the scheme. This decision involves assessment of the elements of biological production that are lost if the scheme is undertaken.

In this regard the elimination of terrestrial production in the inundated land has often been overlooked. This production may be natural, i.e., culminating in wild plants and animals (some of them deemed useful); however, it may be managed production, i.e., yielding agricultural crops, livestock, or forest crops. Values for current production may be estimated with relative precision. More difficult to obtain are values of the unmanaged natural production. This production may be very high for wild animals, nature study, tourism, and recreation, and as raw materials for subsistence, construction of dwellings, or manufacture. Even more difficult to obtain, and perhaps less precise when it is obtained, is the potential production derivable from application of known techniques or from theoretical application of possible future technologies.

It has been noted that the potential area for a different kind of agriculture from that practiced in the former river bottomland is highest in the drawdown zone and in the immediately adjacent land. For most tropical man-made lakes to date, the evaluation of this potential has been inadequate.

Gains versus losses in aquatic production. Like considerations apply to aquatic production. Elimination of actual and potential riverine production can be compared to anticipated gains from production in the new lake.

Aquatic production is most evidently composed of fish, but among other living organisms it also includes green plants from microscopic through large; shellfish (crustaceans and mollusks); amphibians; and other aquatic animals such as reptiles (e.g., alligators and crocodiles), birds (e.g., resident and migratory waterfowl and shore birds), and mammals (e.g., beaver, otter, and manatee). Although man has learned to use some of each of the foregoing kinds of organisms, many remain unexploited. Concern therefore centers on the kinds that are now considered useful, and we must recognize that these value judgments may change with time.

Government statistics often provide a good measure of the worth of a stream fishery prior to inundation by the reservoir. Where statistics are not available, a substantial survey should be part of the feasibility studies. Census sampling methods can be used to obtain an estimate of stream fishery catch within specified limits of accuracy. Since the new fishery cannot begin to be managed scientifically without the recording of the catch and monitoring of its biological condition along with that of the stock in the lake, costs incurred in these operations must also be charged against development of the fisheries.

Whereas the actual and potential values for production may be estimated with relative ease in many rivers, techniques for prediction of yield from large stabilized reservoirs are far from perfect. As was previously indicated, predictions are being made with practical success in some areas by two methods: (1) comparison with known catch in existing bodies of water judged to be similar to the one that may be created and (2) application of morphoedaphic indices and multiple regressions based on combinations of selected physical and chemical characteristics of the lake and its basin, including amounts of dissolved electrolytes in the water and preliminary estimates of primary and secondary production and biomass. The second of these two methods holds the greatest hope for the precision required if economic and social values of the fishery are to be assessed properly.

A tidy, straightforward index advanced by *Ryder* [1965] for use in estimating fish yields from certain North American natural lakes has been shown to be applicable to prediction of fish crops and angler harvests in reservoirs in the United States [*Jenkins*, 1970]. The index (total dissolved solids divided by mean depth) explained 62% of the variability in standing crop in 37 hydropower storage reservoirs and 28% of the variability in the sport fish harvest in 103 reservoirs. H. Regier and A. Cordone (unpublished manuscript, 1971) have recently applied such morphoedaphic indices in estimating potential commercial fish harvests in African lakes and reservoirs.

Biological system during planning and construction. In the planning and construction stage (stage 2) the study and resource management activities for both the terrestrial and aquatic parts of the biological system are much the same. They center on the action best taken before inundation of the substrate. Thus these activities concentrate on favoring species and communities considered useful or rare or endangered and on suppressing species and communities not so considered, including ones that may become obnoxious or nuisances in the modified ecosystem. The activities involve manipulation of species populations, multispecies communities, and the environment and thus constitute a beginning of production management in the biological system. At this stage, land in the drawdown zone and immediately adjacent to it can best be prepared for agriculture. Also during this stage, experiments may be conducted in regard to improved agricultural uses and agricultural practices eventually possible in the environs of the lake.

During the time when the dam is under construction, the future lake bottom should be prepared for aquatic production as well as for the harvest of aquatic crops, safety and convenience in navigation, and reduction of health hazards by disease vectors. If it is concluded that aquatic production is favored by installation of cover, shelter, or spawning beds for fish, these may be provided. Similarly, where tree and bush clearance is judged to favor fishing and boating, such clearing is best done in advance of flooding. At Kainji Lake, 40 km^2 (some 10,000 acres) were cleared at high cost, but early experience in fishing suggests that fishing yields are highest per unit of effort in the shallows that were not cleared [*El-Zarka,* this volume]. At Lake Kariba the experience was similar. For both lakes the tentative conclusion is that lanes for fishing and boating are the most efficient forms of clearing. Clearance may also be required for other purposes, such as to suppress the buildup of weed beds or calm-water areas that encourage multiplication of mosquito and snail disease vectors.

The marking of the future shoreline by surveying techniques prior to filling is advantageous for environmental manipulations for aquatic production. Marking is also required for shoreline clearance and site preparation for foreshore agriculture; for construction of port, dock, and other shore facilities; and for the siting of towns and planning of intersecting roads.

Experience shows that construction operations can be ecologically devastating at and in the vicinity of the damsite. Blocking anadromous fish migration during construction frequently has disastrous effects. Hypothetically, even a fine fishway would be to no avail if obstruction during the construction period prevented spawning by a sufficient number of year classes to exterminate a species locally. For example, the tiger fish (*Hydrocyon*) of the Pongola River in South Africa did not make it into the Pongola Reservoir. Furthermore, the Pacific salmon are particularly vulnerable to construction effects because their spawning populations are so frequently made up of one or two age groups. There are many instances in the Pacific Northwest of North America of the long-lasting effect from short-term stream obstruction. Although disruption of flow during construction may be only temporary, denudation of the landscape, creation of erosion sores, and local destruction of wildlife can also require lengthy periods for recovery. Unnecessary obliteration of landmarks constitutes an irreparable loss since damsites inevitably become centers of interest for visitors. As for the town that initially serves the labor force of the damsite, its future will continue to have an impact on local habitat.

Biological system during filling and stabilization. When the reservoir begins to fill for the first time (early part of stage 3), the terrestrial and riverine (lotic) environments progressively disappear, and the lacustrine (lenitic) environment originates and expands. The interrelationships between the biological system and other components of the ecosystem (especially the hydrologic system) are in rapid transition. As the reservoir changes, the plant and animal communities also change. In the lake basin, there is a sequential shift from dominance by flowing water species and communities to dominance by those of more quiet water. Soil moisture and microclimatic conditions are modified around the expanding and lengthening shoreline. At this time it is advantageous to begin verification and adjustment of predictions made during the feasibility stage (stage 1) and adjustment of the substrate and other preparations made during the planning and construction stage (stage 2) in order to offset unwanted effects. During this adjustment phase, unanticipated responses of the organisms are discerned and possibly redirected.

At this stage the advice of biologists and ecologists has commonly, and often belatedly, been sought. In one instance, diversion of water to enable dam construction so increased the hazard of river blindness by creation of an improved stream habitat for the blackfly (*Simulium*) vector that costly and environmentally problematic control was required. This instance is representative of the kind of error of omission that turns a feasibility study into a salvage operation.

If selection of the time of closure of the dam is based solely on hydrologic considerations (usually when the river is lowest just before a seasonal rise), chances are against the choice's being biologically advantageous. Unfortunately, there is only sketchy experience with this overall problem of timing. For example, if there is a chance that a desired migratory fish species may become adapted to life upstream from the dam, a spawning run might be permitted to pass upstream before the dam is closed regardless of the sort of stream discharge at closure.

During lake filling, there have been opportunities to further efforts begun during the planning and construction stage (stage 2) to encourage or suppress species or communities deemed either desirable or unwanted and to implement measures for the protection of rare or endangered species, especially in the aquatic habitat. In some instances, 'rescue' operations have been conducted during lake filling for organisms threatened by drowning. We view such actions as biologically unwarranted regardless of however else they may appear to be justified, with the possible exception of nonmobile rare species and more or less fixed communities. Costly rescue and translocation of animals threatened by flooding at Lake Kariba were judged to be a failure from a biological point of view but may have had social benefits in focusing attention on a problem of land use conflict. The same judgment is true of the similar experience at Lake Brokopondo, Surinam [*Bardach and Dussart*, this volume]. We know very little about the impact of the outward movement of land animals as the water rises or of their competition with the resident populations in the areas to which they may migrate. We also do not know what happened to rescued animals that did not end up in zoos.

The most striking event in the first filling is the sudden beginning and rapid development of the lacustrine system. The cycle of biological production is fueled initially at least by a microbiological population explosion in the new standing water habitat. This explosion releases nutrients equally explosively from the submerged organic matter, which is quickly cycled (in days) into primary production, i.e., the initial harnessing of solar energy by planktonic algae. With differential rapidity, depending among other things on latitude and on the food web involved, this upsurge in primary production is typically transferred through the food chains (food web) to its most evident manifestation, a rapid (in months) rise in fish production; often there is a consequential convergence of large numbers of fishermen.

In deep reservoirs, such accelerated and differential biological production may be accompanied by seasonal density and chemical stratification of the water. This stratification is characterized by deficiency of dissolved oxygen in the deeps. Thus it not only may slow down nutrient release from the deepwater layers of the reservoir but also may make them uninhabitable for fish and other organisms. These fish and organisms may become so laden with hydrogen sulfide, for example, that they may become toxic to other organisms on the food chain and corrosive to engineering installations. Cases of this effect are known for Ayamé Lake, Ivory Coast, and for Volta Lake, Ghana, among others. Although stagnation can be overcome by artificial, pumped aeration, such action has not yet been feasible in large reservoirs.

Because of imperfect understanding of the biodynamics of production in reservoirs, especially in reservoirs of the tropics, there is a scientific advantage in launching studies of the processes and interrelationships of changing communities during the first filling. These studies need to be related to the ultimate, more or less stabilized production. Studies of successive dominance and evolution extend from phytoplankton at one extreme, through intermediate food webs, and to fish at the other extreme. Other examples would include aquatic plant and disease vector communities. A major requirement here is knowledge of the biology of the dominant species and of the regulatory mechanisms of this dominance.

Most of the rapid ecological changes started by filling continue while the new lake is stabilizing. During the stabilization process, lake evolution is irregular in speed and direction; after stabilization, future change is slowed and is usually overall in a predictable direction. Knowledge of the processes of the telescoped evolution in the early history of the lake can be of great value for predicting eventual production.

In the stabilizing period the first benefits in fisheries and agriculture become available; some of these benefits may even have been derivable during filling, depending on the length of time involved. The fixation by the lake itself of the high-water shoreline and the extent and timing of the drawdown zone enable new agricultural and aquacultural development. Establishment of favorable and predictable soil moisture and microclimatic conditions adjacent to the foreshore also enables agricultural development, given favorable policy.

It is in the early part of the process leading to stabilization that the greatest production per unit area occurs in terms of useful aquatic organisms, especially fish. For example, fish catch, as a partial indicator of production, in the section of the Volta River later covered by Volta Lake changed within 5 years from 4000 to some 60,000 metric tons per year in the new lake. Also, in Nam Pong Reservoir of the Mekong basin, the fish catch soared in the third year after filling to some 1200 metric tons to constitute a revenue of $500,000, which was two-thirds of the annual income from the production of hydroelectricity [*Bardach and Dussart,* this volume].

At this time, explosive development of nuisance weeds has also occurred. In the tropics, nuisance weeds include the water hyacinth, water fern, and water chestnut. One of the more evident characteristics of a lake in the process of stabilizing can be a rise or decline in the area covered by emergent aquatic weeds and the occurrence of dense phytoplankton blooms. In Lake Brokopondo the spread of emergent aquatics covered some 53% of the surface area of the lake in 3 years [*Leentvaar,* this volume].

Up to the present, no valid predictions of the rate of increase and peak of early aquatic production have been made. Thus it has been impossible for fisheries to manage with precision the early rate of exploitation, the entries into the fishery, the kind of gear to be used, and the investment in such gear. A common response of people to the early and predictable upsurge in fishing is like the response to a gold rush with all of its social, economic, and resource management problems. Public action should be designed to assure that a large proportion of suitable safeguards is established in advance.

During the stabilizing period, selection of environmental and population parameters for measurement over the long term will be critical to obtain improved understanding and management of the biological production system and of the other systems that impinge on it. In the long term, some of the parameters may only need to be monitored and may not need to be continually investigated in depth.

A central problem of monitoring is that the sampling processes must be representative and reliable. Water composition measured at only one station in the lake has seldom been representative of the whole lake. Reservoirs, like natural lakes, show depression and basin individuality as well as local influences from tributary streams. Such individuality has been evident at Kariba and Volta, among other lakes. In a biological sense, differences in water quality are reflected in differences in species composition and growth rates as well as in community organization. In addition, communities are different according to substrate and depth, i.e., in the littoral and profundal zones and in the benthic and pelagic zones.

The effects of water level on the biota become established toward the end of this stage, as does the relation of its fluctuations to biological production. On the basis of this new experience the system of regulating water outflow can be revised and integrated for optimal returns, full consideration being given to the multiple-use aspects of the reservoir.

Thus the interactions of the biological part of the lake ecosystem (including man) begin to become manifest during the stabilizing stage. With establishment of the shoreline, settlement along it will soon take place whether the settlement is planned or haphazard.

The human population now is exposed to hazards that are different from those to which it was formerly exposed. These new hazards are from waterborne or aquatic animal–vectored diseases. Suppression of vectors through biological, physical, or chemical means often is undertaken at this stage, as is intensified education in public health. Although the best means for health hazard suppression are obviously those that are most ecologically compatible, the history of man-made lakes shows conspicuous failures in this regard.

Artificial culture of aquatic plants or animals, if it is planned as a part of the development scheme, often begins at this stage. Nevertheless, it is ecologically best that such action not involve exotic species but that the initial experiments be made with indigenous forms, be they plant or fish or other animal. The hazards of escapement from live rearing cages or small adjacent ponds into the reservoir are so great and the extermination of unwanted introductions is so likely to be impossible that every means should be taken to avoid the early use of exotics. This precaution pertains most strongly to the aquatic environment since species selective and ecologically compatible means of control of introduced plants or animals are so little developed; however, the problem also arises when the importation of new human groups is contemplated.

Man's ignorance of the cultivability of most aquatic organisms is a barrier to progress in this connection. For example, of the some 20,000 species of fish in the world, only a very few have been explored for their aquacultural suitability. Furthermore, opportunities to develop particular strains by selective breeding are also largely unexplored.

The effects of a dam on migratory fish stocks first become evident early when the new lake is stabilizing. The effects are generated in part by the purely physical barrier that the dam creates and in part by the effect of the storage reservoir on the pattern of discharge and water quality downstream.

For most species of migratory fish it is convenient to consider the effects of dams and reservoirs as comprising a set of effects on adults going upstream and a set of effects on young migrants going downstream. In some cases a reservoir may inundate a spawning ground for migratory fish, but, in general, the problems of movement of mature adults and downstream juveniles are much more serious.

For adults, the central problem is the disturbance of the timing and energy budget for their upstream migration. Changed patterns of seasonal discharge may modify the speed of passage and in some cases may create obstructions to migration and in other instances may render migration upstream easier. Modified temperature regimes may also have either beneficial or detrimental effects. Where a dam may be provided with orifices that will discharge water from different depths, there are opportunities for manipulating temperature regimes to enhance the ease of migration. A particular problem, however, may be created by the discharge of water from great depths in a reservoir. Concentrations of dissolved gases may reach supersaturation levels and may cause gas embolisms and death of fish for several miles downstream.

Provided that the adult fish can adequately negotiate the river up to the damsite, they are then confronted with the problem of finding the entrance to a fish pass if one has been provided. The most common mistake in the design of fishways, fish ladders, or other such devices is to assume that the fish will know that a device has been put there for their benefit. In fact, it is a rather simple matter to arrange for the mechanical transport of migratory fish over a dam. The major problem is to get the fish into the devices without delay. These problems increase with the size of the discharge, the variability in discharge, and the number of fish to be passed. In general, if a dam is >30.4 meters (>100 feet) in height, it is usually not possible to construct facilities that will move the adults upstream past the dam without delaying their migration substantially (say, by a week or 10 days).

The consequence of this kind of delay in migration is that the fish may reach the spawning grounds at an inappropriate time and that they may have exhausted their energy reserves and die without spawning. This problem may be a very great concern if the size and the physical structure of the reservoir also cause delays in passage. It is commonly observed that adult fish do not move upstream through reservoirs as quickly as they would through a natural river system. There are many recorded instances in which migratory fish pass upstream over a dam and are subsequently swept downstream over the spillway; then the whole passage must be renegotiated. It has also been experienced with the Volga sturgeon that, although the fish were passed over a high dam, their upstream spawning grounds were spoiled by later reservoir flooding.

For the young fish in their seaward migration a reservoir may create short-term delays in passage downstream, and for some species a reservoir may act as a trap in which downstream migrants remain throughout their life-span as 'residuals.'

It has also been the experience that reservoir conditions favor the development of populations of predators. Natural losses to predators are thus increased because of the changed conditions.

At the dam the effects on downstream migrants depend on the route. If the fish go over the dam, there are mechanical injuries from abrasion on the spillway and at the impact of the spill with the water below the dam. These losses may be ameliorated by special design of the spillway and the tailrace, but, in general, they are difficult to avoid, especially on dams of >30.4 meters (>100 feet) high. If the migrants pass through underwater orifices and through turbines, they are subject to injury from cavitation effects at the turbines and sudden pressure changes as they are released into the tailwater. Mortalities of 20–30% are common. As a rough approximation, loss is about 10% per 30.4 meters (100 feet) of head. These losses are also difficult to avoid; in consequence, for most large dams it is desirable to design facilities that will divert downstream migrants into a safe bypass channel. These facilities usually involve very substantial expenditure because the techniques of guiding downstream migrants by light, sound, and so on are imperfect; mechanical screening or use of louver systems is often of prohibitive expense and only partial effectiveness. If the downstream migrants have successfully passed the dam, they may still be affected by gaseous supersaturation in the tailwater and a variety of downstream changes in water quality.

Because of the many effects on migratory fishes at damsites and in reservoirs, large-scale collection and transportation facilities may be suggested as devices for moving adults and/or juveniles around the dam and/or reservoir. For small populations of migratory fish confronted by high dams, these transportation schemes may be feasible, but, for large populations and large reservoirs, there are many technical problems and a prohibitive price tag.

Special problems are created when a river system is developed with a series of dams. The effects of delays on both adults and juveniles are accumulated. Additionally, as the fish pass either upstream or downstream, there is a progressive deterioration of their ability to cope with additional stresses. Many of these effects are as yet not well understood, but there is substantial evidence that the total effects of a series of dams are more than the sum of their potential individual effects.

It is thus apparent that, where a very large dam is to be built or where a series of small dams is to be constructed, one cannot be optimistic about the economic conservation of migratory fish. In consequence, it is common practice to examine the possibilities of mitigating losses by the use of hatcheries, artificial spawning channels, or other fish culture devices.

In some circumstances, fish culture practices have been notably successful in increasing the production of migratory fish. In large measure, however, these successes have been arrived at empirically, i.e., at the expense of a much larger number of failures. For most species of migratory fish, there is far from adequate experience with artificial methods of culture to encourage the belief that these methods could satisfactorily substitute for natural production. For this reason, where migratory fish are concerned, it is more likely to be a question of reservoir or migratory fish rather than reservoir and migratory fish. Substantial literature on these problems is available for Pacific salmon on the west coast of the United States and Canada, and this literature is strongly indicative of the complexities of reconciling migratory fish conservation with damming for major power development and flood control on large river systems.

Stabilized biological system. The stabilized stage (stage 4) in the life history of a man-made lake is reached when fluctuations in its biological parameters of production exceed only slightly, if at all, those in a natural lake of similar physical characteristics and like latitude and elevation. As an example, stabilization would be characterized by a seasonally cyclic balance in the oxygen budget of the lake. Stabilization is also shown by the emergent aquatic plants when their rapid initial spread has ceased, attained an extent from which there is little annual change, or even retreated from an initial maximum extent as it has at Lake Kariba. The population of commercial fishermen will also have leveled off or even declined, although the number of sport-fishing visits may continue to rise.

In an idealized system, biological stabilization also occurs when equilibrium is reached between mortality and natality of the organisms of the system and when, furthermore, the species and community composition of the system becomes relatively fixed. It is to be noted, however, that natural lake systems may show wide fluctuations in the abundance of organisms from year to year, even though the productivity characteristics of the lake remain fairly constant. Obviously, such conditions could never occur during the stage of environmental expansion when a man-made lake is filling, nor could accelerated nutrient enrichment occur during filling or when the lake is first filled. Neither should it be assumed that full stabilization is ever assured. As has already been noted, changes in water use can cause a complete revision in the scheduling of water level fluctuations and can render the biosystem very unstable again.

In addition, it must not be assumed that the processes are simple enough to be understood easily or that they are completely understood. The concept of the stabilized condition is one of a mean of variable short-term fluctuations. Fluctuations are natural functions of the biogenic capacity of regulation within the system. The amplitude of the fluctuations may be exaggerated by unusual events in the hydrologic regime (an extremely dry or hot year), in the biological system (an epidemic), or from human interference (overfishing or drastic pollution).

Throughout the development of a reservoir ecosystem, there are opportunities for fishery stock assessment and for fishery management. These opportunities have not often been firmly grasped, even though they enable rational harvesting policies on a year to year basis without comprehensive understanding of the complex web of circumstances that underlies production. Simply stated, production is the excess of reproduction, growth, and recruitment over natural mortality. A number of model systems are available that combine estimates of these parameters and indicate the rate of harvesting that is consistent with maximum yield for any stated size of first capture or, conversely, a size of first capture consistent with a rate of fishing. The various model systems available differ in their data requirements and their accuracy, and, in general, it is necessary first to approximate the properties of a fishery by simple model systems before proceeding to the use of more sophisticated, more precise but more data-hungry models. There is certainly no lack of research or experience on which to base dynamic programs of fishery management.

For all fisheries whether they are riverine, estuarine, marine, or freshwater, it is the usual practice to manage species singly. This procedure may seem unrealistic because of the many interrelationships among species. Nevertheless, it seems to work well, at least as a first and short-term approach, perhaps because of the dominance of a relatively few species in most aquatic systems. The absence of a theory of harvest for complex associations of species that occur in many tropical lakes and reservoirs is thus often bemoaned unnecessarily. Nevertheless, this area is in need of much further study.

Whatever model system is used as a basis for the management of fish stocks, a good statistical network is essential to provide data on quantity of catch, composition of each catch by species and size, and amount of fishing effort (kinds and quantities of gear used and measures of their efficiency). With this basic information, assessments of the state of fish stocks and their likely fluctuations coupled with knowledge of rates of production can direct fishery management practices as well as contribute further to our accumulating experience of reservoir biology.

Fish production is, of course, geared to human consumption and sport, and it is notable that the potential for food production in a reservoir may not be realized because of inadequacy of the mechanisms for catching, handling, distributing, and marketing fish. The anticipation of these phases of fish use should substantially precede reservoir filling. Also, the routine of statistical assessment after establishment of fisheries should perforce include data on the fate of the fish after they are caught.

The management of 'stable' species complexes (such as those in large lakes or in the world's oceans) is still largely a matter of conjecture, and it seems likely to remain so for some time. It is nevertheless characteristic that, when one or a few species are overharvested, their places are taken by other species and total production remains relatively constant. This statement implies that, if fishery management fails in its objectives, the failure may be of little consequence provided that 'other species' of fish are as acceptable to human consumers. Humans, though, are notoriously conservative in their feeding (or angling) habits. Rather arbitrarily, they characteristically assign to certain species names such as 'trash fish,' even though these fish may have equal nutritive values to 'preferred fish' or perhaps equal sporting value. It must therefore be kept in mind that social customs are a major factor influencing potential use of the aquatic production from reservoirs. Where complete flexibility of the consumers exists, a 'laissez faire' attitude toward the fisheries would seem appropriate until rates of harvest on all species are higher than those permissible for maximum sustained or maximum economic yield. Where consumer habits are less flexible or not easily manipulated, a more circumspect management is appropriate.

Consideration of the terrestrial part of the biological production system is limited here to the landward limit of soil moisture and microclimate as directly influenced by the lake. This set of lake influences is largely unexplored. For practical purposes the soil moisture effect is beyond the scope of our consideration when that effect is not available to plants that are either useful or noxious to man or his domestic animals. The fact that mobile animals, including man, may be directly influenced by the lake or may carry their lake influence far from its shore is excluded at this time from our consideration of the lake ecosystem. Thus the critical question is, To what extent is the habitat modified and what are the new advantages that may be extracted from the modified habitat by various forms of investment and technological applications? Little can be done on a rational basis to take advantage of improved soil moisture and microclimatic conditions in many parts of the world without further study and experimentation followed by extension and institution of the necessary monitoring and statistical systems.

Interest in some terrestrial potential may have to be subservient to other needs. For example, since the lake will typically be so attractive to many people, there is every likelihood that its immediate surroundings will need to be studied in greater detail and its development will need to be regulated more intensively than those of other regions. Included among the considerations have been the assignment of land for natural areas, parks, marinas, and other touristic uses; for roads, docks, and other communication facilities; for settlements, villages, and industrial sites; and for possible access means to new resources. The principal objective then is to assure that multiple-use conflicts on the shoreland as well as between land and water uses can be minimized or reconciled on reasoned grounds. With the terrestrial part of the biological system as with the aquatic part, study, experimentation, monitoring, harvest statistics, and modeling are required as a basis for rational action.

Requisites for modeling. The advent of computers has made possible the large-scale numerical simulation of complex systems such as reservoir ecosystems, for which traditional mathematical treatment poses intractable analytical problems and massive problems of calculation. In essence, the technique requires a conceptualization of quantities and the processes that transform these quantities in a dynamic system. For natural biological systems, there are characteristically a large number of quantities, and the processes that link them are imperfectly known. In consequence, the art of modeling ecosystems for predictive purposes is presently in an early stage of development. Nevertheless, there is promise of rapid scientific advance, particularly because of the impetus that has been given to such studies by various major projects, e.g., some of those conducted under the aegis of the International Biological Program.

Serious attempts to model stable reservoir ecosystems with inputs of nearly 100 physicochemical and biological parameters are now under way. Among the efforts in this direction are those of the Czechoslovakian scientists. A three-dimensional model is being developed for Walnut Creek, California, and the U.S. Department of Interior, in cooperation with the University of South Dakota, is attempting to model biological production in the 11,400-ha Lewis and Clark Lake.

In a model of aquatic biological production in a reservoir, the following initial components can be visualized. Values for some of these components are taken from the data of related physical systems, others are obtained from continued monitoring of physical and biotic factors (autometered where possible), and still others require particular studies. When the model is operational, even with extrapolated or assumed values where empirical data do not yet exist, such a model not only can become the basis for rational exploitation and management of the living aquatic resources of the reservoir in question, but also can be of great predictive value in the feasibility and planning efforts for man-made lakes yet to come.

The following have been selected for minimal automated monitoring with special attention to the use of physical data in modeling of aquatic biological production on man-made lakes (the monitoring is to be done at different stations corresponding to areas of morphometric and water quality individuality): water temperature, solar radiation and light penetration, dissolved oxygen, conductivity and dissolved solids, redox potential, and density currents. All the foregoing areas need to be measured and registered at appropriate depths and times in order to provide useful data at warranted cost.

Where they are not otherwise similarly obtained and adequate, the following factors may be added for the atmospheric system just above the surface of the water: wind direction and force, relative humidity, and precipitation. Of course, selected instruments to obtain data on other factors dealing with aquatic biological production or on water characteristics related to other water uses may be added to the instrumentation column at each station as specific needs dictate.

It will always be desirable to backstop such quantitative monitoring with calibration by classical methods and with selected qualitative measurements of interpretative value, e.g., the amount of turbidity that is due to plankton and the qualitative composition of crops of phytoplankton, zooplankton, and benthos. Automated sampling of plankton for both quantitative and qualitative purposes is beginning to prove both feasible and valuable.

In spite of the thousands of published studies on aspects of terrestrial and aquatic production in new lake systems, both the scientific understanding of the processes and their management leave much to be desired. The overriding need is for international review (more penetrating than has been possible in this report) of existing knowledge to disclose what is known adequately for predictive purposes, what studies should be pressed forward with greatest vigor, and which theories are in need of testing. Such a review would be prerequisite to the needed intensified efforts at modeling the processes involved and would be part of interdisciplinary reviews of the other related systems. It should include diagnoses of the differences and similarities in the mechanics of biological production in artificial lakes and in natural lakes (about which most is known) and between tropical reservoirs and temperate reservoirs (about which most is known). The result would be welcomed by scholars and resource managers, and great gains in investigational and managerial efficiency could be anticipated. Short of the foregoing international review, measures to increase information flow and retrieval would serve to encourage investigators to undertake relevant studies.

SOCIOCULTURAL SYSTEM

When a man-made lake is created, the members of the lake basin population are displaced, crowded, or supplemented by new migrants and are often stirred by the political repercussions of enforced relocation. Beyond that population, a much larger area is affected by the development of new conditions of life and livelihood. Generally, the larger the lake, the greater and more complex the impacts on the sociocultural system.

Lake Basin Population

Within the lake basin the human population can be divided into four general categories, of which the first two pose the most problems. These categories are (1) those who must relocate because their homes and fields will be partially or totally inundated by the reservoir (the relocatees), (2) those among whom most of the relocatees must be resettled (the hosts), (3) those lake basin inhabitants who are neither relocatees nor hosts, and (4) immigrants who move into the lake basin and seek new opportunities that accompany dam construction and reservoir creation.

Throughout the world, most relocatees desire to remain as close as possible to their original homes or family or tribal associations, although a significant minority opt to use relocation to seek a new life elsewhere. As for the hosts, they may or may not be members of the same society or tribal group as the relocatees. Even if they are members of the same group, differences in dialect, behavior, attitudes, and expectations may set the two populations apart at the time of relocation. Furthermore, both will differ from immigrants who are often risk takers and who are more apt to innovate.

Increasingly, planners attempt to bring benefits of the dam to the lake basin population. This attempt by the planners is especially true for the relocatees who must give up their homes and surroundings for the national good. For this purpose, it is important during the stage of feasibility studies (stage 1) to analyze carefully the benefits and costs of relocation and of alternate development strategies for the entire lake basin population. Some of those strategies have major implications for other management objectives of the reservoir. The social and economic benefits, for example, of extensive lake margin agriculture, one requirement of which would be regularized drawdown and filling, might be sufficiently great to warrant some sacrifice of power, flood control, and other benefits. Such analysis is now done in planning projects in certain industrial countries. Also during the feasibility stage, important policy decisions are needed on who should participate in new resource opportunities and on the spatial pattern of settlement. If the local people, for example, have no fishing skills, immigrants from other fisheries may move in and fill that occupational niche before lake basin residents respond. The implications of this possibility need to be carefully assessed in terms of a wide range of factors, including continued productivity at relatively low costs; relationships between immigrants and basin residents; availability of other occupations for relocatees and hosts; capacity of government agencies to provide training, extension, and other services; and so on.

The local population is part of a complex sociocultural system, which is intricately interrelated with the physical and biotic components of the lake basin habitat. The people are members of a dynamic coping system. Corresponding with the lake basin and the reservoir site, the sociocultural system is already a man-made ecosystem to a considerable extent. Though the local people may not be responsible for dam construction, their future activities and especially their land and water use will modify their habitat just as surely as the habitat will influence these activities. Because we are dealing with people who can innovate or accept innovations, the range of possible interactions with the lake basin is very great.

Lacking a general theory to predict these interactions and their consequences, we must fall back on careful planning as an ongoing process in which attempts are made to assess the impact of particular development ahead of time. Subsequent evaluation of actual activities may then help to identify problems before or as they arise and to propose appropriate solutions.

Relocatees. From the human point of view, relocation has been one of the least satisfactory aspects of reservoir projects. Not only is it an incredibly complex process, but it is expensive in money, personnel, and time. Rather consistently, analysis of the implications of relocation has not been included in feasibility studies. As was the case at Kariba, the numbers of people involved are often seriously underestimated, whereas the diverse needs of different categories of people (children and the elderly, landowners, tenants, landless laborers, and so on) seldom receive sufficient attention. Also seriously underestimated is the financial cost of compensating and physically moving people, the cost of forming new communities and new systems of production, and the time required for essential help. In the major African projects, per capita relocation expenses and final estimates have varied from approximately \$200 per capita to >\$2000. In all of these projects the relocation expenses have been at least 3 times the original estimates and sometimes substantially more. Had planners known from the start that relocation costs would rarely be <25% of the combined cost of power generation and transmission and dam construction, they would have approached feasibility studies in a rather different way. Sometimes, financial costs of resettlement may be sufficiently great to offset expected benefits of dam construction in comparison to alternate uses of funds. This kind of judgment must be faced in future large projects such as the proposed Pa Mong project in the Lower Mekong basin.

Although it may be desirable to involve eventually the entire local population within the integrated development of the lake basin (which itself must be carefully integrated within national and regional development), the relocatees require special attention initially. Compulsory relocation of an entire population incurs stress (physiological, psychological, and sociocultural). Every relocation project has an initial transition period during which the relocatees attempt to alleviate stress. This period begins as soon as they become aware of the possibility of relocation, usually early during the stage of planning and construction (stage 2). The period ends when the relocatees are once more economically self-sufficient and when they have come to terms with their new surroundings, including the hosts. For the majority the length of the transition period is seldom, if ever, less than 1 year from the time of actual resettlement. Where the people are incorporated in ambitious but poorly planned government schemes to transform their economies and life styles radically, project failure can prolong the transition period well into the stage of stabilized lake conditions (stage 4). Even where planning is effective, some (especially the aged) will never come to terms with their new homes. For them the transition period ends only with death. A government takes on that social responsibility when it causes compulsory relocation.

The period of transition is a period of coping during which the sociocultural system of the relocatees is adapted to new circumstances. Initially, the system reduces their behavioral complexity. Certain premises and attitudes may also be dropped. Although the actual situation will differ from reservoir to reservoir according to a wide range of variables (including the sociocultural system and the goals of policy makers), some behavioral patterns are dropped simply because of their ties to the old surroundings or because they are inappropriate within the new surroundings. With insecurity, some people may minimize their vulnerability by doing as little as possible, and others may engage in random exploration. Furthermore, people may cease temporarily to practice distinctive customs for fear of alienating the hosts. The very fact that government can uproot people against their will can undermine the confidence in their capacity to control their own lives or at least to influence the impact of external forces. By analogy to ecosystems, simplification of the sociocultural system can be dangerous in that it can lead to breakdown and demoralization. However, it can be a mechanism for leaving behind forms of behavior that are counterproductive in terms of subsequent modernization or that could not be jettisoned in the old habitat. Regardless of the situation, it is important that the relocatees regain their self-respect and self-sufficiency.

The initiation of environmental change thus provokes a crisis of individual and cultural identity. Whereas this crisis appears inevitable in that no preparation can in fact eliminate the shock of being physically uprooted (and the accompanying sense of helplessness), the relocation authority can do a number of things to ease the stress and to end the period of transition as rapidly as possible.

1. Completion of suitable social surveys will, among other purposes, identify those relocatees who wish to move as communities and those who wish to move as families and individuals. Though those with certain job skills and education may need no government assistance at all in finding new opportunities and homes even in postindustrial societies, lower-income groups, minorities, and the elderly will need more help than that which they have received in the past. In developing areas the probability is high that most relocatees will wish to move as communities, although in some projects (e.g., Nam Pong in Thailand) a significant proportion may wish to relocate themselves. Because of the complexity, costs, and high risks associated with planned resettlement, it may be in the government's short-term interests to facilitate wherever possible individual and family movement; however, it may cripple the community by removing leadership. The capacity to facilitate is closely tied to the ability of the relevant agencies to understand the desires and abilities of the relocatees, and this understanding should be linked with flexibility of action.

2. Continual two-way communication with the relocatees (and to a lesser extent with the hosts) to educate them for the movement and to determine their major wishes and concerns is helpful. In spite of a wide range of potential difficulties, special consideration should be given to involving the lake basin population, through carefully selected representatives, in the planning, execution, and evaluation of resettlement and lake basin development. Such involvement may undermine local leaders unless they are given a genuine role.

3. Educational and training programs should be initiated early so that relocatees and other lake basin residents can benefit from new opportunities. Where people wish to move as a group, it is also important, prior to relocation, to create pilot communities and supportive land use systems based on the means available to the average producer so that the relocatees can have some idea of what the future holds in store for them.

4. Relocate people into communities where essential services are operative from the beginning. At the minimum, these services should include housing (which may or may not be government built), an adequate water supply, sanitary facilities, equipment or domestic stock, and medical services.

5. Restore community self-sufficiency at the earliest possible date; i.e., develop economic production systems. Whereas the strategies used obviously depend on government policy, lake basin development takes time. Where planning is delayed until actual construction begins, there is insufficient time to prepare new land use systems and other economic opportunities. This lack of time has been the situation in the major African projects where relocation has taken on many of the aspects of a crash program to remove the peo-

ple from the reservoir area before inundation. Because new production systems were not operative when relocation occurred at Kariba, Volta, Aswan, and Kossou, it was necessary for the government to arrange food relief to the people for 1 or more years. This operation is expensive and unproductive, and it runs the risk of creating a dependency syndrome among relocatees who come to expect the government to continue to meet their basic needs. Although the best corrective is advance planning, a more flexible timing of dam closure also deserves consideration where social circumstances warrant such an action. Although flexible timing has not been possible with narrowly conceived hydroelectric projects where dam construction is rushed to meet rising energy demands, future careful assessment of a wider range of benefits may justify delayed closure in some circumstances.

It is also important to involve the hosts in new development opportunities, including, for example, the lake fisheries. Otherwise, deteriorating relationships among administrators, relocatees, and hosts interfere with social and political stability and economic growth. Because the better resettlement areas usually are already partially occupied, relocation almost instantaneously increases population density and the demand on land resources and job opportunities. Higher population densities require careful planning so that the land and job opportunities support both relocatees and hosts at an adequate standard of living. In some areas, this standard may not be possible solely with agricultural intensification and may require special provisions for attracting industry. It may also be necessary to reserve, at least temporarily, the fisheries and the lakeshore margin for exclusive use by the lake basin residents. Thus traditional fishing rights of migrant fishermen may be endangered.

Continuity and change. Continuity is important for those who must relocate in connection with reservoir formation. Rational irritation and local loss of faith in government may accompany relocation, but rapid and dramatic changes in ideology have not been documented during the transition period for any man-made lakes. Rather, two complementary coping mechanisms have been observed. One amounts to a form of sociocultural withdrawal whereby the total inventory of behavioral patterns is reduced. The other is outward directed and initiates the process of adaptation, first, to the threat of resettlement and, second, to the new surroundings. Although certain dramatic changes in behavior may occur at this time (e.g., farmers experimenting with full-time fishing or tenants with land ownership), it would appear that, within the context of resettlement, people change only as much as they have to in order to continue the realization of relatively fixed cultural goals.

Neither of the two mechanisms necessarily has negative implications for government attempts to induce change. Whereas a severe crisis of sociocultural identity may temporarily immobilize much of the population, the dropping of certain customs in the long run may be beneficial. A process of adaptation that includes some experimentation presents selective opportunities to development planners. This situation is especially true in regard to the better-educated, more mobile, and innovative members of the lake basin population. As the proportion of these members within the population increases, the opportunities for rapid and radical change rise. Hence the initial opportunities for economic change within the various lake basins of the Tennessee Valley in the United States exceeded those at Kariba, for example. Nevertheless, with compulsory resettlement, everyone must be moved, including the elderly and the conservative as well as the young and the progressive. Even in postindustrial nations with high literacy and mobility, rural populations tend to contain a greater proportion of the elderly and the traditional than urban centers. Over one-half of the people resettled in connection with 20 Tennessee Valley Authority (TVA) reservoirs were tenants who were less apt to have the resources to innovate than landowners and businessmen.

In the past, river systems served as important routes for prehistoric migrations and for settlements. All too often, reservoirs have been created before archaeologists have had sufficient opportunity to survey the area to be flooded and to excavate the more important sites. Similarly, people were moved before historians and social scientists could record their traditions and study their customs and interrelationships with their river basin habitat. As mankind becomes increasingly concerned about the future and interested in the past, we cannot afford to destroy our past without first obtaining some sort of record. The reasons to support this view are both practical and theoretical. It is practical in that information about the past is a part of the local heritage that nations may wish to incorporate into their schools and into their national culture and in that base line studies of the contemporary population help planners choose an appropriate development strategy. It is theoretical in that knowledge of the past forms a data base for the testing of theories. Archaeological, historical, and contemporary sociocultural studies should be completed at some minimum level of expenditure in river basin areas where there is reasonable probability of a future reservoir. It is anticipated that the findings from these studies will provide sufficient reason for rejecting a particular damsite or height or for choosing an alternative to building a particular dam.

Incorporation within the national fabric. Reservoir creation speeds up the incorporation of the lake basin population into the nation of which it is part. New roads to the damsite and reservoir channel people, goods, and services both in and out. Rural development tends to speed up the integration of local residents into a wider economic context. Construction of the dam requires a large labor force, most of whose members may be from outside the basin and who introduce new ideas and customs. Resettlement is usually accompanied by new schools and other social services.

The benefits and costs associated with this process depend partly on who calculates them. Not only do they vary between various age and occupational categories among the local people, but they also differ from the viewpoints of individual members of these categories. From the government's point of view, benefits and costs will vary according to the interests of the agencies and personnel involved and the development following impoundment. Increased communication with the outside world causes local expectations to rise. If these are not met through improved job and land use opportunities, the gap between aspirations and achievement widens. Aside from discontent and potential unrest, one probable result is accelerated migration of young people to cities that may or may not be able to absorb them. Although a distinctive ecosystem is created, the change knits the lake basin more closely into a widened fabric.

Central Planning and the Lake Basin Population

Man-made lakes characteristically are the result of external planning by a relatively autonomous development authority or a centralized agency. In developing countries, big dams like Volta Dam or the Aswan High Dam may be the most expensive projects within national development plans. Partly for this reason the lake basin population is seldom involved in the planning, execution, and evaluation of a program directly affecting their future, although there are important exceptions. So far as communications permitted, the Volta relocatees were consulted regarding plans, but tragic political errors then were made.

Increasingly, social scientists study the interrelationships between the lake basin population and government agencies as part of one system. The effort is to understand the behavior and goals not only of the local people but also of the administrative officers. Conflicts are apt to arise among agencies and between agencies and the local population, and from the outset the resolution of those tensions influences the design of the reservoir and accompanying investment.

Much research on the interrelationships between organizations and populations is undertaken so late that there is little or no impact on either the agencies or people. One responsibility of such research is to assess the capacity of the development agencies to achieve their goals. Another is to explain the ecological system perspective to the developers to help them to better understand not only the relationships but also the potential sources of friction and inertia within the system. A third responsibility is to facilitate two-way communication between all participants in order to reduce the likelihood of major misunderstandings. In developing countries a relatively uneducated lake basin population tends to be suspicious of government goals and personnel, whereas the latter expect the people to be immediately grateful for government help. By contrast, in some industrial societies, the citizenry increasingly demands a role, often a leading one, in the decision making relative to regional development and to reservoir operation. In the absence of effective mechanisms for bringing together those who want a piece of the action, there is a need to institutionalize such new concepts as 'open planning.' It may be expected that future planning of man-made lakes will place growing weight on the part of citizen groups in setting goals and operating schedules.

Lake Basin Development

Development of new land use systems: agriculture, livestock, and forestry. An integrated land use system is the key to increasing the productivity and maintaining the quality of the terrestrial communities of the lake basin in relation to water use and aquatic communities. Agriculture, livestock management, and forestry affect each other and combine to modify the social, physical, and biological systems. Forest reserves protect water catchments, tributary banks, and the lake perimeter, and their sites influence recreational, domestic, and industrial needs. In a developing area, forests may be the principal source of wood for family cooking, building, and cottage industries. Livestock pastured along the lakeshore margin may promote water pollution, disease, and reservoir silting.

Within developing countries the intensification of lake basin agriculture has been one of the least satisfactory aspects of reservoir projects. Although TVA has a more successful record, the extent to which tenant farmers, landless laborers, and other low-income groups shared in that success is still not clear.

In developing areas the lake basin may be only an incidental part of a big dam project. Agriculture is more apt to be stressed in irrigated areas below the dam. However, agriculture requires discerning attention within the lake basin for two reasons: (1) a large proportion of the lake basin population must continue to support itself by agriculture for a long period, and (2) relocation usually increases population density. As has already been noted, resettlement increases the probability of severe environmental degradation through overcultivation and overgrazing. A risk today at Kariba and a threat at Volta and Kossou, development of a new land system may impair the physical and biotic base of terrestrial communities.

Induction of agricultural change is complex, intricate, and poorly understood. Settlement schemes have a high failure rate around the world. They provide housing and social services but often are unable to assure viable land use. Viable here means a system of satisfactory production that is simple enough to administer and that achieves the cooperation of the settler and does not reduce yields per acre and unit of labor as a result of land degradation. In a broadened content the viability of new land use systems is also linked with their capacity to absorb additional labor if the regional or national economy has increasing unemployment and underemployment.

Few developing countries have a suitable agricultural plan for the lake basin at the time of flooding, let alone the administrative capacity to execute a plan following inundation. More emphasis has been placed on resettlement areas, some of which are outside the lake basin, as is the case of the Aswan High Dam. People usually are shifted before new land use systems are sufficiently productive to support them. One adverse result in connection with the major African reservoirs (Kainji being the major exception) is a prolonged and potentially demoralizing period of food relief.

There is no easy procedure for developing new support systems for relocatees and other inhabitants. In the case of most African projects except Volta, planning for resettlement and lake basin development was delayed until preparatory works began at the damsite and in some instances until dam construction began.

The obvious means to avoid this failure to provide for resettlement is to broaden the feasibility surveys to include agricultural, sociocultural, and ecological analysis. A major function of agroecological studies is to identify areas that can be cultivated. As populations increase, the task becomes harder. Another function of agroecological studies is to provide information on how the land may be allocated, individual choices being taken into account. The extra cost of the needed surveys during the feasibility phase is small in comparison with the potential benefits. Based on information on the economy, habitat potentialities, and individual expectations, training and extension programs can be drawn up.

A technically feasible plan is of little use if the local people are unwilling or unable to exploit it with the desired results. One function of sociocultural studies is to assess those aspects of present land use systems and farmer attitudes pertaining to the change that the people and agencies think is promising. An effective extension service requires two-way communication. On one hand, its task is to extend to the farmers the results of agricultural experience gained elsewhere. On the other hand, it must inform those developing the new land use systems of bottlenecks relating to the farmer's capacity, ability, and willingness to produce. Even if production is successfully intensified through the use of monocropping, manure, chemical fertilizers, pesticides, herbicides, and supplemental irrigation, the ecological implications of such techniques are only partially understood in the tropics as elsewhere. The risk of ecological boomerangs is sufficiently great to require periodic assessment of the environmental effects of new land use systems. This assessment should have a corollary alertness to breakthroughs in research, the implications of which are compatible with preserving the habitat.

A unique feature of man-made lakes is the drawdown area. Where the primary purpose of the dam is power generation, the annual drawdown may be more irregular than the annual regime of the river prior to impoundment, as was true at Kariba. In these circumstances the risks to the farmer are usually too great to justify the use of drawdown for cultivation. This situation poses a policy choice, since the drawdown area at Kariba and other tropical reservoirs has the potential for supporting thousands of small holders. At Volta, some research has already been carried out on the biological capacities of drawdown soils for cultivation, and immigrants are doing so on their own. More research of the same nature is required before new projects are undertaken, and there is a special need to test different land use techniques within the drawdown area. These tests should include a wide range of crops and should be conducted with and without the use of supplemental water. Efficient use of the drawdown area for agriculture and animal husbandry requires that the drawdown regime be carefully regulated. To do so in a multipurpose project requires that the benefits and costs of drawdown use be compared with the potential uses of the water other than the primary uses. Because such analysis is generally lacking, no one knows the extent to which drawdown areas could contribute to national production and employment.

Fishing. One of the more gratifying aspects of man-made lakes is the speed with which a reservoir fishery develops and the extent to which fish landings and fishery jobs increase. In the tropics, rural residents respond rapidly to new opportunities, and, indeed, fishery development may slow down movement to the cities and may even bring back former migrants. On Kariba's north bank, >2000 local fishermen were landing >3628 metric tons of fish per annum within 5 years of reservoir formation, and outward migration reduced significantly. At Nam Pong in Thailand, approximately 1000 fishermen were present after a similar time period, and the figure at Volta was estimated to be as high as 20,000 fishermen using 12,000 canoes and landing up to 60,000 metric tons of fish per annum. The response was spontaneous; fishery development was not facilitated by government action, as it was at Kariba.

Notwithstanding the potential of reservoir fisheries for providing food and jobs, it cannot be assumed that landings and number of fishermen will increase. Quite to the contrary, the figures quoted from Kariba's north bank correspond to the period of reservoir formation (stage 3). Thereafter, landings dropped off rapidly so that 10 years after closure there were only about 907 metric tons of fish landed per annum, and the number of fishermen fell equally dramatically.

Although landings at Kariba began gradually to rise as the lake entered its early stabilization phase, fluctuations in lake productivity pose complex problems. If the trend that occurred at Kariba also occurs at Volta, perhaps half the fishermen may go out of business. There are at least two possible solutions. One is to slow down the buildup of fishing during the initial period of high productivity; the other is to be prepared to take compensatory action in the fishery at the time productivity peaks, possibly by introducing new gear and techniques and by encouraging the use of previously unused or underharvested species stocks. The latter option, if it can be made to work, may be preferable, since productivity and employment opportunities during the bloom period would otherwise be lost to the nation.

At both Kariba and Volta, only a small proportion of the reservoir is currently being fished. If improved boats, new gear and techniques, and revised management and conservation measures were introduced before the drop in productivity, it might be possible to employ the same labor force by intensifying the existing fishery and expanding the area fished. Another issue concerns who is to fish a new reservoir. If the lake basin population has no history of commercial fishing, as was true at Kossou, outsiders may immigrate into the area and fill the new occupational niche. Although this immigration may be desirable in some cases, it is also wise to decide before impoundment who shall best compose the population of fishermen. A fishery training program for lake basin residents may diversify their occupational structure and reduce pressure on the land. In any event the policy decision on the training program needs to be initiated before impoundment occurs.

This decision, in turn, raises the question of balance between alternative fishing technologies. In a few instances a highly efficient capital intensive operation employing a small labor force may make sense. Elsewhere, the balance may shift to a small-scale, artisanal fishery that does not necessarily correlate with lower labor productivity. The problem is to increase net income to the maximum extent compatible with the habitat and also to meet employment needs of the lake basin population.

Even though these questions also arise for temperate reservoirs, the emphasis on recreational fishing is stronger there. In the Tennessee Valley reservoirs the tonnage landed by sport fishermen exceeds the production of commercial fishermen. The overall economic impact of this combined fishery is estimated at about $90 million per annum. For the United States, commercial harvest from approximately 1 million ha of reservoirs averaged only about 8 kg/ha, though potential yield has been estimated at 23 kg/ha from 2 million ha of large impoundment. The annual commercial harvest from USSR reservoirs is about 44,000 metric tons.

Recreational fishing ties in closely with tourism. Seeking the proper balance through time between recreational and commercial fisheries calls for analysis of the relationship between tourism and development within the lake basin and of the recreational needs at the national level. Once again we return to the need for benefit-cost analysis or regional accounts within a widened context.

Industrial development and lake basin electrification. Industrial development is perhaps the most difficult topic to relate directly to a man-made lake. In planning such development, analysis of regional social accounts in relation to national accounts is possible for both labor and material resources. There are, however, only trial frameworks for regional and national economic analysis, including the effects of industrial complex development. In the absence of refinements in such methods it is necessary to make practical decisions on investment and resource management.

Where hydropower is generated by the dammed water, industries may be drawn to the lake basin partly because of a plentiful supply of electricity at reasonable rates and of water. However, the economics of power transmission are such that most of the generating capacity of the turbines often is used outside the lake basin.

SUMMARY AND RECOMMENDATIONS

In viewing man-made lakes as ecosystems, policy makers face the problem of the extent to which the lake basin should be electrified as an aid to development. Here a major factor is the distribution of population and its ability to use electric power. Contemporary extremes range from Kariba, where the entire generating capacity of the dam is exported except for the electrification of the Kariba township, to TVA, where the per capita consumption of local power by the lake basin population is higher than the per capita consumption elsewhere in the United States.

RECOMMENDATIONS

The far-reaching effects of lakes thus far created by man and the prospect that many more will be proposed for construction in the years immediately ahead make it important to initiate certain action at the national and international levels for the enhancement of human capacity to act sensitively and intelligently when major environmental modifications are undertaken.

Since man-made lakes are major elements both in enlarging human production and in disturbing natural systems, part of the needed action involves policies of governmental and intergovernmental agencies, and part involves the design and promotion of research. These steps are recommended not only because they promise improvement in dealing with man-made lakes but also because the experience with such a finite system has implications for action on the broader front of overall environmental management and economic development.

In suggesting desirable public action, we are acutely aware that the scientist and the public decision maker may have different perspectives. The scientist is interested in obtaining the maximum amount of relevant data and in refining analysis: he is concerned with the discovery of scientific regularities and the modeling of processes. The public decision maker, in contrast, needs to have the optimum amount of data required to make timely decisions that have an acceptable probability of capturing the greatest part of the potential benefit available. He would like to know the full effects, but he will never have that mastery of the world and must always settle for something less.

When we speak of increasing accurate techniques of modeling the complex ecosystem that is a man-made lake, we are interested primarily in identifying whatever small number of critical variables must be clearly identified and, wherever possible, quantified to make the decision-making process ever more effective. This identification, in turn, is a constructive step for the planning of research; it helps the attempt to get the right questions investigated at the right time and at the right scale.

The immense number of investigations from which the findings in this report are abstracted may be assembled in a variety of ways, and this volume brings these investigations together in the most comprehensive fashion yet attempted. For reasons previously noted, such efforts lack the synthesis necessary to make them fully useful in guiding policy. Characteristically, studies of man-made lakes are pursued either as exercises in a particular scientific discipline or as routines of a government bureau. Sometimes they are the object of special study teams. Ironically, the most comprehensive efforts in many parts of the world have been salvage operations. The result is an unevenness in treatment, fragmentation of information on any one project or subject, and almost invariably a failure to provide a holistic focus on the total impact of a reservoir in a general geographic context. In this review we have pointed out numerous places where more incisive assessment could change the impacts in the ecosystem. Thereby, we have indicated the social significance of the decisions and the scientific grounds on which they are made.

The following recommendations are aimed at policy makers and scientific administrators who have the power to apply the lessons thus far learned and to promote research activity, communication, and cooperation to generate understanding needed for decision.

Essentials of Public Policy

On the basis of available knowledge about these new ecosystems, three aspects of public policy may be recognized as being essential to the consideration of further construction.

1. Assessment of alternatives. Any decision to build a man-made lake should be based on a comparison of the effects that are likely to result from the construction of a man-made lake with those that would result from alternative technical and social actions to serve the same public aims. This comparison requires at least preliminary assessment of the relationships outlined in this report. To carry out such an assessment is an extremely difficult task, and the government agency must decide how much uncertainty in the results it is willing to bear.

2. Canvass of impacts. It is transparently evident that, unless care is taken to anticipate the full consequences of building a new lake (including the impacts on the sociocultural system), the responsible public agency courts serious damages and expensive salvage or corrective operations. A policy of going ahead with the development of a man-made lake will not do without a systematic canvass of those relationships and without a willingness to take measures to cope with the most difficult ones before they arise. A policy of neglect does not pay in either the long or the short run. There already are enough cases in which the costs of only one unanticipated side effect have increased the economic burden of the undertaking by 50–100% above the figure used in the feasibility finding.

If a thoroughgoing canvass of the full consequences of a new dam is made, it may lead to one or more responses:

1. The proposal may be encouraged with the understanding that certain precautions will be taken in the unit design, construction, and filling phases of the project or that the design will provide for greater flexibility of eventual operation.
2. The proposal may be delayed until further investigations are made of questions that appear to be serious, unanswered, and suited to study.
3. Investigations of critical problems involved in operation of the dam may be launched to proceed parallel with the preparation of final construction plans.
4. The proposed project may be deferred in recognition of the social costs attached to it.

3. Consultation with the people affected. If unfortunate consequences are to be avoided, a necessary provision of public policy is to arrange for the involvement of the people directly affected by displacement or by associated actions in the future lake basin system. As has been shown, the people whose lives are disrupted often are taken into the confidence of the builders only after a final decision has been made. Then it may be possible to prevent some of the human injury, but it is too late to avoid or remedy such distress in the planning. The people touched by the environmental transformation caused by a man-made lake are to be treated as a potentially dominant part of the ecosystem in transition. In the choices that must be made on who will be disturbed and what assistance they are given, their voices should be heard. Some distress is inevitable, and bearable stress must be weighed against future advantage.

It should be clear that, in the face of inability to predict many of the possible results and of the futility of halting all action until we learn how to predict, it behooves us to develop flexible administrative machinery. With man-made lakes as with environmental management in general, the human race's scientific and engineering capacity has run far ahead of its ability to single out objectives and implement them effectively. Any realistic analysis of effects needs to be framed with regard for the structure and capacity of the governmental systems to carry out the program. This consideration includes the ability of government agencies to generate needed information, to pass some of it along to the people affected (providing opportunity for the people's response to be heard in setting aims and selecting alternatives), to evaluate extra-market factors, to use external help, and to gage the distribution of effects among different social classes and geographic areas. An important aspect is the government's willingness to bear uncertainty and at the same time to push for the achievement necessary to its survival. All of these factors are a part of examining the full effects and of consulting the people concerned.

The policies suggested will apply during the period of lake management as well as during the period preceding construction. Over that time the administrative organization changes completely and sometimes suffers from being more attuned to building than to operation.

These policies are simple and fundamental to the thoughtful creation and management of a new lake. To execute them is troublesome for planners unaccustomed to thinking in these terms, and several measures would expedite their acceptance.

Intergovernmental Support

4. *Criteria and impact statements.* The response of governmental and intergovernmental agencies to proposals for new man-made lakes would be enhanced by use of a somewhat uniform set of criteria for appraising proposals for study or financing of new lakes. The major outlines for criteria may be deduced from this report and are given in general form by *Lagler* [1969]. These criteria will be stated as questions in the section on that topic in the forthcoming Economic Commission for Africa publication on water resource planning in Africa. They include appraisal of the chains of reactions in the hydrologic, atmospheric, biological, and social systems that have been noted.

Such criteria should become the point of departure for whatever revised or extended statement may be prepared by cooperation among the chief study and financing agencies for guiding the appraisal of environmental aspects of economic development projects. The principal intergovernmental agencies involved with work in developing countries are the UNDP, the International Bank for Reconstruction and Development (IBRD), the Inter-American Development Bank, and the Asian Development Bank. The same criteria should apply in higher-income countries. The agreed criteria might well be published in a form intended to reach engineers, biologists, economists, and others concerned with lake design.

One of the frequent recommendations for improvement of economic development planning is that environmental impact statements be required as a part of any new financing proposals. These statements are expected to specify what is known about environmental consequences. If the criteria that are suggested by our efforts were to be put into practice by operating agencies, such statements would be a normal part of any feasibility report, but they would be impact statements in a broader sense than that which has prevailed heretofore. The statement would attempt to touch on the whole range of impacts in the ecosystem of which man is a part. They would use benefit-cost analysis wherever appropriate but would not be tied to it.

It would not be reasonable to expect that the criteria could be drawn in such a way that all the questions asked could be answered; however, these criteria could assure that the right questions are asked and that candid replies are given to responsible officials and to the people directly affected. In a strict sense, effective adoption of criteria would eliminate the need for special requirement of impact statements. However, that time is far distant for several reasons.

The fundamental consideration in moving toward the application of criteria is that the methods of examining the whole set of impacts as outlined in this report are so poorly developed that the best-intentioned planning group is sorely pressed when it attempts to produce an appraisal dealing with the subject as adequately as scientific knowledge permits. In addition, there are no exemplary demonstrations of the kind of analysis required, there is no thoroughgoing examination of accrued experience, and there is only a little training of people with scientific competence to carry out such activities. The remainder of the recommendations indicate practical action that should be taken to assure that desirable criteria are applied in the field.

Three general observations should be made about the preparation of feasibility reports and social impact statements. The first is that rigorous appraisal concentrating on only one set of effects and largely ignoring others (such as when fisheries are omitted from a sophisticated feasibility study of a power project) may be more dangerous than no appraisal at all. This sort of appraisal conveys a false sense of confidence and discourages attention to factors that are less susceptible to quantitative measurement than engineering works or benefits that are long term. The second is that no feasibility report or social impact statement is adequate if it is viewed as a solitary exercise never to be repeated or checked. These reports should be viewed as only one step in a continuing process of system change and manipulation. A third observation is that the sheer size and complexity of these great enterprises demand that no effort should be spared to bring the best brains to bear on their appraisal and planning.

5. *Early warning system.* The present informal 'early warning system' operated by the UNDP should be extended to include all the intergovernmental agencies, but one agency should continue to have the primary responsibility. The present system provides for notification of interested agencies when there are commitments to study new reservoir projects. Spreading the word is helpful, but it needs to be supplemented by arrangements to provide, on request, any interested national or regional agency contemplating a new lake with advice on the practical steps that might be taken to anticipate and deal with the full consequences of construction. This service might be expected to be most used by developing countries. However, a number of developed countries have also shown that they could benefit from early identification of likely problems. Such advice probably could come best through teams of consultants made available by intergovernmental agencies. As a minimum the teams would include persons with breadth of administrative view and with scientific experience in biological, hydrologic, and social aspects of man-made lakes and in interdisciplinary assessments.

In time the need for both the early warning service and the supporting teams would be eliminated by the building of suitable competence among the planning agencies. However, that service will be slow in coming, and meanwhile the limited scientific experience needs to be marshalled in a fashion that will avoid the cumbersome and competitive procedures of the intergovernmental agencies. At present it is impossible to assemble at the international level the kind of team suggested here without formal negotiation with the United Nations, IBRD, FAO, World Health Organization (WHO), United Nations Educational, Scientific and Cultural Organization (Unesco), and World Meteorological Organization (WMO). As a result, almost never has a genuinely integrated team been sent into the field.

The precise administrative responsibility for such a service may need to be determined in the light of whatever new agencies, if any, may be created as a result of the Stockholm conference. Some agency, whether a new one or an old one with enlarged authority, should be empowered to operate the service and to draw proficient scientific personnel on a standby consulting basis without being subject to the customary agency restrictions on appointment and tenure.

6. *World register, classification, and global evaluation.* We support the proposal by *Fels and Keller* [this volume] to establish an international register for providing a central source of accurate information on all reservoirs completed or authorized for construction with a surface area of >100 km^2. The register should be maintained by an agency having ready access to national planning activities. Wherever they are, reservoirs have certain common features and considerable similarity in the problems they pose. As a minimum for discussion purposes it is suggested that the register include the following information: identification of reservoir by name and geographical coordinates of dam; maximum height of water at dam; elevation of water height above sea level; estimated maximum surface area; estimated maximum volume of storage; estimated maximum shoreline length; expected annual and long-term fluctuations in reservoir level;

mean annual discharge of streams flowing into reservoir; drainage area above dam; mean annual precipitation on the lake and in the drainage area; mean annual air temperature in January and July; principal purposes; population relocated, including number, government expenditure per capita, and livelihood; and, if possible, map showing maximum extent of water surface and bottom topography.

Positive and negative experience with existing reservoirs can be an important source of new planning methods. One of the difficulties obstructing the use of this experience is the variety of local conditions. Another is the trouble involved in gaining access to results elsewhere. The world register would be a simple, first step that would extend the few present and out-of-date compendiums. It should be coordinated with the Project Aqua list of aquatic sites proposed for conservation.

The register should be supplemented by a problem-oriented classification based on combinations of major factors affecting the quantity and quality processes that are known. This classification would include lake size and geometry, water balance, climate, soil and vegetation in the basin and at the lake site, and human population and livelihood. The Committee on Water Research of the International Council of Scientific Unions (ICSU) should be requested to advise on the register and to develop the basis for such a classification.

The world register could serve as a basis for making a preliminary assessment of the trends and magnitude of the effects of the earth's man-made lakes on the global environment. The following would be assessed: changes in radiation and heat balance, relation of evaporation to both land and atmospheric phases of the water cycle, relation of new lakes to primary production, and direct human impacts. An assessment of this sort would be an appropriate activity for the Special Committee on Problems of the Environment (Scope).

7. Clearinghouse service. The early warning service and world register would find a useful supplement in a clearinghouse service on current scientific investigations on man-made lakes. The service would gather and disseminate minimum information such as the following for each problem under investigation: sponsoring organization, principal scientific investigator and address, location of work, statement of problem being studied, and duration of investigation.

The format and problem descriptors would require careful selection to expedite the use of automated equipment. An information service of that type should be viewed as part of the massive problem of exchanging scientific information, and whatever method is found would have to struggle with ways of reaching the large number of disciplines affected. The only reason that an activity of this sort is seen as a practicable action at this stage is that the actual number of projects, in contrast to studies, is relatively small, that the overwhelming proportion of research on them is supported by a few government funds, and that a closer linkage of the intergovernmental agencies and research institutions in a few countries (principally, France, India, the Netherlands, the United States, and the USSR) would cover the major part of current activities. The ICSU should seek funds to carry out this activity, perhaps advantageously as a part of the Unesco program on man and the biosphere.

8. Training. As a short-term but timely operation, intensive training courses based on national needs should be provided for national and international personnel who are seeking to further interdisciplinary work on man-made lakes. These personnel are needed at three levels: administrators, middle-level technicians, and scientists. Knowledge can be translated into effective policy and design only with the help of scientists who have been exposed to integrated approaches. The courses might well be arranged to permit field observations in specified regional conditions. They should be organized by Scope in collaboration with the interested scientific unions and the United Nations, the regional economic commissions, FAO, Unesco, WMO, IBRD, and WHO. There are numerous training programs for engineers to design new dams and a few in economic analysis, but there are almost none for those who must deal with other aspects of ecosystem modification.

Scientific Cooperation

In the long run the influence of these efforts to obtain more careful and balanced examination of man-made lakes will only be as strong as the scientific activity necessary to deepen the knowledge of relationships.

9. Major thrusts. In addition to the activities already recommended, major thrusts need to be encouraged by a variety of scientific organizations in the following directions:

1. A comprehensive, sustained effort should be made to construct models of the processes involved in the evolution of reservoir ecosystems. Prediction of inflows and discharges from physical model systems is a relatively well-developed science. Practical predictions of the physical and chemical dynamics within reservoirs are not yet completely feasible, even though these dynamics are dominated by the singularities of inflow, outflow, morphometry, climate, retention time, surface area to volume ratio; values for all these factors are often readily obtainable. The need remains for model studies over a more representative range of conditions, including parameters of biological production and water quality management. Without more experience in particular situations it is doubtful that a satisfactory general model of reservoir structure can be developed. Models involving social and economic elements are even less well developed and should be vigorously encouraged.

2. A thorough benefit-cost analysis should be applied to the impacts and planning of sample projects. The emphasis here would be on refinement of methodology to deal with intangibles, with different spatial patterns of distributions, and with the effects of value assumptions.

3. A pilot demonstration of the instrumentation, data processing, analysis, and automated monitoring of a major man-made lake should be carried out.

4. A study group should prepare at least two exemplary social and ecological impact statements for a man-made lake proposal. These statements should include the complete set of factors discussed in this report. They would assess the role and cost of base line studies and the risks of decision making without adequate data.

5. Pilot communities should be set up to demonstrate new production systems for relocatees and other lake basin inhabitants. Training and extension would be incorporated, and continuing evaluation would be essential.

6. Special international reviews of interdisciplinary problems of high importance in predicting transformations in man-made lakes should be conducted. Those problems having particular urgency are the effect of water balance, watershed management, and flow conditions on water quality; mud-soil ecology in the drawdown zone, and biological production; the effect of aquatic vegetation on physical, chemical, biological, and human use aspects of man-made lakes; and the conditions in which new technology, social organization, and livelihood are diffused among lake basin populations.

Certain aspects of the foregoing points may well be incorporated in symposiums or seminars now being planned. Thus the International Association of Scientific Hydrology is planning a field seminar on the Great Lakes in 1972 (International Field Year on the Great Lakes), and a symposium on lakes is to be held in Finland in 1973. One practical way to stimulate more intensive work on these fields would be for Scope in cooperation with concerned intergovernmental agencies to convene an international study group of not more than 24 members to review the field and to identify the most promising new lines of research.

The actions proposed here would be mutually supportive and are not in any sense exclusive of other needs or opportunities. The essential policies of development agencies and governments cannot be carried out effectively unless improved analytical methods and comparative data are available. The underlying research and training will not be undertaken unless governments are disposed to canvass the whole range of impacts of a man-made lake and to call for personnel capable of anticipating and dealing with these impacts. The underlying requirement is an integrated view of man as being dominant in the new ecosystem. In this regard, man-made lakes may point the way to constructive modes of action wherever human society considers a massive change in the environment.

REFERENCES

Ackermann, W. C., G. F. White, and E. B. Worthington (Eds.), *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, this volume, AGU, Washington, D. C., 1973.

Bardach, J. E., and B. Dussart, Effects of man-made lakes on ecosystems, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Benedict, B. A., E. M. Polk, Jr., F. L. Parker, L. H. Motz, and J. E. Edinger, Movement of heated water discharges from power plants in man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Benson, N. G., A century of fisheries in North America, *Spec. Publ. 7,* Amer. Fish. Soc., Washington, D. C., 1970.

Dendy, F. E., W. A. Champion, and R. B. Wilson, Reservoir sedimentation surveys in the United States, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Dubreuil, P., and G. Girard, Influence of a very large number of small reservoirs on the annual flow regime of a tropical stream, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

El-Zarka, S., Kainji Lake, Nigeria, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Fels, E., Die Grossen Stauseen der Erde, *Z. Wirtschaftgeographie, 14*(8), 229–244, 1970.

Fels, E., and R. Keller, World register on man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Filatova, T. N., and T. O. Kalejarv, Some results of 20-year network observations on currents in Tchudsko-Pskovskoe Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Fruh, E. G., and H. M. Clay, Selective withdrawal as a water quality management tool for southwestern impoundments, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Granju, J.-P., J. Garrison, and J. Price, Hydraulic transients in man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Jenkins, R. M., The influence of engineering design and operation and other environmental factors on reservoir fishery resources, *Water Resour. Bull., 6,* 110–119, 1970.

Lagler, K. F. (Ed.), *Man-Made Lakes: Planning and Development,* 71 pp., Food and Agriculture Organization, Rome, 1969.

Langbein, W. B., Water yield and reservoir storage in the United States, *U.S. Geol. Surv. Circ., 409,* 1959.

Leentvaar, P., Lake Brokopondo, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Lowe-McConnell, R. H. (Ed.), *Man-Made Lakes,* Academic, London, 1966.

Lvovich, M. I., *Water Resources of the Future* (in Russian), Praswestenie, Moscow, 1969.

National Academy of Sciences, *Water and Choice in the Colorado Basin: An Example of Alternatives in Water Management, Publ. 1689,* Washington, D. C., 1968.

Obeng, L. (Ed.), *Man-Made Lakes, The Accra Symposium,* Ghana Universities Press, Accra, 1969.

Rothé, J. P., Man-made earthquakes (in French), *Tectonophysics, 9,* 215–238, 1970.

Ryder, R. A., A method of estimating the potential fish production of north temperate lakes, *Trans. Amer. Fish. Soc., 94,* 214–218, 1965.

Szesztay, K., The hydrosphere and the human environment, paper presented at IASH-Unesco Symposium on Hydrological Experimental and Representative Basins, Int. Ass. of Sci. Hydrol., Wellington, New Zealand, 1970.

Timofeev, M. P., *Meteorological Regime of Reservoirs,* 290 pp., Gidrometeoizdat, Leningrad, 1963.

United Nations, *Integrated River Basin Development,* Department of Economics and Social Affairs, New York, 1958.

Wunderlich, W. O., and R. A. Elder, Mechanics of flow through man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

World Register on Man-Made Lakes

E. FELS[1]
Munich, Federal Republic of Germany

R. KELLER
Institute of Geography, University of Freiburg
Freiburg, Federal Republic of Germany

In these last decades of industrialization and rapid population increase, human intervention on the balance of nature has never been so various and so extensive as it is today. Changes in land use, urbanization, construction of highways and industrial complexes, large-scale open-pit mining, river regulation, and water and air pollution are all well-known man-made influences that generally have a negative effect on the balance of nature. The word generally, however, should be emphasized, for in many localities the value of a natural region has indeed been increased by human interference.

Man-made lakes may be included among the most significant modifications in the general appearance of a natural region. In contrast to the other alterations mentioned above, a lake, even a man-made lake, generally offers an improvement to the natural surroundings. In scarcely any other intervention in the balance of nature has man such extensive possibilities of exerting a positive influence on the balance of a natural region.

Man-made lakes provide possibilities for the development of numerous natural communities. Plants and animals that were never before observed in the area make their appearance. Waterfowl colonize the area, bringing with them animals and plants from distant localities. Naturally, plants and animals that were not expected in the plans of engineers and farmers may also take possession of the area that is newly available for habitation.

The water in man-made lakes possesses entirely different properties from the water of natural lakes in respect to content of nutrient materials, hardness, and temperature. The water in man-made lakes affects the surrounding areas. These lakes alter the natural runoff regime with high and low water, the suspended load, the groundwater, and possibly in arid climates also the salinity of the underground. They also alter the climate of the littoral regions and in many vicinities the economic and social structure of the area. This latter phenomenon again has an effect on the natural balance of these regions.

Just as every natural lake is an individual phenomenon, which does not appear again in an identical form on the earth's surface, every man-made lake is likewise a unique occurrence. In the case of a natural lake the development of settlement and adjustment in the balance of nature may not be traced, but, with man-made lakes, all stages in development may be observed. There is also the possibility of controlling the conditions in the lake itself and in the surrounding littoral areas.

The prerequisite for such control, adjusted to natural conditions, is, however, a knowledge of the processes and interrelationships between the lake and the surrounding area. Certainly, much of the copious information on natural lakes in scientific publications may be applied to man-made lakes. But it is also certain that in fundamental problems the man-made lakes react in a different manner from natural lakes. For this reason, in the near future, more intensive investigations of man-made lakes are absolutely necessary if unpleasant negative effects concerning the balance of nature are to be avoided.

There are numerous scientific investigations on the natural lakes of the world, their origin and

---

[1] Professor emeritus of the University of Berlin.

morphology, the problem of evaporation, their water balance generally, the composition of their water and its alteration due to human interference, the fauna, and the physical conditions (e.g., currents and water temperature at various depths) as well as investigations on the influence of the lakes on the climate of littoral regions and the development of the natural and cultural regions of adjoining areas. In comparison, the number of investigations on corresponding topics for man-made lakes is incredibly small, although these investigations are of even greater practical significance. For natural lakes the adjustment and consequences of the balance of nature are generally known. In contrast, it is generally unknown how natural phenomena will adjust to the man-made lake. Numerous technical articles deal with storage dams, but there are almost no publications dealing with the reservoirs themselves that lie behind those dams. The reason for this discrepancy is not that their scientific questions are of less significance because of their number and surface area. On the contrary, information and data concerning these lakes are lacking. Although data have been collected for natural lakes over many decades, only a little is known about the artificial lakes. From the fact that the larger lakes of Central Europe, e.g., Lake Balaton (592 km²), Lake Geneva (581 km²), and Lake Constance (539 km²), probably were dealt with in more than 2000 scientific publications whereas man-made lakes with a larger surface are known chiefly by name, the urgency for research on the man-made lakes is clear.

What about the literature on the man-made lakes? The *World Register of Dams* [*Brown et al.*, 1964] is a worldwide survey of about 10,000 dams of at least 15 meters in height. From 1963 to 1968, two supplements with further details, corrections, and additions for about 2000 dams were added to the register. Without a doubt, this excellent world register was handicapped because several remarkable countries (e.g., China) did not participate.

The *World Register of Dams* provides copious and valuable data about the dams (height, length, volume, and so on) but gives few specifications concerning the dammed lakes, although these are the main objects of the efforts of the engineers. This omission is easy to understand because the register deals with dams and not with lakes. Engineers are mostly interested in the lakes only as they serve to supply water and energy or to regulate runoff. The specific hydrologic needs are of minor significance to the builder of the dam. Only the storage capacity or water volume is always mentioned. All other morphometric data are left out. We can be sure that the builders of a dam know the morphometric data yet regard these data as being less important and unworthy of publication.

Hydrometric and morphologic data are an important base for hydrologic, climatological, and geographic research as well as for studies concerning man and environment. For example, the water balance of a lake can be measured only if the morphometric data on the surface, the length of shoreline, and the maximum and mean average depth are known. Unfortunately, these data are not mentioned in the *World Register of Dams*. No publication is known to us wherein these data are stated, not even for the largest 100 man-made lakes. Who is aware of the 50 biggest man-made lakes or of the hydrologic and morphometric data of the lakes with an area of >1000 km²? We have collected the data for 41 man-made lakes (the completed ones and those under construction) with an area of at least 1000 km² (Table 1 and Figure 1). The surface of these 41 man-made lakes is about 115,500 km². We estimate the total of all water surfaces created by man at >300,000 km², i.e., 20% more than the Great Lakes of North America (248,000 km²).

Gâştescu and Breier [this volume] show how numbers and areas of small lakes may add up in the so-called 'small countries.' In Romania the approximately 1200 man-made lakes can be classified according to construction and regional use. These lakes cover an area of 475 km², although the three largest man-made lakes of Romania account for an area of only 10–35 km² each. The large man-made lakes primarily serve for the production of electricity, whereas the smaller ones are multipurpose and are used for fishing, irrigation, flood control, water supply, and tourism. *Lessent* [this volume] describes two large man-made lakes in Ivory Coast, Ayamé and Kossou, which are primarily used for hydroelectric power purposes. In India, water storage has more than 30 centuries of tradition, and *Ganapati* [this volume] points out that almost all the major and minor rivers have been dammed to form man-made lakes of different sizes. He mentions that there are 295 reservoirs with a total area of 1,197,000 ha, excluding the hundreds of minor irrigation reservoirs. The object of these reservoirs is to conserve the immense floodwaters

TABLE 1. The World's Reservoirs with the Largest Surface Areas (≥1000 Square Kilometers)

Lake	In Operation since	Country	River	Area, km^2
Volta (Akosombo)	1965	Ghana	Volta	8730
V. I. Lenin (Kuybyshev)	1955	USSR	Volga	6500
Churchill	under construction	Canada	Hamilton	6200
Bukhtarma*	1960	USSR	Irtysh	5500
Bratsk	1961	USSR	Angara	5426
Nishne Kamskaya	under construction	USSR	Kama	5400
Kariba	filling started in 1958; full capacity in 1963	Rhodesia/Zambia	Zambezi	5180
Nasser (Sadd-el-Ali)	1968	UAR	Nile	5250
Rybinsk	1941	USSR	Volga	4550
Kamenskoye	completed	USSR	Ob	4500
Grand Rapids	1964	Canada	Saskatchewan	4100
Cheboksary	under construction	USSR	Volga	3780
Congress (Volgograd)	1958	USSR	Volga	3160
Tsimlyansk	1952	USSR	Don	2700
Caboro Bassa	under construction	Macambique	Zambezi	2700
Sanmen	1962	China	Hwango	2350
Kremenchug	1961	USSR	Dnepr	2500
Kakhovka	1955	USSR	Dnepr	2155
Krasnoyarsk	1966	USSR	Yenisey	2130
Conservation area no. 3A (Everglades)	1963	USA	Florida	2038
Wilyuiskaya	under construction	USSR	Wilyui	2010
Saratov	1965	USSR	Volga	1950
Manicouagan 5	1968	Canada	Manicouagan	1942
W. A. C. Bennett†	1968	Canada	Peace	1761
Kama	1954	USSR	Kama	1720
Furnas	1965	Brazil	Rio Grande	1606
Sounda	under construction	Congo (Brazzaville)	Kouila	1600
Gor'ky	1955	USSR	Volga	1570
Afobaka (dam) Brokopondo (lake)	1967	Surinam	Suriname	1560
Oahe	1965	USA	Missouri	1520
Kossov	under construction	Ivory Coast	Bandama	1500
Garrison	1960	USA	Missouri	1488
Seul Reservoir	?	Canada	English	1396
Gouin Reservoir (La Loutre)	1917	Canada	St. Maurice	1295
Manouane	1961	Canada	Maouan	1290
Kainji	1969	Nigeria	Niger	1243
Rincón des Bonete	1946	Uruguay	Rio Negro	1140
Très Marias	1961	Brazil	Rio Sao Francisco	1130
Votkinsk	1962	USSR	Kama	1120
Novosibirsk	1957	USSR	Ob	1070
Kelsey	1960	Canada	Manitoba	1012

*Lake Zayzan (1900 km^2) is included.
†Formerly Portage Mountain.

Fig. 1. World's reservoirs with surface area of ≥1000 km².

from the few weeks of monsoon rains, chiefly for irrigation.

We propose the organization of a world register on man-made lakes. Perhaps one of the United Nations organizations in collaboration with the International Commission on Large Dams and the International Geographical Union or the Scientific Committee on Water Research could be entrusted with this task. The world register on man-made lakes would complement the *World Register of Dams.*

It may be useful to submit a list of the needed data:

1. The name of the reservoir, which usually is not that of the dam, would be required.

2. The geographical coordinates of the extent of lake at maximum filling would be necessary information.

3. The height of the maximum dammed lake surface above the river surface should be included. The height of the dammed lake is always less, sometimes even considerably less, than the quoted structural height of the dam. The structural height is significant to the engineer as a building attribute but is not important for hydrologic purposes. The height of the dammed lake means the difference between the mean average of the original river and the highest sea level. On Franklin D. Roosevelt Lake, for example, the height of the barring of the Grand Coulee Dam on the Columbia River amounts to 168 meters, but the height of the dammed lake is 113 meters, the difference amounting to 55 meters.

4. The height of the lake surface above sea level should be included.

5. Maps indicating the depth and bottom topography of these lakes are urgently needed. An extraordinary example is the Lake Manicouagan 5, situated in Quebec, Canada. This lake has an area of 1942 km² that rings an isle of nearly the same extent and has wide-reaching outlets to the surroundings.

6. The maximum and minimum heights of the lake level with time indications are also necessary.

7. The extent at highest filling, measured on the largest scale available, should be included. This area of the reservoir is the most important specification.

8. The length of the lake (often 300–500 km) should be indicated.

9. The maximum breadth (mostly 30–40 km) taken by maximum storage should be specified.

10. The medium breadth at maximal lake level (i.e., quotient of area and length) should be included.

11. The length of shoreline at maximum filling is necessary. From the area of the lake itself we can take the length of the shoreline as the best indicator of its irregularity. The proportion of shorelines in man-made lakes is mostly rather high and more intensive than that in natural lakes.

12. The area of the drainage basin is essential in respect to the judgment of capacity. Besides the natural catchment area, there may be an artificially widened catchment area (inflow from other river areas or diversions into other river basins).

13. The storage ratio quotes the time for the filling up of the basin. This factor is important for estimating the yielding capacity of precipitation. For this estimate the data on the annual discharge of the tributary waters are necessary.

14. A map of the reservoirs with scale should be included.

15. The storage capacity of the lake should complete the necessary data. Only this figure is stated in the list of the *World Register of Dams* mentioned above.

Would it be necessary for a world register on man-made lakes to provide data about the physical, chemical, and biological character of these lakes? *McFie*'s [this volume] paper on Tasmanian hydroelectric power developments points out the importance of such data. The question of whether the water temperature of depth and surface, the *p*H values, and so on should be recorded in a world register on man-made lakes (so far as these data are already known) should be examined. Information may be furnished on thermal reaction whether the lake is dimictic, monomictic, or meromictic.

The storage capacity of the large man-made lakes all over the world is estimated at about 4000 km³, which is nearly one-third of the total water content of the atmosphere. Nearly all the reservoirs with a volume of 4000 km³ and a water surface of about 300,000 km² were constructed in this century. Before World War II, only one giant reservoir with a surface of >1000 km² existed. The Gouin Reservoir (La Loutre) on the St. Maurice River in Quebec, Canada, with an area of 1295 km² opened in 1917.

Information is available on only three reservoirs, each with a surface area of >1000 km²,

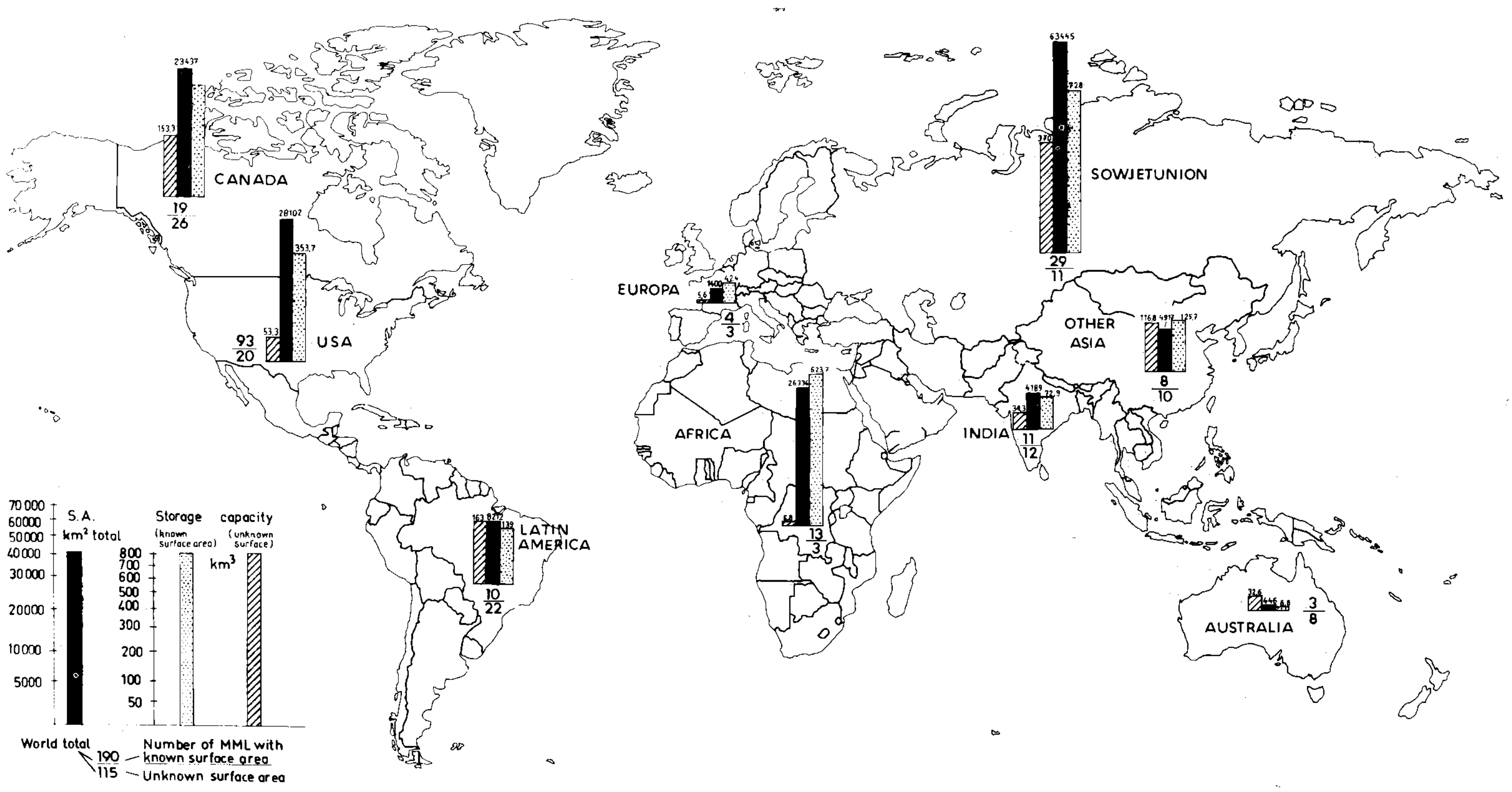


Fig. 2. Large reservoirs with surface area of ≥100 km² classified by continents and countries.

TABLE 2. Large Reservoirs with a Water Surface Area of ≥100 Square Kilometers

		Man-Made Lakes with Known Surface Area			Man-Made Lakes with Unknown Surface Area	
Continent or Country	Total No. of Reservoirs	No.	Total Surface Area, km^2	Storage Capacity, km^3	No.	Storage Capacity, km^3
Europe	9	5	1,951	45	4	8.7
USSR	40	30	64,408	730.2	10	365.0
India	25	15	5,567	93.9	10	23.7
Other Asian	18	11	6,396	154.4	7	90.2
Australia	12	5	967	23.4	7	32.7
Africa	17	14	27,466	618.2	3	6.8
Canada	51	27	35,727	497.2	24	126.9
United States	112	95	28,507	360.6	17	41.4
Latin America	31	14	9,943	181.1	17	120.5
World	315	216	108,932	2704.0	99	815.9

This table is adapted from information provided by E. Fels (unpublished data, 1973).

constructed before 1950. From 1950 to 1959 we learned about the existence of eight man-made lakes, and, from 1960 to 1969, 21 newly built reservoirs with a surface area of >100 km^2 each were registered. The Tangkiangho in China with a storage capacity of 51.6 km^3 (opened in 1962) and a few other reservoirs are not considered. Undoubtedly, they also belong to this category; their surface area, however, is still unknown. In 1971, at least six man-made lakes were under construction, each of them having a surface of >100 km^2. The three basins built before 1950 cover an area of 7000 km^2, the eight basins opened between 1950 and 1959 cover an area of 24,000 km^2, and the 21 reservoirs opened in 1960–1969 extend over an area of 55,000 km^2. The lakes under construction up to 1970 amount to 27,600 km^2.

Of the man-made lakes in Romania, 11 were constructed before 1950, eight in the period from 1950–1960, and 40 later than 1960. We may observe that the trend indicated for the 41 largest man-made lakes of the world is equally true for the smaller lakes. The same trend appears in the Tasmanian lakes. Man-made lakes of ≥100 km^2 are summarized in Table 2 and Figure 2.

To suggest the total area of man-made lakes, other data not included in Table 2 are given for lakes of <100 km^2 in a few countries. Japan has a lake surface area totaling 156 km^2; Federal Republic of Germany, 111 km^2; Romania (including 'Iron Gate,' 795 km^2), 475 km^2; and Tasmania, 860 km^2. The number of large and small dams under construction is unknown for the time being. In view of the considerable increase of man-made lakes in the past 50 years and the continuing additions from year to year, it is urgent to compile an inventory of them. Undoubtedly, a world register would cause, in the near future, an intensification in hitherto neglected investigations on problems of the influence of these lakes on the natural and cultural regions as well as the influence of man and the surrounding areas on these lakes.

REFERENCES

Brown, J. G., et al. (Ed.), *World Register of Dams*, International Commission on Large Dams, Paris, 1964.

Ganapati, S. V., Man-made lakes in south India, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Gâştescu, P., and A. Breier, Artificial lakes of Romania, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Lessent, P., Man-made lakes in Ivory Coast, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

McFie, H. H., Biological, chemical, and related engineering problems in large storage lakes of Tasmania, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Artificial Lakes of Romania

PETRE GÂŞTESCU AND ARIADNA BREIER

Geographical Institute of the Academy of the Socialist Republic of Romania, Bucharest, Romania

In Romania the practice of constructing lakes for water storage is quite old. One can assume that such lakes existed in the Apuseni Mountains (the western Carpathian Mountains of Romania) in Roman times. The lakes were laid out in the mining regions and were used for the separation of ores. One may also suppose the appearance during the same period of some briny lakes in the area of the ancient salt mines. Documentary evidence of artificial lakes dates back to the fifteenth century; it concerns some ponds in the Transylvanian plain and probably some ponds in the Moldavian plain (Jijia-Bahlui depression). In his work entitled *Descriptio Moldaviae*, dating from the first half of the eighteenth century, Dimitrie Cantemir mentions the great number of ponds in this geographic region. During the eighteenth century, notice was taken of two lakes of interest to mining at Dognecea, and, during the nineteenth century, two more such lakes were noticed near Oraviţa in Banat (these lakes still exist today but are used only for fish culture).

The artificial lakes of Romania having a long history can be grouped in two categories: lakes of mining interest in the mountainous zone of Transylvania and Banat and lakes used for fish culture and irrigation in the Transylvanian and Moldavian plains. Throughout the latter region the ponds and dams have been the dominant landscape, their number having been much greater in the past than at present (though their surface areas were more limited in the past). A study of maps of a scale of 1 : 20,000 that we have recently undertaken has shown that there were about 1000 ponds on the Moldavian plateau (these ponds could be discovered next to the ancient basins and preserved dikes) and that 600 of these were in the Moldavian plain.

The present picture of artificial lakes in Romania is incontestably modified, as much with respect to surface area and volume of water stored as with respect to diversity of types, depending on the objectives for which these lakes were constructed. The water supply for industry and localities and the use of water for the production of electricity and for irrigation in zones of deficient water balance are the principal factors that have contributed to the appearance of storage reservoirs in Romania. The distribution of artificial lakes over the countryside is determined by two important factors, namely, the peculiarities of the hydrographic network and the development of the economic-industrial potential under the conditions of a planned economy and an equalized territorial distribution of productive forces.

The hydrographic peculiarities of the Romanian territory are closely related to factors of climate and relief. The central location of the Carpathian arc and the altitudes that decrease toward the periphery of the country impose an obvious vertical zonality on the climatic and hydrographic values.

In the zone of high and broken relief (Carpathian and sub-Carpathian), where the water balance shows a surplus and where cultivated fields are small in number, the construction of reservoirs for irrigation is unnecessary. Instead, conditions here favor the construction of reservoirs for hydropower production (thanks to the elevated hydraulic potential) and for the supply of drinking and industrial water. In the zone of the plains and plateaus, where the water balance is deficient, where the small streams have an intermittent character, and where the need for water for irrigation is great, most lakes are used, of necessity, for agricultural and fish-raising purposes.

An entirely singular zone is made up of the floodplains of the great rivers, chiefly in the Romanian plain (Danube, Jiu, Olt, Argeş, Ialomiţa, Buzău, Siret, and Prut). Here the diking of overflow zones and the drying up of lakes have spurred the development of reservoirs and fish hatcheries.

One may say therefore that, in the Romanian territory, there are storage lakes for hydropower and water supply (drinking and industrial use) and there are small reservoirs for irrigation and fish culture. Then there are fish ponds and fish hatcheries for carp and trout; the hatcheries exist only in the mountains where the climatic conditions are favorable for the reproduction and raising of trout (Figure 1).

To avoid a misunderstanding, we specify that by reservoirs (iaz in Romanian) formed by dams we mean lakes formed by the construction of a transverse dam across a valley, behind which water accumulates; by fish ponds (elesteu in Romanian) we mean water basins, regardless of the size of their surface area, that have been constructed in flat, low, and marshy terrain and that are encircled by dikes. Whereas the reservoirs formed by dams are elongated, take on the form of the valley in which they are located, and have their maximum depth near the dam, the fish ponds are of geometric design (polygonals) and are typically of uniform depth throughout.

In certain regions where salt springs arise, small pools have been constructed for baths (héliothermes). Although their number so far is small because of numerous salt lakes located at abandoned salt mines or natural salt lakes on the coast of the Black Sea and the Romanian plain, the development of heliothermal lakes for water cures will be more frequent in the near future.

In Romania, there are also two types of artificial lakes that are on the road to extinction. The first type comprises small ponds on which rafts were constructed and from which the water was free to flow to the river for the transport of these rafts. Called haït in Romanian, these ponds were very common along rivers in the mountains where forests were exploited. Besides the Bistriţa River and its principal tributaries located upstream of Bicaz, there are also such 'haït' along the rivers on the southern slope of the Făgăras Mountains (Topolog, Argeş, Vîlsan, Rîul Tîrgului, and Dîmboviţa rivers), along the Lotru River and its tributaries, along the Sebeş River (in the Parîng, Cindrel, and Sebeş mountains), and finally along the Iara, Ampoi, and Someş rivers in the Apuseni Mountains. At present the number of haït is much reduced because, owing to the construction of a forest road network, the transport of logs is done by trucks.

The second type of artificial lake that is disappearing occurs only on the Cotmeana plateau located between the Argeş and Olt rivers. In the gravel beds of Cîndeşti, where groundwater is found only at great depths (50–60 meters), small, square or rectangular basins (cisterns) dug into the impermeable clayey horizon accumulate water from rain and snow. Through a sand and gravel bed the water from these artificial lakes (bent in Romanian) filters into a well supplying the inhabitants. At present, this method of supply is being abandoned in great measure and is being replaced by the installation of conduits for drinking water that is supplied either from other regions or from deep groundwater.

We have already stated that the statistics on artificial lakes in Romania as elsewhere are continually being exceeded on the one hand because of the intensity of construction of lakes (especially small reservoirs) and on the other hand because of the large number of constructors. One may, however, extract a series of data on reservoirs constructed for various purposes from official documents in the Romanian water register (Table 1). In 1968 the number of lakes, including controlled natural lakes, was about 1200 and the total surface area was >47,000 ha. The greatest number of lakes were reservoirs dammed for the purpose of fish culture and agriculture (1100). These dammed reservoirs sometimes form true belts along small valleys in the basins of the Prut River (in the Moldavian plain), the Vedea and the Argeş rivers (the tributaries in the plain are the Cîlniştea, Glavacioc, Neajlov, Dîmboviţa, and Pasărea), and the Mostiştea River.

The storage lakes for hydropower and the supply of industrial and drinking water are not so numerous (about 50); however, they represent the most important hydraulic works. Aside from their basic function, these lakes have also become important national tourist centers (e.g., Lake Izvorul Muntelui on the Bicaz River; Lake Vidraru on the Argeş River; and Lakes Văliug, Gozna, and Secul on the Bîrzava River).

Small reservoirs with dams are the most numerous type of lake in Romania. They are found especially in the Moldavian plain, the Transylvanian plain, and along all the valleys sculpted into the loess deposits of the Romanian plain to the east of the Olt River (Figure 2). The principal function of the small reservoirs with dams in these areas is to serve fish culture and agriculture, but there are some in the environs of certain urbanized areas (Bucharest, Iaşi, Botoşani, and so on) that also serve recreational purposes.

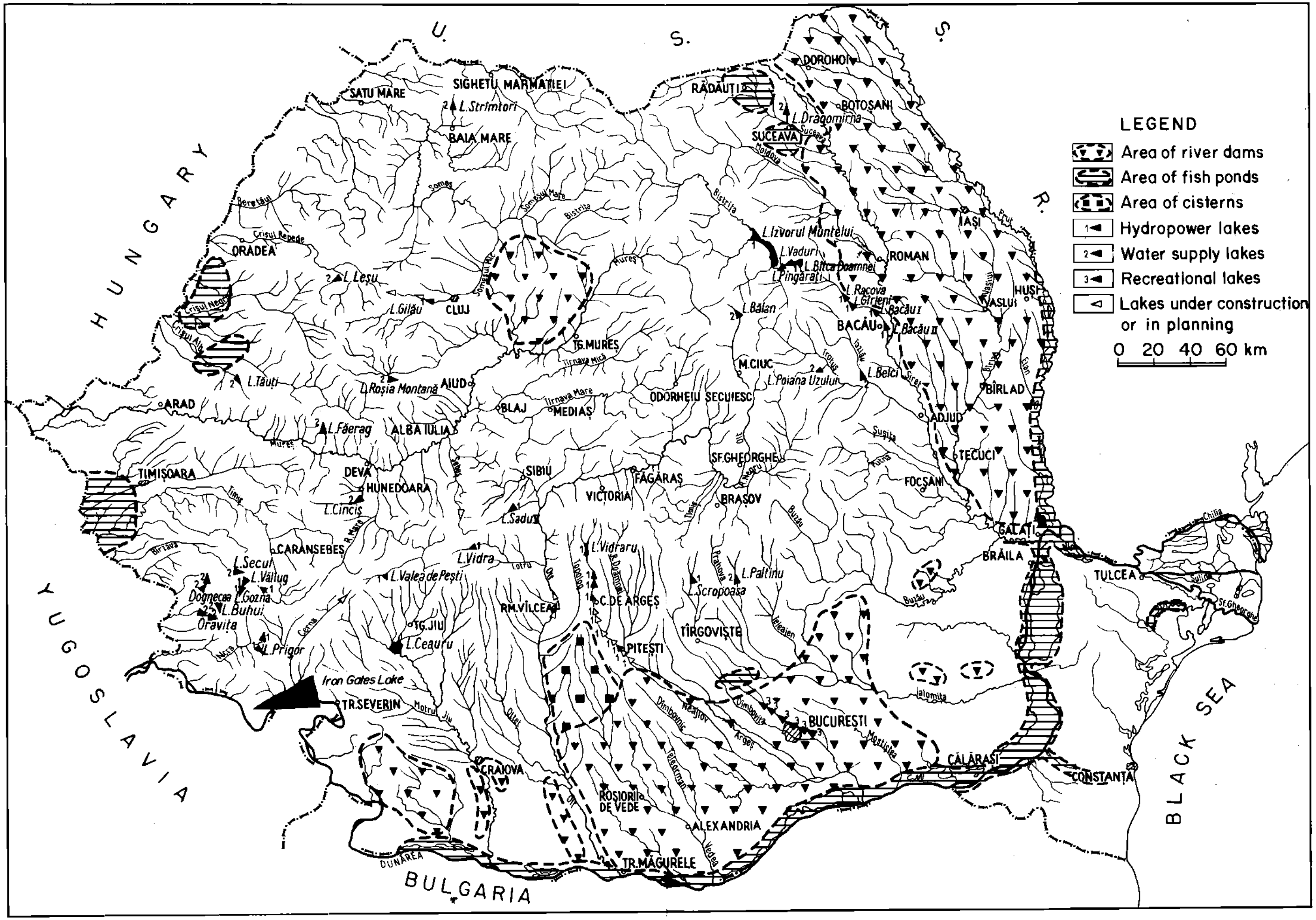


Fig. 1. The principal artificial lakes and their zones in Romania.

TABLE 1. Artificial Lakes Grouped According to Hydrographic Basin (1968)

Hydrographic Basin	Lakes for Hydropower Generation			Lakes for Fish Culture and Agriculture (Irrigation)			Lakes for Other Uses*			Total		
	No.	Surface Area, ha	Volume, 10^6 m^3	No.	Surface Area, ha	Volume, 10^6 m^3	No.	Surface Area, ha	Volume, 10^6 m^3	No.	Surface Area, ha	Volume, 10^6 m^3
Upper Tisa				1	0.12	...				1	0.12	...
Someş-Crasna				7	291.60	3.5	1	131.0	17.6	8	422.60	21.1
Crişuri-Bereteu				17	1,515.10	28.7				17	1,515.10	28.7
Mureş-Aranca	1	2.0	0.15	17	378.95	6.6	1	261.0	43.5	19	641.95	50.25
Bega-Timiş-Caraş	2	71.0	11.9	19	474.75	7.8	5	113.6	15.0	26	659.35	34.7
Nera-Cerna				2	1.01	0.1				2	1.01	0.1
Jiu				10	22.20	1.8	2	2000.0	100.8	12	2,022.20	102.6
Olt	2	39.0	6.5	25	245.95	8.3	7	25.0	1.3	34	309.95	16.1
Vedea				123	1,388.00	25.0				123	1,388.00	25.0
Argeş	3	946.0	473.8	133	3,453.00	34.6	10	1500.0	44.0	146	5,899.00	552.4
Ialomiţa	1	21.0	0.55	91	1,649.70	33.2	1	6.0	0.8	93	1,676.70	34.55
Siret	8	4545.0	1282.0	104	4,184.00	26.1	2	360.0	18.2	114	9,089.00	1326.3
Prut				281	9,374.00	91.4	6	722.0	16.0	287	10,096.00	107.4
Danube				255	10,069.00	108.0	42	1060.0	25.3	297	11,129.00	133.3
Coastal				13	2,698.00	45.0				13	2,698.00	45.0
Total	17	5624.0	1774.90	1098	35,745.38	420.10	77	6178.6	282.5	1192	47,547.98	2477.50

*Including water supply, flood control, and recreation.

Most of the small reservoirs have simple earth-fill dams (sometimes with sluice gates for the regulation of outflow) and surface areas of about 1–50 ha. However, there are also reservoirs whose surface area exceeds 50 ha, and some reservoirs (e.g., the reservoir of Dracşani in the Moldavian plain) are as large as 400 ha. These large reservoirs are stable hydraulic works whose dams are constructed of concrete or earth fill reinforced by concrete slabs, and they have provisions for observation of water level, evaporation, and so on.

In the construction of small reservoirs created by dams a double purpose has been pursued: the storage of part of the water from rain and snowmelt for the use of fish culture and irrigation on the one hand and the regulation of flow to avoid flooding, very common and often catastrophic in some regions, on the other hand. We note in this connection the Bahlui River and its tributaries, where a complete series of projects (seven earth-fill dams in Bahlui channel alone), some of which have been completed and some of which are under construction, provides flood protection to 3000 ha of agricultural land as well as to the city of Iaşi and the Paşcani-Iaşi railroad line. Also, in the Carasu Valley in the province of Dobrogea, 40 reservoirs have already been constructed. Such work is urgently needed on the Bîrlad River and its tributaries, as well as on other rivers that have a torrential flow regime. The belt of lakes created by damming valleys also contributes to a modification of the dry climate in some areas through the enlargement of the water surface and the resulting increased evaporation.

Another example of a region of small reservoirs created by dams is the Mostiştea basin, hydrologically typical of a plain having limited possibilities for surface water supplies, which several centuries ago was transformed into a chain of lakes. The name of the river itself, Mostiştea (deriving from the Slavic most, or bridge), means river of many bridges, i.e., many transverse dams.

The fish ponds used to be more common in the western plain of Romania, especially in the Criş basin. Among the oldest fish ponds there are those of Cefa (668 ha), Tămaşda (210 ha), Inand (170 ha), Ineu (160 ha), and Homorog (105 ha). In the south of the country the best known fish ponds are those of Nucet and Comişani in the Argeş basin and those of Frăsinet in the Mostiştea basin; at present, fish ponds are becoming more and more numerous in the floodplain of the Danube. Here, because of the diking off of overflow areas and the drying up of

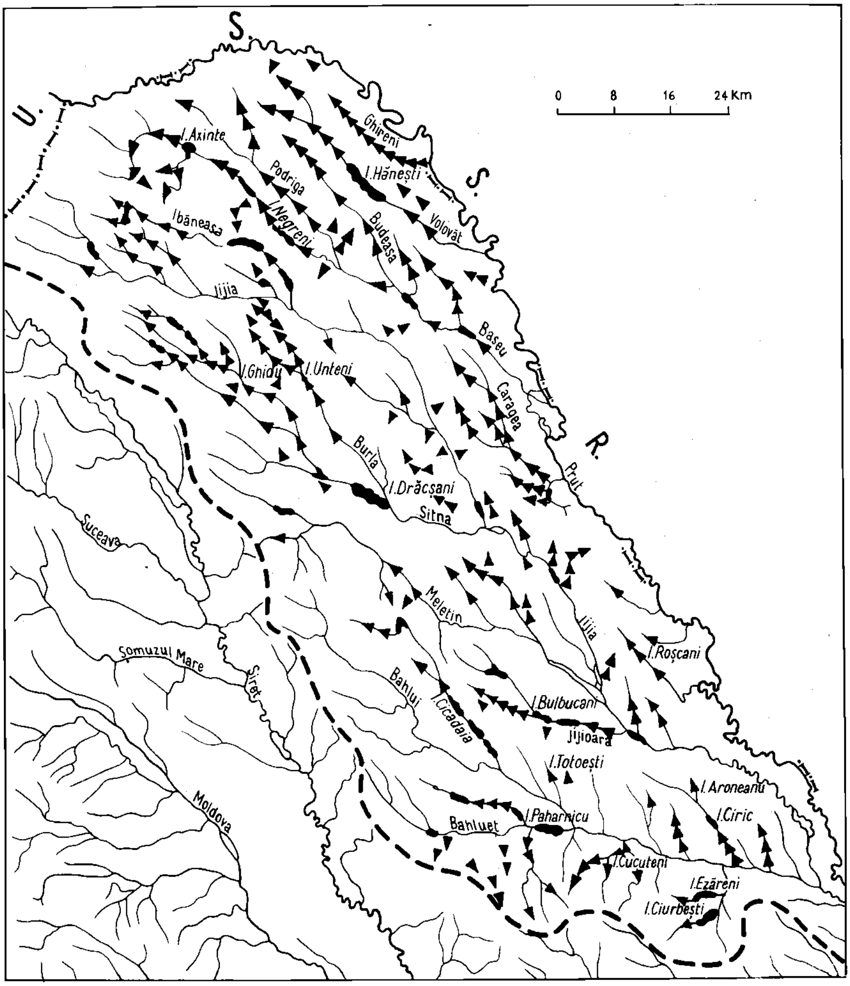


Fig. 2. The small lakes created by dams in the Moldavian plain (1968).

lakes, the deepest portions of the ancient lakes (where rainwater accumulates and water infiltrates owing to the hydrostatic pressure of the phreatic water in the main channel) are managed as fish hatcheries and fish ponds. Further, in the basin of the ancient lake of Brateş (which had an area of 7400 ha) a fish pond of 2000 ha has been laid out; similar fish ponds have also been laid out in the ancient lakes of Jijila, Suhaia, and Bistreţ, as well as in the lake beds of the ancient lakes of Călăraşi, Greaca, Potel, and so on.

Another important area of interest to fish culture is the border zone located north of Lake Razim (between Murighiol and Sarichioi) between the belt of vegetation constituting the actual shore and the cliff of the ancient sea bay. It has been recommended that regulation be extended up to the Bay of Ceamurlia. In these fish culture units the managed and intensive growth of fish is assured, as is the reproduction of species for reintroduction into rivers and natural lakes.

The lakes for hydropower purposes are constructed primarily in the mountainous regions where the greatest fall of water can be employed. Excepting Lake Scropoasa (on the Ialomiţa River) constructed in 1930, all other lakes for hydropower have been constructed during the last 2 decades. In most cases, they form true systems for use of hydropower. Thus, for example, on the Bistriţa River, Lake Izvorul Muntelui is the most extensive (3250 ha,), has the largest volume (1230 million m^3), and possesses the highest dam (127 meters).

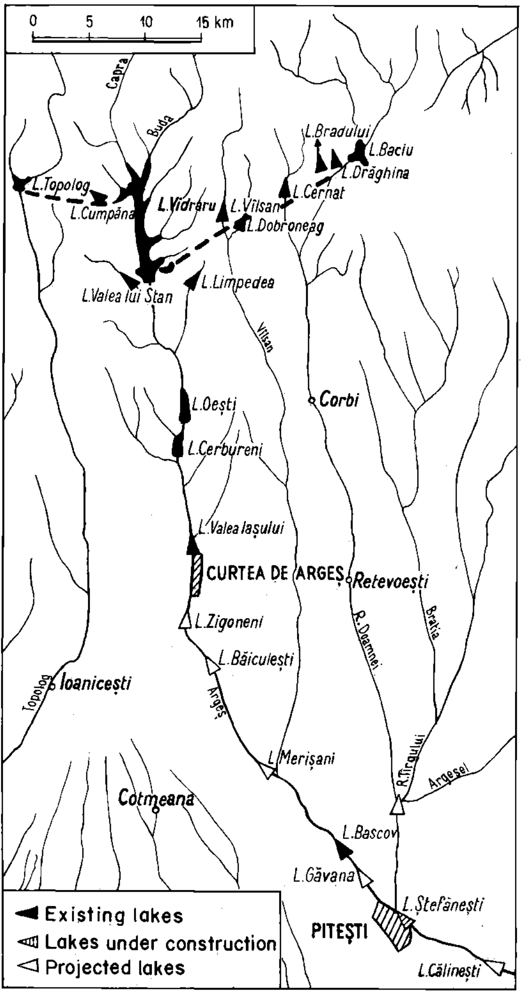


Fig. 3. The system of hydropower and water supply on the Argeş River.

However, there are also eight small lakes (in series) with a combined volume of 52.4 Mm^3. The volumes of each lake in downstream order are: Pîngăraţi, 6 Mm^3; Vaduri, 4.8 Mm^3; Bîtca Doamnei, 10 Mm^3; Roznov 1, 0.3 Mm^3; Racova, 10 Mm^3; Gîrleni, 6 Mm^3; Bacău 1, 0.3 Mm^3; and Bacău 2, 6 Mm^3.

In the upper Argeş basin the situation is different. To make better use of the water supply from Lake Vidraru, a series of 10 small storage reservoirs was recommended: Oieşti, Cerbureni, Curtea de Argeş, Zigoneni, Băiculeşti, Merişani, Bascov, Găvana, Piteşti and Călineşti. These reservoirs are now under construction or in planning, and they will supply drinking and industrial water as well as water for irrigation. As a part of this framework for hydropower use, Lake Vidraru has a concrete dam (constructed in an arc) that is 167 meters high, the highest in Romania; the lake has a surface area of 865 ha and a capacity of 465 Mm^3 (Figure 3).

Among the other lakes for hydropower use, we note Lake Gozna (Văliugul Nou), having a capacity of 10 Mm^3, and Lake Breazova (Văliugul Vechi), having a capacity of 1.2 Mm^3; both lakes are located on the Bîrzava River. We also note Lake Sadu 5 on the Sadu River, having a capacity of 6.3 Mm^3.

The following have recently been finished: the Iron Gates Dam on the Danube, behind which is a storage lake that is not too large in comparison to the flow of the river; the energy system of the Lotru River where the principal lake (Vidra) has a volume of 340 Mm^3 and a dam 116 meters high; and Lake Leşul on the Iad–Crişul Repede (volume of 26 Mm^3).

Projects in planning include systems for hydropower on the Sebeş, Crişul Repede, Rîul Mare, Jiu, Olt, Siret, and Buzău rivers. These projects will be built successively in stages following the plan of electrification of Romania.

The lakes for the supply of drinking and industrial water as well as multipurpose lakes are grouped near urban, industrial, and mining centers. Among the oldest lakes we cite those of the Apuseni Mountains (Roşia Montană and Făierag), those near Baia Mare (Baia Sprie and Ferneziu, or Bodi), those of Banat near Dognecea and Oraviţa, and those near Anina (Buhui and Mărghitaş). Among the recently constructed lakes we mention Lake Strîmtori on the Firiza River (near Baia Mare), Lake Cinciş on the Cerna Mureşului River (near Teliuc), Lake Bălan on the upper Olt River, Lake Belci on the Tazlău River (near the city of Gheorge Gheorghiu-Dej), and Lake Dragomirna (near Suceava). Among the recently built-up lakes are Lake Poiana Uzului on the small Uz River, Lake Paltinu on the Doftana River, and so on.

The lakes cited so far are used partly for purposes of hydropower and partly for recreation, but there are also lakes constructed especially for recreation. From this point of view the most representative are those of the valley of the Colentina near Bucharest (Buftea, Mogoşoia, Băneasa, Herăstrău, Floreasca, Fundeni, and Cernica).

Biological, Chemical, and Related Engineering Problems in Large Storage Lakes of Tasmania

HENRY H. MCFIE
Civil Engineering Branch, Hydro-Electric Commission
Hobart, Tasmania, Australia

MANAGEMENT AND DEVELOPMENT CONCEPT

The Tasmanian Hydro-Electric Commission has seven man-made lakes with capacities of $>124,000,000$ m^3 ($>100,000$ acre-feet) and an additional three under construction (Table 1, Figure 1). The Hydro-Electric Commission has also built and operates for power production 21 smaller lakes, and two more are under construction.

The commission is an autonomous governmental power utility that is responsible to the state legislature through the appointed minister (the Premier) for power production, reticulation, and sales. With the exception of several small residual mining installations the commission investigates, designs, constructs, and operates the Tasmanian power system and associated works by using its own staff and resources except for some special contractual activities. Until recently, generation was almost exclusively water powered, the first units being installed in 1895.

The economically advantageous water power sites and the commission's policy of using its own resources for the development of these sites have resulted in a long and continuous engineering experience in these fields and a high growth rate of low-cost power with a strong metallurgical base load. Because of these factors, power development has dominated water use in Tasmania for the past 50 years and has required the construction of large storage lakes from which secondary benefits of considerable value have resulted. However, Tasmania's 33 man-made lakes have been largely unipurpose in concept, legislative enactment, and operation.

The construction of these storages and the various aspects of the management of their catchments involve the Hydro-Electric Commission with other governmental and semigovernmental agencies, namely, the Forestry, Inland Fisheries, Rivers and Water Supply commissions; the departments of Agriculture, Public Health, Tourists, Public Works (principal roads and bridges), and Lands and Surveys; the Animals and Birds Protection Board, Scenery Preservation Board, and Rural Fires Board; and rural councils, private landowners, and common interest organizations. The more remote areas, which include the catchments of the tabulated lakes, are largely Crown lands including forestry reserves and national parks together with limited leasehold and privately owned lands used for their timber products and summer grazing. In these regions, large areas have been acquired by or vested in the Hydro-Electric Commission over which fee simple rights are exercised.

GENERAL ASPECTS

Because of clearing costs of Aust\$25,000–50,000 per square kilometer (Aust\$100–200 per acre) the majority of the storages are not cleared prior to flooding. Clearing is restricted to small areas adjacent to the damsites and to certain peripheries, and partial burning of the felled debris is the practice. Stands of dead trees and scrub occur in many lakes, and this timber, both standing and felled, along with the understory and the low flora and peats of the marshy plains provides adequate source material for an intensive biochemical activity, anaerobic conditions occurring in the thermally stratified lakes. The quantities of material involved, their decay rates, and the likely long-term effects have not been studied, but the persistence of these drowned and reexposed trees can be observed at Great Lake where, although they are diminishing in numbers, dead trees are still standing after 40 years.

With the exclusion of Lakes Rowallan (1967) and Barrington (1969) where immediate and

TABLE 1. Large Man-Made Lakes of the Tasmanian Hydro-Electric Commission

Storage Lake	Full Supply Level above msl		Normal Operating Range		Maximum Water Depth at Full Supply Level		Surface Area at Full Supply Level		Area of Fluctuating Verge		Lake Capacity at Full Supply Level		Natural Catchment Area		Diverted Catchment Area		Year Inundation Commenced
	meters	feet	meters	feet	meters	feet	km^2	acres	km^2	acres	10^6 m^3	ac ft	km^2	mi^2	km^2	mi^2	
Great Lake	1023.7	3358.5	5	16	8.5	28	132	33,000	26	6,500	687	557,000	396	153			1912
	1030.2	3380	11	36	15	49	148	37,000	43	10,700	1,792	1,452,000	396	153	285	110	1922
	1033.6	3391	15.5	51	18.5	60	156	39,000	63	15,800	2,305	1,870,000	396	153	588	227	...
Arthurs Lake	943.2	3094.5	2	6	5	16	38	9,500	6	1,500	105	85,000	262	101			1905
	952.2	3124	9	30	14	46	64	16,000	26	6,500	510	413,000	262	101			1962
Lake King William	713.8	2342	23.5	77	45.5	150	32	8,000	30	7,500	308	250,000	567	219			1949
	719.9	2362	29.5	97	52	170	41	10,300	39	9,800	537	436,000	567	219			1966
Lake St. Clair	736.7	2417	6	20	213.5	700	28	7,100	5.5	1,400	...	...	248	96			1937
Lake Echo	846.4	2777	13.5	45	23	75	41	10,300	7.5	1,900	706	573,000	129	50	583	225	1952
Lake Rowallan	487.7	1600	21.5	70	33.5	110	9	2,200	7	1,700	131	106,000	344	133			1967
Lake Barrington	121.9	400	4.5	15	73	240	7	1,700	0.5	130	180	146,000	740	286	865	334	1969
Lake Cethana	221.0	725	6	20	94.5	310	5	1,200	0.5	180	145	118,000	610	236	865	334	1971
Lake Pedder	308.5	1012	1.5	5	35	115	240	60,000	7	1,700	2,965	2,401,000	735	284			1972
Lake Gordon	307.9	1010	18.5	60	128	420	268	67,000	45.5	11,400	11,630	9,440,000	1290	497	735	284	1972

stable thermal stratification has occurred and Lake St. Clair where a thermocline is indicated but supporting data are lacking, there is no evidence that stratification occurs or has occurred in any storage of the Hydro-Electric Commission. It appears that any other thermoclines that may have occurred were of short duration and have not caused noticeable effects (such as hydrogen sulfide) in bottom discharging outlets or in the occasional release of bypass water from low-level valves in the terminal diversion dams with high-level power outlets.

Other than the bypass requirements, single-level outlets have been installed. Their location is determined by the operational range of the storage, some headwater dams having no useful low-level outlet. This type of installation results from the high costs associated with multilevel outlets and at present the absence of economic justification. A maximum surface-water temperature of 18°C is within the tolerance limit for cold-water fish.

Apart from the recent stratification effects, the acidic low-solid surface waters from the reservoirs have caused corrosion problems in hydraulic machinery and pipelines. These problems have been caused principally by the tuberculation of steel with penetration rates of 0.1–0.2 mm/yr (0.004–0.008 in./yr) and by attack on zinc, copper, and aluminium together with extensive manganese bacterial slimes in closed conduits (principally the stalked *Hypomicrobium*) and aquatic mosses and algae in concrete canals. At Tarraleah these are chiefly *Bryum* sp., *Fissidens strictus*, and *Tridontium tasmanicum* in a diverse microflora largely consisting of diatoms, *Gomphonema gracile, Navicula* sp., and *Tabellaria flocculosa*. These biological deposits have reduced the effective capacity of the 20-km-long (12-mile-long) Tarraleah canal from Lake King William by 10% and increased rugosity values in tunnels and penstocks (where the slimes uniformly cover steel, painted steel, woodstave, and concrete surfaces). The result has been a capitalized loss of Aust$3,000,000 for the four power stations in this area alone.

These and related problems have been investigated since 1952. During this time, biological and certain chemical aspects have been identified and examined. Trial and full-scale chemical experimentation, including trout toxicity tests principally with copper sulfate and chlorine, has been carried out; and the performance of materials,

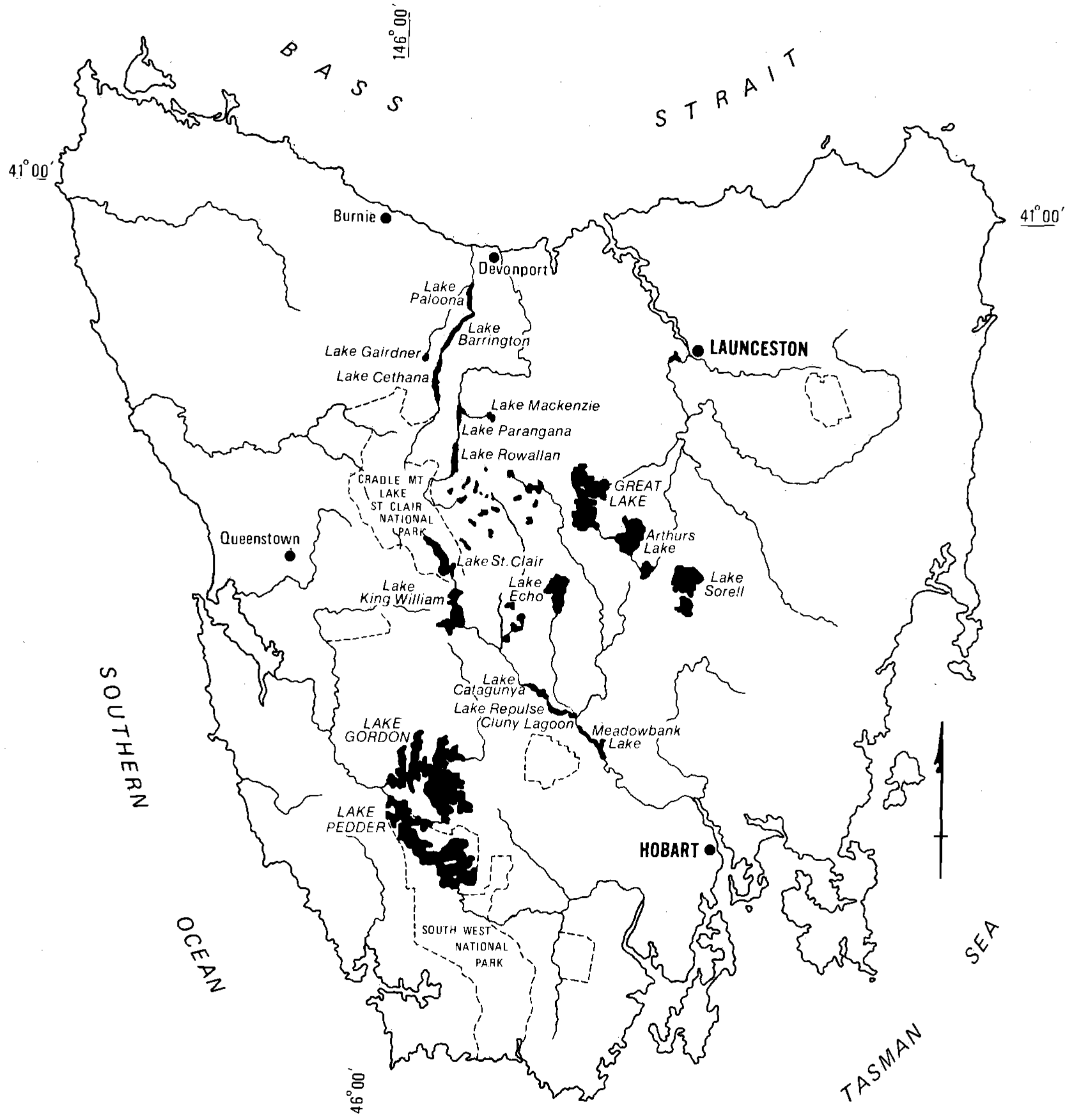


Fig. 1. Map of Tasmania showing the hydroelectric power developments and the completed and proposed large storage lakes (scale: 1 cm = 25 km, approximately).

rugosity variations, and economic aspects have been tested and assessed. A completely effective low-cost solution using intermittent chlorine injections (1 hour per 15-day period with power station discharge residuals of <0.5 mg/l of free chlorine) was proven after 12 months of field trials, but possible long-term deleterious effects on the biota of the downriver lakes and their trout fisheries have deferred the introduction of these procedures. Extensive chemical and limnological research may succeed in allaying this concern. Nevertheless, a trial period of chlorination for 4 or 5 years with monitoring of biological parameters appears warranted on the present evidence.

As would be expected in these unbuffered waters, an inverse relationship exists between surface-water inflow rates, *p*H, and chemical content. Low runoffs with their high proportion of groundwater and seepage generally have *p*H values of 7.0–7.5 and total dissolved solids of up to 100 mg/l. During high inflows, *p*H values reduce to 5.0–5.5 (4.0 for the Serpentine River), and total solids reduce to <40 mg/l. The effect of the weak fulvic-humic acids derived from the plants, peats, and litter is evident. Organic coloring is generally high, Hazen maximums being 50 in the highland lakes and about 150 in the southwest rivers.

Descriptions are given of only three of the seven existing large lakes of the Hydro-Electric Commission (Table 1) and their drainage areas and problems. Two large lakes of the three being completed are also described.

GREAT LAKE (1911, 1922, 1967)

Prior to development for hydropower, Great Lake consisted of two shallow morainal lakes joined by a middle reach except during periods of high inflow. A low masonary dam completed in 1911 was made obsolete by a multiple-arch concrete dam in 1922, which caused the further inundation of marshes, open moorland, and lightly timbered areas. In 1967 the 18.3-meter-high (60-foot-high) rock-fill no. 3 dam was built downstream of the arch, but the lake level has not yet exceeded the 1947 peak, which was 0.6 meter (2 feet) below the arch crest.

There is no permanent snow, but snow falls on about 40–60 days per year, and rainfall varies from 2300 mm (90 inches) on the western scarp to 900 mm (35 inches) to the east. At Great Lake, ice forms over some of the bays about once in 10 years, and severe frosts are frequent.

Sources of pollutants are mainly sheep, which are summer grazed at 250–750 per square kilometer (1–3 per acre) on the native grasses of the unimproved moors; native animals, chiefly the marsupial Bennett's wallaby (*Wallabia rufogrisea*); and approximately 400 mainly primitive fishing shacks infrequently occupied by sporting fishermen. Extensive burning has taken place for >100 years and has resulted in a degenerative environment and widespread but shallow loss of surface soils and organic material from the residual peats. More serious soil losses have been prevented by the protective effects of the high stone content of the clay soil matrix and by partial recovery during periods of high precipitation. To date this erosion has not caused a silt problem in the lake.

The filling and emptying cycles of the lake will vary with the growth of the power system and hydrologic conditions, but, in general terms, the maximum change in level is 1 meter (3 feet) per month, and the average is 0.3 meter (1 foot) per month. Only minor regeneration occurs on the stony foreshore.

The lake is extensively fished for trout, chiefly brown (*Salmo trutta* Linn) and rainbow (*S. gairdneri* Richardson), which apparently benefited from the nutrient gains that followed the initial and subsequent floodings and from diversions to the lake. There has been some concern during recent years that the fish population and growth rate have decreased, but whether this decrease has been due to more frequent fishing, lake level fluctuations, or a decrease of nutrients requires further study. If we exclude future man-made influences, it is probable that the lake will slowly return to a senescent neooligotrophic condition with a decreasing fishery capacity.

The acidic (*p*H of 6–7) typical moorland waters of Great Lake are generally clear (silica scale turbidity of <5 mg/l and Hazen color of <10), dissolved solids being <20 mg/l, manganese being <0.03 mg/l (generally 0.01 mg/l), and iron being <0.2 mg/l. In the smaller lakes and tarns, local organic enrichment results in a maximum manganese content of 0.08 mg/l and a maximum Hazen color of 50.

Prior to diversion of Arthurs Lake to Great Lake in 1966, the Great Lake waters caused only a thin gelatinous slime rich in silica and iron in pipelines, but manganous types have since become established. The diversion has increased the Great Lake yield by about 25%. Other than the initial leaching of surface laitance and fines, these waters are not aggressive to concrete but cause the loss of protective zinc (galvanizing) at approximately 0.025 mm/yr (0.001 in./yr). In common with similar experiences in the United Kingdom, these pure waters with their low iron, manganese, and organic values cause corrosion problems to unprotected steel, and expensive protection systems to all wetted surfaces are required.

LAKE ST. CLAIR (1937)

Lake St. Clair is a narrow overdeepened glacial lake about 13 km (8 miles) long by 2.5 km (1.5 mile) wide that is upstream of and in the Lake King William catchment and that has a maximum depth of about 200 meters (700 feet). Surrounded by peaks of up to 1500 meters (5000 feet) above mean sea level with heavily forested lower slopes and subalpine uplands, the lake is a major scenic and tourist lake and salmonid fishery. A multiple-gated weir that is 3 meters (10 feet) high (completed in 1937) and a pumping station (completed in 1940) control 7.3 meters (24 feet) of the enlarged lake. With a low effective storage to inflow ratio of 0.5, the water levels fluctuate intraseasonally, the minimum level occurring about once in 15 years. The inundated verge was not cleared, and large quantities of trees and scrub were drowned.

Before and after being regulated, the lake apparently fished well. Adequate plankton populations were reported in the first significant Tasmanian limnology survey made in 1937–1939, but later data are meager. More recently, the limited chemical and physical results indicate an unbuffered, slightly acidic (*p*H of 6–7) water with extremely low solutes and maximum values of 2 mg/l for calcium, 0.01 mg/l for manganese, 0.05 mg/l for iron, and 25 mg/l for total dissolved solids. Turbidity and color are also low. Temperatures measured at monthly intervals for 3 nonconsecutive years show that, from −46 meters (−150 feet) to −152 meters (−500 feet), water temperatures are consistently isothermal, the annual variate being 2°C (5.5–7.5°C); the upper water varies seasonally from 6° to 15°C, the depth of the upper isotherm extending to about −37 meters (−120 feet) by autumn. Except for the leaching of weak cement mortars and their corrosive effects on unprotected steel, these waters have not caused any apparent engineering problems.

Since Lake St. Clair is an old natural lake with a significantly altered regime, suitably designed studies with periodic updating could result in its becoming an ecological bench mark, or reference lake, from which the behavior of the newer man-made lakes could be correlated and their future behavior could be predicted.

LAKE ROWALLAN (1967)

Lake Rowallan is a sheltered narrow man-made storage 11 km (7 miles) long in the deeply incised Mersey River Valley. The inundated valley floor consisted of summer-grazed marshes and grasslands with pockets of dense scrub and trees. Up to 900 meters (3000 feet) above mean sea level the catchment is heavily timbered, principally with eucalyptus and mixed eucalyptus-myrtle forest. It is uninhabited but is visited by bush walkers, hunters, and fishermen, and there is logging in the vicinity of the lake. Reservoir clearing was restricted to the areas adjacent to the dam. Mean annual rainfall varies from 2500 to 1800 mm (100 to 70 inches), and irregular snow falls above the 900-meter (3000-foot) level.

The storage filled and spilled in September 1967, 4 months after closure. Hydrogen sulfide in the discharge and extensive fungal growth, *Saprolegnia* sp., *Leptomitales* sp., and bacteria on the bypass valve dissipator were evident in January 1968. Water temperature profiles and chemical analyses taken by the Hydro-Electric Commission in February 1968 confirmed that the lake had stratified, water temperatures being 17.5°C near the surface and 7.2°C at the 33-meter (108-foot) depth.

The thermocline persisted until late May 1968 and reformed during the following two summers from December to May when it was broken by high inflows with subsequent spilling. Until mid-1969, only sufficient data were collected to define the situation in general terms, since there was a slight possibility that the continuous operation of the Rowallan power station during the summer of 1968–1969 would cause sufficient mixing to replenish the oxygen deficiency at depth. When this possibility did not occur, a more extensive program of chemical sampling commenced in August 1969 and has continued since.

Since August 1969, data collection has been carried out at monthly intervals at four buoyed stations in the lake and at additional stations in the power station discharge, in the diversion pondage 9.65 km (6 miles) downstream (Parangana), and downriver. Full chemical sampling has been taken from two to four depths at each station in the lake; the number of samples taken depends on water depth but includes a sample from 0.6 meter (2 feet) above the lake bottom. Bacteriologic examination of certain discharges for plate counts, coli-aerogenes, and fecal coliforms (*E. coli*) were also made.

The pressure conduit through the bottom of the dam is in situ concrete connecting the low-level outlet to a surface steel penstock; internal paint systems are epoxy on a section of the concrete and spun coal-tar enamel and tar epoxy on the steel. Inspections in August 1968 and subsequently showed that all internal surfaces were coated with 4 mm (0.15 inch) of red brown iron-rich slime with high organic content, principally bacilli, yeasts, and some fungi. *Gallionella* and chlamydobacteria were not evident, whereas *Hypomicrobia* were only present in small numbers. The hypolimnionic enrichment of the lake has increased the iron and manganese solutes from 0.1 mg/l to 3.0 and 0.5 mg/l (maximums), respectively; the dissolved carbon dioxide from about 3 mg/l to 21 mg/l: and the dissolved sulfide to 0.3 mg/l with low or no DO (dissolved oxygen) at depth for 3–4 months per year. From limited evidence it is apparent that the plankton numbers have not significantly increased, and there are no signs of any deleterious effect in the epilimnion. Phosphate is about 0.06 mg/l as PO_4.

During summer the noxious odor of hydrogen sulfide is evident at the power station and for some 5 or 6 km (3 or 4 miles) downstream; river gravels are coated with iron precipitates, and some small fish (trout) kills have occurred in this reach. However, the river is shallow and fast flowing, and reoxygenation occurs in the first few kilometers; atmospheric dispersion of these weak gases is rapid.

There is no evidence of deterioration of hydraulic machinery, concrete surfaces, or painted steelwork (either immersed or exposed) other than the formation of sulfide oxides on silver relay contacts. Artificial destratification that would reduce the downstream iron concentration, increase discharge water temperatures, decrease the lake surface evaporation, and have esthetic and limnological benefits is currently under consideration.

LAKES PEDDER AND GORDON (1972)

Situated in wet, uninhabited, and undeveloped southwest Tasmania, the Gordon River Power Development (stage 1), when it is completed, will consist of a deep underground power station with an installed capacity of about 725 Mw, four dams, and two large man-made lakes. Lake Gordon will have the largest live storage in Australia.

Mean annual rainfall varies from 1800 to 3300 mm (70 to 130 inches), and there is hail and infrequent snowfalls at the reservoir elevations and nonpermanent snow on the peaks. The rocks of the basin are Precambrian and Paleozoic, extensive glacial outwash forming large marshy flats at about 275 meters (900 feet) above mean sea level. Large areas of the catchment consist of leached low-nutrient shallow soils, gravels, and rocky outcrops with peaty sedge lands, heaths, and low shrubberies. However, in Lake Gordon's catchment basin and reservoir and to a lesser extent in the eastern portion of Lake Pedder, there are significant forests of eucalyptus and mixed eucalyptus and rain forest (chiefly myrtle). Scattered small stands of trees occur on the hills, and patches of wet sclerophyll occur on the watercourses. The Gordon River source is adjacent to Lake King William, and there are subalpine ecological areas in this region.

There are no private lands in the catchment basins, and the required works and storage areas are now vested in the Hydro-Electric Commission, the adjoining Crown lands being partly scenic reserve included in the large southwest fauna district. Because of these restrictions, domestic animals and exotic plants are not permitted in the area, and hunting is prohibited.

Lake Pedder will be formed by a 40-meter-high (130-foot-high) dam on the Serpentine River with a bottom outlet for occasional flood releases, a 45-meter-high (150-foot-high) dam on the adjacent Huon River, and a 15-meter-high (50-foot-high) saddle dam. From this common lake the conjoined waters will be diverted to Lake Gordon via 3.2 km (2 miles) of shallow cut and canal. The existing Lake Pedder, an attractive 10-km² (2500-acre) shallow natural lake, will be drowned in the enlarged lake. Lake Gordon, the headwater reservoir for the Gordon power station, will be formed by a dam approximately 137 meters (450 feet) high. Both storages will be practically 100% regulated, inflows passing through the underground station via a single intake shaft at an elevation of 254 meters (830 feet) above mean sea level in the base of the 76-meter-high (250-foot-high) concrete tower standing in Lake Gordon.

Extensive perimeter clearing with burning or burial of the debris is planned at Lake Pedder, where the normal operating range is 1.5 meters (5 feet). However, because of its size, the operating range, and the related cost, clearing in Lake Gordon will be restricted to small areas adjacent to the dam and the main access road. Both storages, which will take several years to fill, have deeply indented bays with partly enclosed sectors, and several years work is anticipated before the littoral debris is collected and burnt. Mount Solitary (12 km², or 3000 acres) will be the largest of the numerous islands and is ideally situated for future use as a permanent primitive ecological reserve restricted to scientific studies.

Prior to the construction of access roads for power development, these areas were visited by 300–400 bush walkers per year. Tourists visiting the area are now about 25,000 per year and are increasing, whereas the accessible wilderness areas have been considerably extended. Fauna, flora, and limnological studies, principally of the Lake Pedder storage area, have been carried out, and there is now considerable scientific interest in what was previously an almost totally neglected region. The relevant initial study was made for the Hydro-Electric Commission in early 1967.

Although Tasmania is not in a region of significant seismic activity, the commission's engineers and geologists have carried out studies for possible earthquake effects following the filling of Lakes Gordon and Pedder. A station forming part of the state seismic grid is being installed at Gordon Dam together with the instrumentation of the nearby Lake Edgar fault to measure microseismic activity. The state seismic grid has also been extended and improved.

Chemical analyses and physical data collection from the relevant surface waters commenced in 1966, and air, ground, and water exposure trials of selected metals and paints commenced at four local and eight related sites in 1968. It was apparent from the known water chemistry (pH of 4–7; maximums of 1.0 mg/l for iron, 0.05 mg/l for manganese, <10 mg/l for calcium, and 10 mg/l for dissolved CO_2; and Hazen color of 150) and from the preliminary results of the testing materials that special design and construction measures would be required in these lakes to avoid potentially severe corrosion and concrete deterioration problems. The chief factors influencing the prediction for engineering purposes of the chemical and biological behavior of these lakes are the long retention times without discharge during initial filling, the immense quantities of organic matter that will drown, and the chemical balance of the mixed waters with appropriate adjustment for the changed environment following inundation. An additional factor is the isolation of the deep water at the principal dams (Serpentine and Gordon including the power intake) from wind and current due to the near-topographic closure of these small sectors of the reservoirs.

This work has been a major factor in determining the relevant design criteria for the components of the immersed structures regarding their safety, maintenance, and cost. Principally, these structures require the extensive use of austenitic stainless steel and plastics; cathodic protection of certain deep structures; special regard for the removal, maintenance, or replacement of deep hydraulic equipment; and the production of dense rich concrete, particularly in certain situations. The main paint systems adopted and proved by the Hydro-Electric Commission in other areas are considered satisfactory in Lakes Gordon and Pedder, but the use of zinc galvanizing (including in the splash zone above ground), copper, and aluminium has been restricted. Chlorination of the cooling water for the station is being examined to control the expected slime deposits in these conduits and on the screens.

Although subject to sudden weather deterioration, Lakes Gordon and Pedder will be centers of major tourist attraction and will provide both terminal points and access ways to these previously inaccessible primitive regions. The biota-deficient acidic rivers of this region are currently unsuitable for sport fisheries, but it is anticipated that the impoundments will have pH minimum of 5–5.5, and biological enrichment will result in a supermesotrophic state and a satisfactory environment for fish. Eutrophication of the upper biotope is not expected.

CONCLUSION

It is evident that some of the engineering matters briefly described in this paper and their relationships to the chemical and biological aspects of the building of major lakes require further work. It is also clear that considerable applied research and methodology is needed to evaluate the basic chemical, physical, and limnological condition of Tasmanian lakes with emphasis on determining the controlling parameters and their long-term effects. Although some good progress has already been made, a satisfactory solution to the problems of non-integrated catchment management for Tasmania is required, and multidiscipline research and assessment to evaluate the various factors are needed.

Acknowledgments. The author wishes to acknowledge the laboratory work done for the Hydro-Electric Commission by Mr. M. H. R. Shipp, B.Sc., A.R.A.C.I., government analyst, from which the chemical data used in this paper are largely derived and to thank Sir Allan Knight, CMG, ME, B.Sc., B.Comm., FIE (Australia), Commissioner of the Hydro-Electric Commission, for permission to publish this paper.

Man-Made Lakes in South India

S. V. GANAPATI

Division of Sanitational Biochemistry, Department of Biochemistry
University of Baroda, Baroda, India

Conditions in the 70 main Indian rivers have no parallel anywhere in the world. Excepting the Indus, the Ganges, and the Brahmaputra whose sources are in the perennially snow-clad Himalayas, the majority of Indian rivers cease to flow during the dry months of the year. The torrential rains confined to a few weeks of the two monsoons, the southwest and northeast, cause heavy floods charged with fine silt in a normal year. For the rest of the period, even the bigger rivers dwindle to trickling streams. In many, there is no continuous flow at all, but the water stagnates in deep pools in the scours on the riverbeds.

The object of constructing dams across rivers in India is to conserve as much of the water from the floods as possible for distribution evenly throughout the year, chiefly for irrigation purposes. Almost all the major and minor rivers and their tributaries have been dammed at strategic points, and man-made lakes of different sizes have been formed. There are 295 reservoirs with a total area of 1,197,000 ha (excluding the hundreds of minor irrigation reservoirs). Of these, 211 have areas of >400 ha each. These reservoirs are peculiar biosystems not seen in Africa, America, or Europe. A few of them have been in existence since the eleventh century A.D. Their problems and environmental effects have been studied for a fairly long period of 2-3 decades in south India. This paper assesses the peculiar effects of certain typical impoundments designed by man in this part of the globe.

IMPORTANT RIVER BASINS AND THEIR DEVELOPMENT IN SOUTH INDIA

The major rivers are the Godavari and the Krishna in the north, the Cauvery in the middle, and the Tambaraparani in the extreme south (Figure 1). All these rivers originate in the western ghats. The smaller Kortalayar River is also discussed. Meteorologic conditions profoundly affect the interdisciplinary character of the man-made aquatic ecosystems formed on the river basins.

Godavari River Basin

The Godavari runs through inaccessible forest and mountainous regions and flows for 360 km through plains in Andhra state before discharging into the Bay of Bengal. In the last stretch the river is dammed first at a place called Dummagudam. Then 241 km lower down it is dammed in four places connecting the three permanent islands in the river at a place called Dowaleshwaram. Thus a huge but shallow man-made lake having a water spread of 35,223 ha and depths of between 5 and 36 meters is formed for most of the year. The river is in spate from June to October. During this time for brief periods of 1-15 days the water level rises about 3 meters above the four anicuts, the importance of which will be discussed later.

Krishna River Basin

On this river a huge man-made lake called Nagarjuna Sagar, which will have an area of 28,600 ha and an average depth of 60 meters, is nearing completion. About 165 ha of forest have been cleared for the purpose. The maximum height of the dam is 125 meters, gross storage is 11,558 million m^3, and live storage is 6796 million m^3. This storage is expected to irrigate 2541 million m^3.

Cauvery River Basin

Of all the rivers in India the Cauvery is perhaps the one most used for irrigation, fisheries, and hydroelectric power. It runs nearly 764 km in a southeasterly direction before emptying into the Bay of Bengal on the seaboard of the Tanjore district in Madras state. From its source to the

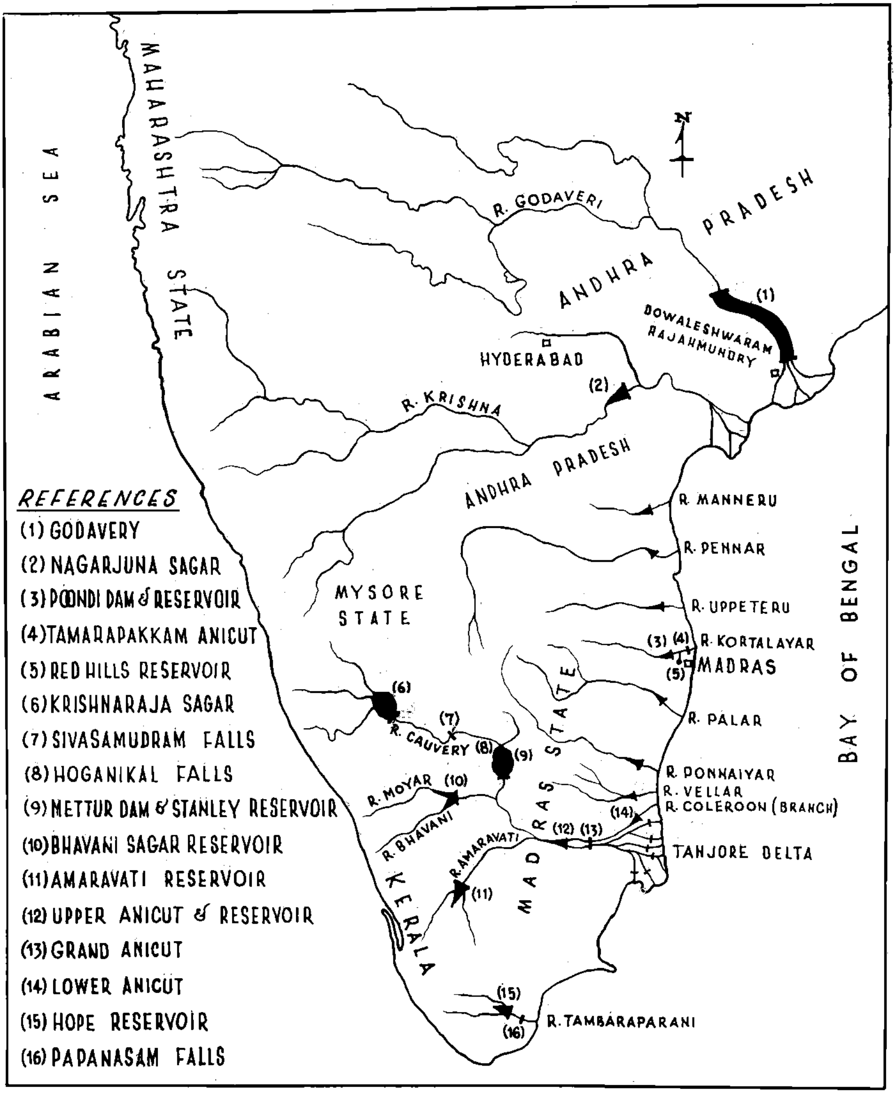


Fig. 1. The important rivers, dams, and man-made lakes of south India.

famous Sivăsamudram Falls, which has a descent of 97 meters in Mysore state the Cauvery passes through tortuous rocky beds with high banks covered with tropical vegetation. Next, in Madras state, it passes through the Hoginakal Falls, which has a descent of about 21 meters in a deep chasm in the rocky bed of the falls. The Hoginakal Falls constitutes the other end of the Stanley Reservoir formed by the dam located in the gorge at Mettur. From the Mettur Dam the river enters the plains, where it is joined by the Bhavani, Amaravati, and Moyar tributaries.

Stanley Reservoir. This reservoir, formed by the Mettur Dam, is a man-made lake of 439 million m^3 of water at its maximum water level, which is 243 meters above mean sea level. The normal flood discharge is through the Ellis surplus to the east of the dam. In times of extraordinary heavy floods an emergency discharge is provided over a saddle to the west of the dam at 241 meters. This Ellis surplus has 10 vents with a span of 18 meters and liftable iron shutters. The channel from the Ellis surplus is 5.6 km long and joins the river about 4.0 km below the dam. The average gradient of the channel from the Ellis surplus is 1 in 100 (Figure 2).

The Ellis surplus overflows for about 100 days on an average in a normal year. When the reservoir level falls below 236 meters (i.e., 1.2 meters above the sill level), the shutters of the surplus are let down, and the supply for irrigation starts from the high-level sluice, which has eight vents (each 9.3 m^2) and a sill level at 219 meters. Normally, the reservoir is not expected to fall below the 224-meter level. Should the level fall below 222.5 meters, the irrigation supply will be through the low-level sluice, which has five vents and a sill level at 204 meters. The low-level sluice is not expected to be used except in very bad years. Thus the high-level sluice is designed to operate with a head of water ranging from 16.4 to 3.0 meters, although 4.6 meters is the lowest expected.

The dam provides for the generation of electricity. Four pipes through the dam for turbines under a maximum head of 46 meters have been provided for a maximum production of 49,000 hp at 195 meters. At the bed level (190.5 meters), there is a dead storage of water that is 4.6 meters deep. The reservoir is affected by the southwest and northeast monsoons. Its main supply is from the former in the upper reaches and from the latter below the dam [*Ganapati,* 1955; *Sreenivasan,* 1966].

Bhavani Sagar Reservoir. This reservoir

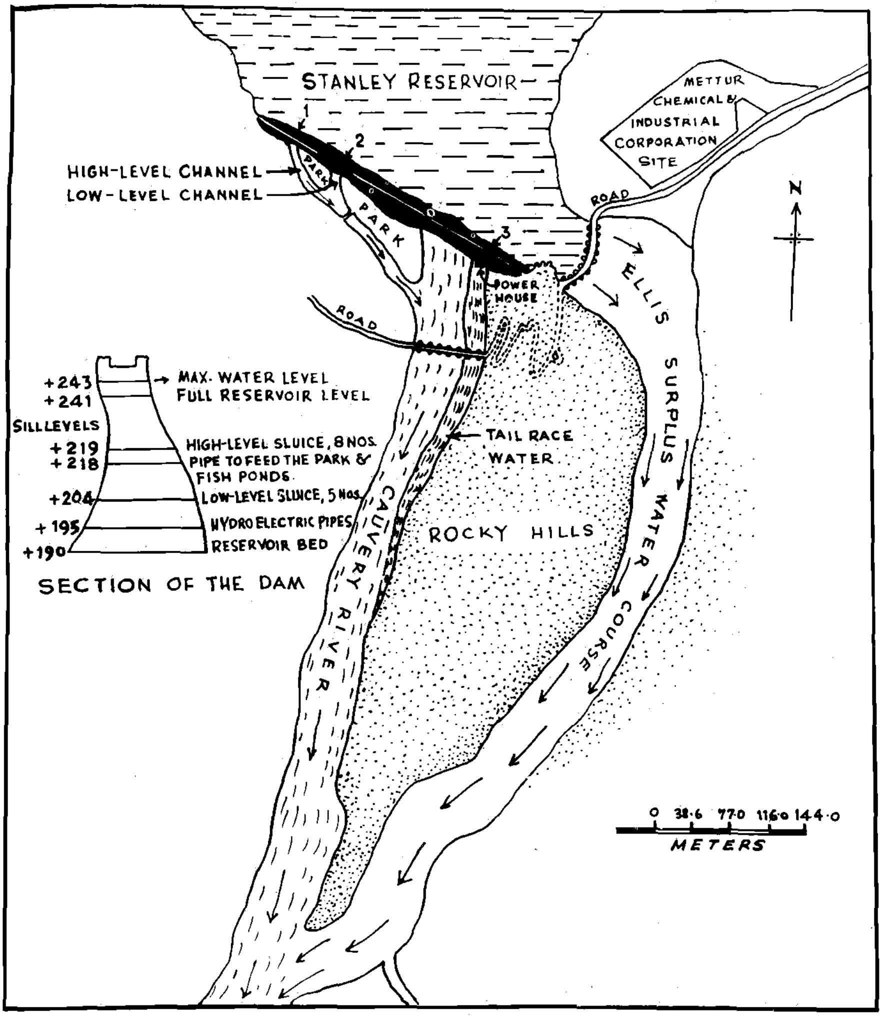


Fig. 2. Stanley Reservior with the Ellis surplus overflow acting as a fish pass for the Cauvery River fish. High-level sluices at 1, low-level sluices at 2, and hydroelectric pipes at 3.

[*Sreenivasan*, 1964; *Sreenivasan et al.*, 1964] is formed by the impoundment of two rivers, the Bhavani and the Moyar, which originate in the Blue Mountains at an elevation of 1525 meters. The length of the dam is 8.0 km (5 miles), and the central masonry structure is 465 meters (1523 feet). The bed level of the river is at 243 meters, that of the river sluice is at 248 meters, and that of the canal is at 256 meters. There are nine river sluices that are each capable of discharging 79 l/sec. The spillway crest is at 274 meters, and the maximum water level is at 279 meters. The area of the water spread is 7852 ha, and the maximum depth is 36.0 meters (118 feet). The reservoir has two sleeves: one is from the Moyar River, and the other is from the Bhavani River and is at right angles to the former. The length of the main rivers up to the dam is 112 km (70 miles).

Amaravati Reservoir. The Amaravati Reservoir [*Sreenivasan*, 1965] is the third man-made lake formed on a tributary of the main Cauvery River, i.e., the Amaravati and its feeder streams at an elevation of 480 meters. The area of this reservoir is 931 ha, and the maximum depth is 35 meters. The bed level of the river is at 325 meters, and spillway overflow is at 350.5 meters.

Again, about 1069 km below the Mettur Dam, the main Cauvery River bifurcates at Sirrangam and forms the Coleroon River in the north and the Cauvery River in the south, which embraces the Tanjore delta. From the bifurcation the river is systematically tapped at several points by a network of irrigation canals, most of which have existed since the days of the Chola kings in the eleventh century A.D. The main flow of the river is through the Coleroon, which carries the bulk of the floods to the sea. The most important hilsa fishery of the Cauvery River occurs in this branch.

So the Cauvery has over a dozen dams and man-made lakes in actual use. The biggest, Mettur Dam, is situated about 402 km from the mouth of the Cauvery and is the fifth dam from the mouth. The four dams below the Mettur are the Upper Anicut and the Grand Anicut, which are both across the main river; the Lower Anicut, which is across the Coleroon branch; and the Cauvery, which is across the main river and forms several man-made lakes [*Raj*, 1942].

Tambaraparani River Basin

This river [*Ganapati*, 1956] has been dammed at two places. The result has been the formation of a 61-meter dam and the Hope Reservoir, which has a water spread of 8500 ha and a maximum depth of 61 meters. Hope Reservoir has two tunnel outflows and a lower dam and reservoir for regulating the resulting flow, which is converted into electric energy. The flow is diverted from the main river course about 1.2 km above the falls through a steel low-pressure pipe that is 2.7 meters in diameter. Four 15-cm penstock pipes that are 158 meters long carry the water from the second pondage down to the hillslope and from the surge tower to the powerhouse, which is located at the foot of the Papanasam Falls.

Kortalayar River Basin

The Kortalayar [*Ganapati*, 1961] is a comparatively much smaller river whose floodwaters are diverted by means of a masonry weir built across the river at Tamarapakkam about 29 km northwest of Madras. Until June 1944 the weir diverted all the waters of the river (excepting the greater flood discharges) into a channel leading to Red Hills Reservoir. To conserve the river water that was overflowing the Tamarapakkam Anicut, the river in 1944 was again dammed at Poondi, which is 19 km above the anicut. The impounded water at Poondi is drawn up to Tamarapakkam Anicut through the Kortalayar River and from there through the upper and lower supply channels into the Red Hills Reservoir, the source of water supply for the city of Madras.

The recently formed Poondi Reservoir has a full tank capacity of 312 million m^3, a water spread of 3100 ha, and a maximum depth of 10 meters. The Red Hills Reservoir was constructed in 1886, has a capacity of 138 million m^3, a water spread of 1813 ha, and a depth of 7.6 meters.

METEOROLOGY

The radiation data obtained for Delhi, Calcutta, Poona, and Madras may be considered to be roughly representative of the climatic conditions existing in the northern, northeastern, central, and southern parts of the peninsula. Delhi (250°35′N, 77°13′E) is typical of the north-northwestern part of the country with its extreme summer and winter conditions, whereas Calcutta (22°39′N, 88°27′E) is typical of the northeastern region with its more humid summer followed by the southwest monsoon and a mild winter. Poona (18°32′N 73°51′E) data may be considered characteristic of conditions in the center of the country and to some extent of the west coast of India. Madras (13°00′N, 80°11′E), farther south and on the east coast of the peninsula, has climatic conditions quite different from those of the rest of the country, the northeast monsoon during October, November, and December being a special feature of this area.

The four stations may generally be considered to be representative of conditions prevailing over India during the four main seasons, which are summer (March to June), the southwest monsoon (July to September), the northeast monsoon (October, November, and December), and cold weather (January to February). Also, the observations in India show that the forenoon values of radiation are slightly higher than the corresponding values in the afternoon except in Madras where the afternoon values are predominantly higher [*Chacko and Venkateshwaran*, 1962]. The evaporation rate in most places in India is 2–3 m/yr.

Violent fluctuations in water level due to drawoff from different levels, sudden input of fresh rainwater carrying highly turbid eroded soil from the watershed, resultant flushing of the reservoir, extreme rates of evaporation, density currents, and shortening of the river stretch are all factors that have a cumulative impact on the hydrology, biology, public health, and management aspects of the man-made lakes described above. Their salient features are discussed below.

HYDROLOGY

Thermometry. The thermal conditions in the man-made lakes are shown in Table 1. The thermal ranges of temperature resemble those recorded for the lakes of East Indies by *Ruttner* [1931], who found the vertical differences to vary from 0.25°C in Danu Batur to a maximum of 5.5°C in Ranu Klindungen. In these cases, Ruttner called them thermally stratified, because the change in density for a temperature difference of 1°C between 29° and 30°C is 2–3 times as great as that for the same difference in temperature between 14° and 15°C. So the stability of thermal stratification in the man-made lakes of south India is really very great despite the smaller vertical differences in temperature, especially during the summer season of March to June.

Second, because the bottom temperature is higher in the range of 22°–30°C, the rate of biochemical reactions will be 4–9 times greater [*Ruttner*, 1931]. So the decomposition of silt deposited at the bottom layers will be taking place at a much faster rate than that in the temperate regions, and oxygen depletion should also be taking place. The process proceeds at this rate, as will be seen from the production of H_2S at the bottom, in spite of the smaller vertical temperature differences in our reservoirs.

Oxygen distribution. These values are shown in Table 2. The surface layer was supersaturated occasionally, but the bottom layers showed considerable depletion in all the reservoirs especially during the summer months of March to June when the level of water was the lowest.

Values of pH. The *pH* values are shown in Table 3. Stratification in *p*H was a regular feature in all the reservoirs especially during the summer months of March to June when the water level was lowest.

Stratification. Data on thermal and chemical stratification are given in Table 4. As *Neel* [1966] has pointed out, 'If decomposition in a hypolimnion exhausts oxygen supplies, the presence of stratification is often indicated by the sulfide odours leaving releases. . . .' Such is the case in these four man-made lakes, where the discharges from the bottommost sluices often contain H_2S especially during the summer months of March to June. This occurrence was clearly

TABLE 1. Temperature Ranges at the Surface and Bottom and Vertical Differences

Man-Made Lake	Depth, meters	Surface Temperature, °C	Bottom Temperature, °C	Vertical Difference
Stanley Reservoir	25 to 43	26 to 32	26 to 29	0.7 to 4.4
Bhavani Sagar Reservoir	18 to 36	24 to 31	22 to 30	0.3 to 2.9
Amaravati Reservoir	9 to 34	25 to 28	22 to 27	0.8 to 2.5
Hope Reservoir	13 to 35	25 to 33	23 to 27	1.0 to 6.6

TABLE 2. Oxygen Distribution Values

Man-Made Lake	Depth, meters	Surface, mg/l	Bottom, mg/l	Vertical Difference
Stanley Reservoir	25 to 43	3.5 to 6.1	2.1 to 5.4	0.4 to 2.6
Bhavani Sagar Reservoir	18 to 36	?	?	?
Amaravati Reservoir	9 to 34	6.0 to 8.8	0.0 to 6.7	1.3 to 8.2
Hope Reservoir	13 to 35	4.6 to 5.7	0.0 to 4.8	0.3 to 5.6

shown in Stanley Reservoir on one occasion when the author actually saw an interesting phenomenon for several days.

The tailrace water discharging from the turbines, operating under a head of 29 meters for generation of electricity, was found to be discolored black and smelled strongly of H_2S. A fourth of the river below the dam was black in color, and the remaining three-fourths was bluish green for a distance of about 1.6 km below the dam. The bluish green colors were the discharges from the upper strata of water through the high-level sluices. The two distinctly colored streams flowing side by side were mixed ultimately and became uniform in color. Samples were taken from five different points along both banks of the river before the two portions were mixed (Figure 2).

The meandering black eastern portion had a lower temperature (about 27°C) and lower oxygen content and *p*H but higher amounts of phosphates, silicates, and nitrates than the bluish green water in the western portion of the river, which was flowing at a terrific speed [*Ganapati*, 1955].

Siltation. There is a gradual accumulation of silt in the bottommost dead storage of water, which varies in depth from reservoir to reservoir. A maximum of 4.6 meters is provided in the Stanley Reservoir, 5.5 meters in the Bhavani Sagar Reservoir, 6 meters in Amaravati Reservoir, and 43 meters in the Hope Reservoir. So the rate and amount of accumulation of silt are greatest in the Hope Reservoir, and H_2S production is also great. Eutrophication is slowly taking place in all reservoirs. This occurrence is contrary to what has been reported in some reservoirs in the west.

Density currents. These are a seasonal feature of all the reservoirs. A typical case is the Stanley Reservoir where the density currents were noted in the discharges from the tailrace water on different dates (Table 5). The occurrence of water that is differently colored from the top layers is an indication of water markedly different in density from the overlying upper strata [*Ganapati*, 1955].

Chemical quality. There is seasonal change in the chemical quality of the surface and bottom layers of water. The upper strata become more and more oxygenated especially during the summer season when there is also a slight increase in the hardness due to photosynthesis and biological productivity. At the same time in the bottom layers of water, anaerobiosis takes place in summer. The result is oxygen depletion, H_2S production, and an increase in the nutrient substances of biological significance. The surface waters do not generally contain nitrates or phosphates [*Ganapati*, 1955; *Sreenivasan*, 1964; *Sreenivasan et al.*, 1964].

BIOLOGY

Fisheries and Fishery Development

The vast number of man-made lakes in India constitute a substantial fishery resource, and, in

TABLE 3. Range of *p*H Values

Man-Made Lake	Depth, meters	Surface	Bottom	Vertical Difference
Stanley Reservoir	25 to 43	8.2 to 9.1	>7.3	?
Bhavani Sagar Reservoir	18 to 36	6.8 to 8.2	6.9 to 7.9	1.8 to 2.3
Amaravati Reservoir	9 to 34	6.7 to 9.1	6.4 to 6.7	0.2 to 2.5
Hope Reservoir	13 to 35	7.2 to 8.6	6.0 to 7.9	0.2 to 2.5

TABLE 4. Thermal and Chemical Stratification

Man-Made Lake	Depth, meters	Months	Temperature Difference	O_2 Difference	pH Difference	H_2S, ±
Stanley Reservoir	30	June	2.7	5.0	...	+
Bhavani Sagar Reservoir	15 to 18	March to June	2.2 to 6.6	High	2.5	+
Amaravati Reservoir	9	April	1.8	8.2	2.5	+
Hope Reservoir	12 to 15	March to May	1.1 to 5.3	4.6 to 5.3	2.5	+

recent years, considerable attention has been paid to their development and exploitation. It is worthwhile to examine how much the construction of dams and reservoirs has affected the fishery interest in south India [*Raj*, 1942; *Chacko*, 1947; *Chacko and Ganapati*, 1956].

Fish populations. The fish populating the rivers of south India may be broadly grouped under four categories: (1) those ascending the rivers from the sea, (2) those descending the rivers into the sea, (3) those moving up and down the upper reaches for breeding and feeding, and (4) the species showing local migrations in the plains.

Those fish ascending the rivers from the sea are the Indian shad, *Hilsa ilisha* (Hamilton); bekti, *Lates Calcarifer*; and *Mugil olivaceus* Day. All of them are quite at home in the estuaries and shallow flats close to the mouths of the Godavari, the Krishna, and the Cauvery. The hilsa alone exhibits the longest migration, a distance of 322 km from the sea for feeding and breeding. The other fish travel a distance of only 96 to 128 km.

The largest hilsa fishery has been very much affected by the construction of dams and man-made lakes on the Godavari and the Cauvery in the last lap of their courses. During the monsoon season the fish ascend in dense shaols into the three major rivers as well as into smaller rivers such as the Korayar and Pamaniyar in the Tanjore district; the Vellar and the Palar in the South Arcot district; and the Pennar, Manneru, and the Uppteru in the Nellore district. In all these rivers, artificial barriers such as dams and reservoirs constructed for irrigation purposes stop the course of the fish, which are then caught and marketed. The barriers are so many and the fishing methods so efficient that the potential breeders are ruthlessly exterminated. In the Godavari alone, hilsa fishery about 2 decades ago yielded an annual fishery revenue worth US$2 million, and in the Krishna and the Cauvery it contributed substantially to the bulk of the riverine crop. There are numerous indications that there is already a definite decline in the catch. Floods of the usual violence and intensity no longer reach the sea to attract the breeding hilsa, and sand bars across the river mouths have adversely affected its migration.

In spite of the barriers, during the monsoon period, a few fish congregations below the dam in the Godavari manage to pass over the dams into the reservoir for spawning when the river is in spate and overflows about 3 meters over the dam for 1-15 days. After spawning in the upper reaches, the hilsa returns to the sea. The fertilized eggs drift down in the river below the dam. In the tidal area the hatchlings thrive and grow. Thousands of hilsa fry have been seen in the deltaic area of the Godavari from November through February; they are also carried by irrigation canals to freshwater tanks where they grow to adult size. The discovery of the freshwater and brackish nursery areas of the fish is now helpful in culturing specimens in the confined waters of the deltaic area.

Still a thorough knowledge of the bionomics, breeding habits, development, and growth of hilsa (such as that of the Pacific and Atlantic salmon) is a necessary requisite for the proper conservation, development, and exploitation of this fishery. Future lines of investigation in this regard should include finding out (1) the degree of obstruction caused by the submersible and surplus flow dams, (2) the biometric data of the hilsa

TABLE 5. Color Changes in Water Discharging in the River below Mettur Dam

Date	Surface Water	Tailrace Water
June 25, 1947	Green	Black
Nov. 14, 1947	Green	Brown
Feb. 20, 1948	Green	Green
June 17, 1948	Green	Green
June 18, 1948	Green	Brownish

catches above and below them, (3) whether or not the hilsa really breeds now in the lower reaches of the rivers, (4) the effect of conservation measures below the dams, (5) whether there are different races of hilsa, and (6) whether the same hilsa ascends a particular river year after year as the salmon does.

The second category of fish, those descending the rivers into the sea, includes the freshwater eel *Anquilla bengalensis* (Ham.), which migrates from freshwater to the sea for spawning. This eel is poorly represented in our rivers.

The third category of fish is those moving up and down the upper reaches of the rivers for breeding and feeding. They are the carnatic carp, *Barbus carnaticus* Jordon; the brown *Hexagonolepis Meelell*; the mahseer, *Barbus tor* (Ham.); and the goonch, *Bagarius yarrallii* (Hamilton). The first three species breed in the upper reaches of the Godavari and the Cauvery. The last breeds in the Tungabhadra River, a tributary of the Krishna River.

Finally, there are a good number of fish showing local migrations.

Adverse effects. Briefly, the adverse effects of the dams and man-made lakes seem to be (1) the insurmountability of the dam at all seasons of the year, (2) the lentic conditions of the reservoir, (3) the moderation of the floods below the dam, (4) the fluctuation of water levels due to the increased diversion of water to agriculture, hydroelectric power, and evaporation, (5) the accumulation of silt in spite of the yearly flushing, and (6) the absence of deep pools in the riverbeds lower down for harboring fish of all kinds and the filling of these pools with sand and silts [*Raj*, 1942].

Protective measures. Some measures have been taken to safeguard the interests of fisheries [*Raj*, 1942]. They are (1) total prohibition of fishing in the river below the dam for 1.6 km, (2) cultivation of suitable varieties of fish such as the Bengal carps in fish farms attached to the man-made lakes for annual stocking, (3) artificial fish breeding by means of pituitary extract, and (4) proper exploitation of reservoirs.

Biological Productivity

Organic production has been studied in three cases and the results are given in Table 6. *Vaas and Schuurmann* [1949] obtained a yield of 15 kg/ha in Rawa Pening, and *Tarzwell* [1944] obtained 28 kg/ha in Tennessee Valley Authority impoundments. According to *Riggs* [1958], 34 kg/ha is normal. In our case the tertiary production in south Indian reservoirs compares very favorably with that in other places.

Resettlement, Marginal Agriculture, and Paddy-cum-Fish Culture

In almost all cases of dam construction and formation of reservoirs, the sites of the dams were in uninhabited forest areas or mountain terrains, so there was no need for resettlement of people. But villages have subsequently grown below the reservoir embankments, and marginal agriculture has developed apart from the increase in acreage of irrigated lands from the reservoirs.

Paddy-cum-fish culture is a normal practice in rice fields under the canal cultivation in the Godavari, the Krishna, and the Cauvery. The fields in the deltaic areas receive a good number of hatchlings along with the water supply from the river and canal systems emanating from the man-made lakes. A period of 4–6 months is sufficient to allow a fairly good growth of fish suitable for the table. About 91–136 kg of fish per acre of paddy field are obtained in such a short period.

In certain other districts this culture is practiced with more encouraging results. In a properly bunded field, three pits, each 3 × 1.5 ×

TABLE 6. Organic Production

Man-Made Lake or Reservoir	Years of Examination	Gross Production, mg C/m^2/day	Photosynthetic Efficiency, %	Fish Production, kg/ha
Godavari	1967*	595 to 1232	0.10 to 0.58	40
Stanley	1963 to 1965	404 to 2246	0.21 to 0.98	23.5
Amaravati	1962 to 1964	484 to 7189	0.28 to 5.0	...

*Six months only.

0.9 meters, are dug at three corners and are interconnected by small channels along the three sides to serve as runways for the fish. The outlet is protected by bars. When water is drained to adjust the water level for the paddy crop, the fish automatically go to one of the runways and pits. Even when the paddy crop is mature and water is drained off for harvesting for 10 days, there is sufficient water for all the fish to remain in the pits. As a result, all the mature fish (450–560 kg/ha) are recovered along with a good crop from the paddy.

Weeds

There is no trouble like that reported in Lake Kariba in Africa from floating weeds in any of the reservoirs. This is a noteworthy feature [*Sreenivasan*, 1964].

PUBLIC HEALTH

Unlike those in western countries, none of the man-made lakes in India receives any sewage or industrial wastes. Still, a kind of eutrophication takes place, as is exemplified by the Red Hills Reservoir in Madras.

Eutrophication. The Red Hills Reservoir is filled with river water and rainwater during the northeast monsoon rains. The maximum level is reached in January every year, and thereafter the water level begins to decline, owing to evaporation and withdrawals for the Madras city water supply and irrigation of a few hundred acres of paddy fields. The lowest level is reached in August or September every year. The man-made lake derives its content of organic matter from washings from its own catchment area after each rainfall, from the feeder channel, from the Poondi Reservoir, from the larger aquatic vegetation in the reservoir, and from the plankton.

The organic matter content has been further analyzed and consists on an average of about 60% soluble, 28% colloidal, and 12% particulate suspended matter. From 1922 to date, estimations of the organic matter have been made indirectly by the oxygen absorption test (or 4-hour acid $KMnO_4$ values) and the albuminoid nitrogen test. The seasonal average variations in values for the last 30 years (1922–1951) compared with the corresponding average water level in the reservoir are shown in Figure 3. Note that there is an inverse correlation between the acid $KMnO_4$ values and albuminoid nitrogen on the one hand and the water level on the other. In other words, with the decrease in water level, there is a corresponding increase in organic matter, which is a kind of eutrophication commonly noted in the reservoirs in India. The general averages and the standard deviations for the above factors are shown in Table 7 [*Ganapati*, 1960].

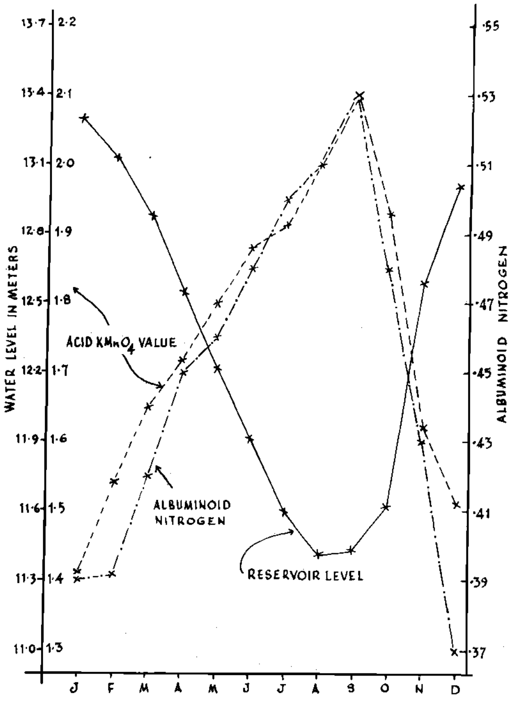


Fig. 3. Relation between the water level and organic matter in the Red Hills Reservoir, Madras.

The regression formulas for statistically calculating the organic matter content in the reservoir for a given water level, air temperature, and rainfall for the Red Hills Reservoir are given by the following equations:

$$X_4 = 0.00098 X_1 - 0.00007 X_2 - 0.00917 X_3 + 0.46390$$

$$X_5 = 0.00009 X_1 - 0.00015 X_2 - 0.00277 X_3 + 0.12961$$

The calculated and estimated values for 4-hour acid $KMNO_4$ values and the albuminoid nitrogen are found to be nearly the same. So it is possible to calculate these values theoretically from a given water level in any reservoir in India.

Pseudopollution and water quality. The two well-known methods of water purification have been tried with the water from the Red Hills

TABLE 7. Correlation between Temperature, Water Level, Rainfall, and Organic Matter in the Water of the Red Hills Reservoir

	Variable	Average	Standard Deviation
Temperature of the air, °F	X_1	84.63	6.22
Rainfall, cm	X_2	9.5	5.43
Reservoir level, meters	X_3	12.3	3.82
Oxygen absorbed	X_4	1.76	0.49
Albuminoid N	X_5	0.45	0.14

Reservoir in Madras with disappointing results. The attempt to purify by the time-honored process of slow sand filtration of the raw water from the Red Hills Reservoir, where the floodwaters of the Kortalayar River receive sunning and storage for 9 months of the year, has the undesirable result of presenting biochemical conditions in the filtered water exactly like those found in the hypolimnion of a highly eutrophied and stratified lake. Anaerobic conditions are created inside the 0.9-meter depth of the fine sand layer of slow sand filters, and the sulfate-reducing *Spirillum desulfuricans* begins to be active. This condition reduces the sulfates in raw water to sulfureted hydrogen; concomitantly, sulfur bacteria are produced (sewage fungus) in the filtered water. For this reason, at Adoni, Agra, Baroda, Kakinada, Salem, and Vizagapatam, the method of slow sand filtration has been found to be quite unsuited for purification of similar impounded surface waters [*Ganapati*, 1961].

The other method of purification (i.e., rapid sand filtration preceded by coagulation and sedimentation), which was adopted since 1957 for Madras, has also been quite unsatisfactory. A very large and uneconomical dose of about 100 ppm of alum is required for clarification of the reservoir water, and during the afternoons there is a tendency for the floc to rise up in the latest model of Paterson clarifiers and to pass on to the rapid filters. Thus the filter runs are very short. This phenomenon is ascribed to a temperature difference in the clarifiers [*Shetty*, 1960] and in the reservoir. But such a phenomenon is not noticed in the waterworks of north India, where rapid sand filtration is being adopted. So, floc rising has to be ascribed to the peculiar meteorologic conditions in this part of south India, where the values of radiation in the afternoon are predominantly higher than those in the morning. This condition is quite the reverse of conditions prevailing in north India.

MANAGEMENT AND USE

Almost all the man-made lakes are being used for irrigation, fisheries, and hydroelectric power. The impounded water in the Godavari is used for boat traffic and for carrying cargo of bamboo and cut wood from the forests in the upper reaches.

Sometimes a conflict arises between irrigation and fishery interests. The following case illustrates the point. Because of the failure of the northeast monsoon rains in Madras, the level of water in the Red Hills Reservoir became so low that the Irrigation Department of Madras had to deplete the waters of the Poondi Reservoir to replenish the Red Hills Reservoir to meet the city water supply and irrigation demands. The way in which this depletion was accomplished was mainly responsible for large-scale fish mortality in the Poondi Reservoir. If the water had been let out gradually, the entire fishery in the reservoir could have been exploited without any fish mortality, and there would not have been loss of valuable fish food.

Now that multipurpose reservoirs are being constructed in various parts of India, it is suggested that the several interests such as irrigation, electricity, navigation, and fisheries cooperate with one another and frame coordinated policies [*Chacko and Ganapati*, 1949].

REFERENCES

Chacko, P. I., The migratory fishes of the inland-waters of the Madras state, *Curr. Sci.*, *9*, 289–290, 1947.

Chacko, P. I., and S. V. Ganapati, A case of large scale mortality of fishes, *Sci. Cult.*, *15*, 238–240, 1949.

Chacko, P. I., and S. V. Ganapati, On the bionomics of *Hilsa ilisha* (Hamilton) in the Godavari River, *J. Madras Univ.*, *28*, 16–22, 1956.

Chacko, A. M. O., and S. Venkateshwaran, Measurements of the total radiation from sun and sky in India during IGY, *Indian J. Meteorol. Geophys.*, *13*, 337–366, 1962.

Ganapati, S. V., Hydrobiological investigations of the Stanley Reservoir and of the river Cauvery at Mettur Dam, *Mettur Chem. J.*, *6*, 1–21, 1955.

Ganapati, S. V., Hydrobiological investigations of the Hope Reservoir and of the Thambaraparani River at Papanasam, Tirunelveli district, Madras state, *Indian Geogr. J.*, *31*, 1–20, 1956.

Ganapati, S. V., Annual variations in the organic matter content of the water in the Red Hills Reservoir, Madras, *Bull. Cent. Pub. Health Eng. Res. Inst.*, *2*, 129–134, 1960.

Ganapati, S. V., Three centuries of water works practice in Madras, *Bull. Cent. Pub. Health Eng. Res. Inst.*, *3*, 52–74, 1961.

Neel, J. K., Impact of reservoirs, in *Limnology in North*

America, edited by D. G. Frey, chap. 21, pp. 573–593, University of Wisconsin Press, Madison, 1966.

Raj, B. S., Dams and fisheries: Mettur and its lessons for India, *Proc. Indian Acad. Sci., Sect. B., 14*, 341–358, 1942.

Riggs, C. D., Unexploited potentials of our fresh water commerical fishes, *Trans. Amer. Fish. Soc., 87*, 356–362, 1958.

Ruttner, F., Hydrographische und hydrochemische Beobachtungen auf Java, Sumatra und Bali, *Arch. Hydrobiol., 8*, 197–457, 1931.

Shetty, M. J., Notes on Madras water supply, *Bull. Cent. Pub. Health Eng. Res. Inst., 2*, 60–61, 1960.

Sreenivasan, A., A hydrobiological study of a tropical impoundment, Bhavanisagar Reservoir, Madras State, India, for years 1956–61, *Hydrobiologia, 24*, 514–539, 1964.

Sreenivasan, A., Limnology of tropical impoundments, 3, Limnology and productivity of Amaravathy Reservoir (Madras state), India, *Hydrobiologia, 26*, 501–516, 1965.

Sreenivasan, A., Limnology of tropical impoundments, Hydrobiological features and fish production in Stanley Reservoir, Mettur Dam, *Int. Rev. Gesamten Hydrobiol., 51*, 295–306, 1966.

Sreenivasan, A., R. R. Soundarrajan, and F. A. Kumari, Limnological studies of tropical impoundments, 2, Hydrobiological features and plankton of Bhavanisagar Reservoir (Madras state) for 1961–62, *Proc. Indian Acad. Sci., Sect. B., 59*, 53–71, 1964.

Tarzwell, C. M., The possibilities of a commercial fishery in TVA impoundments and its value in solving the sport and rough fish problems, *Trans. Amer. Fish. Soc., 73*, 137–157, 1944.

Vaas, K. F., and J. J. Schuurman, On the ecology and fisheries of some Javanese fresh waters, *Comm. 97*, pp. 1–60, Gen. Agr. Res. Sta., Buitenzorg, Java, 1949.

Man-Made Lakes in Ivory Coast

P. LESSENT

Direction de la Peche et de la Pisciculture, Centre Technique Forestier Tropical
Nogent-sur-Marne, France

At present the Ivory Coast Republic has two large man-made lakes for hydroelectric power purposes. The smaller is Ayamé Lake on the Bia River, filled in August 1959; the larger is Kossou Lake on the Bandama River, and it is being filled this year (1971).

AYAMÉ LAKE

Characteristics of the lake. Ayamé Lake is located at 5°30′N, 3°W and at an elevation of 90 meters above sea level. The mean annual air temperature is 26°C with a minimum of 24°C in August and a maximum of 28°C in February. The mean annual rainfall is 2000 mm. The seasons include a long dry season from December to February, a long wet season from March to July, a short dry season in August, and a short wet season from September to November. The total length of the dam is 610 meters, and the lake area has a minimum of 8400 ha, a maximum of 18,600 ha, and a mean of 14,000 ha.

The temperature of the deeper water in the lake is a steady 25°C, and the surface water varies from 24° to 32.5°C. The *p*H in depth is 6.0 and at the surface is 6.6. Dissolved oxygen is present above −8 meters, and there is a high H_2S content, which increases with depth.

Fishing. The main species of the original fish population of the Bia River are classified according to their feeding habits in Table 1. After various studies were carried out at the Bouake fish culture research station from 1957 to 1960, 400 kg of *Tilapia nilotica* fingerlings (average weight of 5–10 grams) were stocked in 1962. In October 1963 the first catch of *Tilapia nilotica* appeared downstream from the spillway. The average weight was 600 grams. Experimental fishing yielded fingerlings of the same species the same year. The introduction was then considered successful, and no more *Tilapia* were stocked.

Heterotis niloticus stocking was not very important since it is difficult to get large numbers of fingerlings of this species. Some hundreds of fingerlings were stocked in 1964 and 1965. Some months later, specimens of 1 kg were caught, and the weight increment was estimated to be 500 g/yr. Since *Heterotis* breeding takes place only at the age of 20–30 months, the growth of the population is comparatively slow. But, as slow as the breeding is, this introduction is rewarding since large *Heterotis* are highly appreciated by the consumer.

In 1964, the number of full-time fishermen was estimated at 120 (all non-Ivorians), to which one must add 200 Ivorian part-time fishermen. A survey at the end of 1970 recorded 600 fishermen, of which 87% were non-Ivorians (most of them from Mali).

Four types of gear are used, and the distribution of the catch according to these types is as follows: gill nets, 96.8%; sleeping long lines, 0.2%; traps, 1.2%; and cast nets, 1.8%. The only craft used are one-man dugout canoes built on the spot. There is no special craft for transporting the fish.

Statistical surveys of fish production have been made every year since 1966 (Table 2), and the average productivity is between 50 and 75 kg/ha/yr. The division of the catch by species is shown in Table 3.

Processing and trade. The fish catch reaches the landing points either fresh or smoked. It is sold fresh if it is caught and sold on the same day; it is sold smoked if it is sold several days after fishing. Unsold fresh fish are smoked on the landing points.

The fish is purchased either by local retailers, including the fishermen's wives, or by wholesalers who transport it to Abidjan in iceboxes when it is fresh or in baskets when it is smoked (the dis-

TABLE 1. Bia River Fish

Feeding Habit	Species
Phytophage	
Macrophytophage	*Tilapia zillii*
Macro- and microphytophage	*Pelmatochromis guntheri*
Sarcophage	
Ichthyophage	*Hepsetus odoe* *Hemichromis fasciatus*
Ichthyo- and entomophage	*Eutropius mentalis* *Alestes rutilus*
Ichthyophage and omnivore	*Malapterurus electricus*
Benthic entomophage	*Mormyrus rume* *Gnathonemus bruyerei*
Surface water entomophage and granivore	*Alestes nurse* *Alestes longipinnis*
Detritivore	
Exclusive	*Mormirops deliciosus*
Entomophage	*Ctenopoma kyngsleyae*
Omnivore	*Chrysichthys walkeri*
Limivorous icthyophage	*Heterobranchus isopterus*
Omnivore	*Synodontis schall*
Browsers of biological cover	*Labeo chariensis* *Varicorhinus wurtzi*

tance from Ayamé to Abidjan is 125 km).

Conclusion. For some years, fishing in Ayamé Lake has given a production of 800–1000 metric tons of fresh fish sold in the southeastern part of Ivory Coast. These results may be considered a consequence of a 4-year study at the Bouake fish culture research station and of the subsequent stocking of the lake with *Tilapia nilotica.* These results indicate the benefit of a rational management of man-made lakes.

KOSSOU LAKE

Characteristics of the lake. Kossou Lake is located at a latitude of 7°–8°N and a longitude of 5°25′W–5°45′W and at an elevation of 203 meters above sea level. The mean annual air temperature is 25°C, with an absolute minimum of 12°C in January and an absolute maximum of 35°C in March.

Total area of the Bandama River basin upstream from the dam is 32,400 km^2. Mean annual flow of the river is 50–320 m^3/sec, and the mean annual water discharge is 4.57 km^3. The dam (made of compacted earth) was closed in February 1971. The impoundment has a total area of about 160,000 ha and a total volume of 20.5 km^3. The lake has a mean estimated depth of 54 meters and a shoreline of 3500 km long.

Fauna. The survey of the Bandama River fauna is being completed. Since this fauna is like that in Ayamé Lake, it appears that microphagous species are lacking. The government of Ivory Coast has therefore requested the Bouake fish culture research station to begin the immediate stocking of the lake while it is filling with the two species already proved successful in Ayamé Lake, namely, *Tilapia nilotica* and *Heterotis niloticus.*

For *Tilapia nilotica* the plan foresees stocking 100,000 5-gram fingerlings per year for 2 years. For *Heterotis,* simultaneous introduction of adult and fingerlings is foreseen. Since Bouake is not very far from Kossou Lake, the cost of stocking will be quite low. The first operation is scheduled to take place in June 1971.

Deforestation. As most of the Kossou inundated area is under forest, taking full opportunity of the Ayamé experience, a study was made to determine the areas to be cleared. The aim of this study is twofold.

1. One objective is to foster fish production. It is highly desirable to keep the major part of the trees or shrubs standing. These trees are both a shelter for young fish and a source of periphyton production.

2. The second objective is to make fishing activities as easy as possible by determining ‘fishing passages.’ The fishing passages are to be located on the lake periphery in zones where the depth will not exceed 20 meters. The width of the passages will be 100 meters.

The plan of deforestation considered the slope of the ground, the kind of vegetation, the road network, the number of inhabitants in the neighborhood, and the navigational facilities (i.e., attention was given to the dominating winds).

Fish production and trade. The future produc-

TABLE 2. Fish Production in Ayamé Lake

Landing Place	Production of Fresh Fish, metric tons								
	1964	1965	1966	1967	1968	1969	1970	1971	1972
Ayamé	...	...	444	643	561	589	504	345	266
Aleykro	...	...	111	265	310	500	...	275	406
Total	160	...	555	908	871	1089	...	620	672

TABLE 3. Fish Catch by Species

	Fish Catch, %							
Species	1964	1966	1967	1968	1969	1970	1971	1972
Tilapia nilotica	0.2	60.0	61.4	59.7	52.3	47.2	66.8	42.9
Chrysichthys walkerii	51.9	26.0	26.3	23.2	18.8	26.2	2.9	19.1
Tilapia zillii	12.4	1.5	1.2	3.7	8.7	10.7	7.0	7.7
Heterotis niloticus	...	...	4.4	3.5	6.1	3.5	14.2	21.9
Heterobranchus	14.2	5.5	1.8	2.3	1.0	0.6	0.9	0.9
Alestes spp.	4.3	...	2.0	5.9	11.0	11.0	6	6.7
Miscellaneous	17.0	7.0	2.9	1.7	2.1	0.8	2.1	0.7

tion of Kossou Lake was estimated to be between 11,000 and 16,000 metric tons per year, the value of which could be between 548 and 844 million CFA francs, or US$2-3 million. These figures probably will be reached in 1980. Studies were made on fishing investments (roads, landings, and so on), fishing equipment (gear and craft), and fish processing and transportation facilities, including ice plants.

Acknowledgment. This paper was previously published by the Centre Technique Forestier Tropical in *Notes et Documents sur la Pisciculture* in November 1971.

Volta Lake in Relation to the Human Population and Some Issues in Economics and Management

E. A. K. KALITSI
Volta River Authority, Accra, Ghana

For several decades the major drawback of the economy of Ghana has been its dependence on a single crop, cocoa. The underlying objective of all the country's development programs has been to reduce this overdependence and to diversify the economy by changing the commodity structure of agriculture and industrialization. The Volta River project is one of the most important instruments of this policy. Its purpose has been to produce the power to support the industrialization program and also to start the specific industry of aluminum. The pursuit of the objective required the creation of an artificial lake, which was bound to alter the existing physical and biological as well as the socioeconomic environment of the people.

The lake has created a number of development possibilities in fisheries, transport, agriculture, wildlife, and tourism. These have in fact become the other major development objectives of the project. The lake has also created a number of problems. These relate to the social engineering associated with the lake, particularly the relocation of people and health problems.

This paper is devoted to a discussion of these objectives and problems. Although the primary aim of the Volta project is power production and its impact is economy wide, the concern here is with the interaction of the lake and the human population, and the focus therefore will be on the other objectives and not on power. Thus this paper will deal with the socioeconomic aspects of Volta Lake; the paper by *Obeng* [this volume] will deal with the physical and biological aspects and the research program.

BASIN AND PATTERN OF SETTLEMENTS

Volta Lake occupies the center of the riverine system of the country and drains most of its rivers. It covers 8482 km^2 (3275 mi^2), or 3.6% of the surface area of the country. It is 402 km (250 miles) long, has a boundary of some 4828 km (3000 miles), and contains 148,080 million m^3 (120 million acre-feet) of water [*Taylor*, this volume, Figure 1].

Archaeological studies conducted by the University of Ghana prior to the formation of the lake show the following facts recorded about settlements in the area [*Davies,* 1965, 1971; D. Mathewson et al., unpublished data, 1967].

1. Men have lived in the basin for at least half a million years.
2. About 3000 years ago agricultural practices were introduced into the area, as is evidenced by stone artifacts used for economic activity that were found in archaeological sites.
3. Later, newcomers introduced simple iron tools.
4. Further invaders and traders, particularly from the northwest, introduced substantial commerce within the river basin and raised the population and settlements generally.
5. From around the seventeenth century to early nineteenth century, there was a relative depopulation partly as a result of riverine diseases that had become endemic (i.e., sleeping sickness and river blindness) and partly as a result of slave-raiding activities in the region. (The depopulation was intensified in the late nineteenth century by the development of the cocoa and mining industries in the forest belt.)

In other words, economic activity in the basin in the past had known some periods of change but had settled to a static level.

Before the area was flooded, there were 80,000 people, or 1% of the population, living (mainly in mud houses roofed with thatch) in 700 villages in the area. The people were mostly subsistence farmers. Only 2% of them were riverine fishermen. Because of the presence of tsetse, there were very few cattle. Except for a small proportion of the people in the south and in the east who were cocoa farmers, the average income of the people in the flooded area was below the average for the country as a whole.

LAKE AND DEVELOPMENT

The lake has created a new economic setting, and it is useful for us to look at it as an instrument for rural development. We may start with the people immediately affected by the lake, i.e., those who had to resettle.

Resettlement

The people to be flooded out of their original settlements were given two options: to accept compensation for lost property and make their own arrangements for resettlement or to be resettled by the Volta River Authority. Fifteen percent of the people opted for compensation and their own resettlement; i.e., most of the people elected to participate in the authority's resettlement scheme. Recall that the majority of the people were farmers. Therefore the new pattern of settlements was designed to suit a farming population initially, provision for new industries being introduced as and when the opportunity arose.

The people were resettled in larger population units. Most units were between 2000 and 5000 in population, and there were 52 settlements instead of the original 700. It seems appropriate to examine the scheme under the following heads: people, selection and preparation of sites, economic activities, and timing.

People. The people to be resettled came mainly from eight ethnic groups: Kwahu, Akwamu, Krobo, Ewe, Buem-Akan, Pai, Krachi, and Gonja. The main source of conflict here was that in some cases these groups were moving from their traditional homelands to new areas. This move was bound to raise problems of political jurisdiction from the hierarchies of traditions, chieftaincy, and so on. Even in cases where the people were to move within their own traditional areas, because they now had to be grouped together, conflicts would arise regarding precedence of chiefs. The issue was not completely resolved. It was hoped that over time new relationships and new hierarchies of leadership would emerge.

Still, a great deal of care was taken about grouping villages as units. Villages from the same area were put together unless they requested otherwise. An attempt was made to settle villages in wards in such a way that adjacent wards would be mutually friendly and that the communities would remain under their own traditional leaders in order to reduce sources of social tension in the early days of the relocation.

Selection and preparation of sites. A great deal of attention was also given to the selection of the right place for the settlers. The most important criteria considered were soil conditions, health conditions, access to other towns, water supply, and the wishes of the people.

Within the time and resources available, the soils at the sites were surveyed and classified to indicate their physical qualities, slope, and erodibility and the types of crops that might do well.

From the point of view of health the new settlements were expected to be, and are in fact, better than the previous villages from which the people moved. Most of the settlements are relatively free from the simulium fly and the tsetse, the vectors of river blindness and sleeping sickness, respectively. Furthermore, the settlements have easier access to health centers in the regions than the previous villages had, and the larger groupings into which they have been formed facilitate the establishment of health posts. Environmental problems, however, have not been entirely eliminated because certain settlements (such as Asukawkaw) are known to be infested with the simulium fly.

The sites were provided with nuclear, or core, houses in settlement townships that were complete with schools, water supply, other public facilities, and access roads. Core houses provided for the settlers had a concrete floor and an aluminium roofing for two rooms and two porches, but only one room was completed before allocation. It was planned that the additional room and two porches would be completed by the settlers themselves on arrival at the new site. The cement for making the landcrete blocks was to be supplied to the settlers together with window and door frames, hinges, locks, and so on. The settlers were left to supply only their labor. The idea was to provide improved housing conditions in the new settlement.

An important matter to consider was the land for farming purposes. Initially, the choices considered were whether to acquire the land outright and grant it to the settlers or to lease the land for the settlers and let them pay rent for the use of the land to the landowners. It was not until 1968 that this question was finally resolved in favor of outright acquisition. The idea now is that the acquired land will be leased to the settlers for 33 years. The lease will be heritable and renewable, but the use of the land will be subject to a certain amount of regulation. Fragmentation is not allowed.

A second issue was to clear the farming land for the settlers before their arrival. Actually, only 3238 ha (8000 acres) of farming land were cleared before the people moved.

Economic activities. The fact that acquisition arrangements had not been worked out before the move posed two immediate problems for the settlers: they had to begin long and tedious negotiations for farming land, and they had to clear the land themselves. Furthermore, they had very little working capital, farming equipment, and so on, and none was provided for them. Predictably, farming was off to a poor start under these conditions.

There was another fundamental problem with regard to farming, i.e., inadequate knowledge about agronomic conditions of production: how to maintain the fertility of the soil without extended bush fallowing, what rotations would be appropriate, and so on. In spite of this background it was proposed that intensive mechanized agriculture for the settlements be introduced partly to solve the problem of land shortages and partly to transfer modern technology into peasant agriculture. Such a scheme, however, required careful prior study, which was lacking.

All this reality contrasts sharply with what had been planned for the settlers. It had been envisaged that each settler would be given enough prepared land to sustain a satisfactory level of living, i.e., comparable to that of the average city dweller.

Agriculture was to be specialized as follows: arable, tree crops, intensive livestock, and pastoral. Each arable farm was to have a minimum of 4.9 ha (12 acres) under mechanized farming, which was to be expanded to 12.1 ha (30 acres) eventually; for tree crops an area of between 2.0 and 6.0 ha (5 and 15 acres) was to be provided; for intensive livestock farming, particularly poultry and pigs, a minimum of 1.2 ha (3 acres) was to be provided; and for pastoral farming a minimum of 12.1 ha (30 acres) was to be provided. The assumption was that this scheme would enable the farmer to generate a minimum net income of N₵700 per year (N₵1 = 100 NP (new pesewas) = US$0.98). Naturally this was an ambitious program that was to encounter practical difficulties in implementation. For the entire program to succeed, systematic planning, marketing organization, and other things were required. But the manpower resources, the skills, and the experience needed were not available in adequate quantities. The result was that initial progress was very poor.

As *Afriyie* [this volume] has pointed out, mechanization required a complete change in the values of the settling peasant farmers and in their attitudes toward new farming techniques and practices. As a completely new concept of farming, mechanization could have had a chance of success only if, first, its introduction to the settlers had been preceded by a vigorous extension program with experiments and demonstrations directly involving the farmers. Second, there should have been a sufficient professional and technical staff trained in the operation and maintenance of mechanical equipment and in the management of mechanical farms as a business. Third, the timing and financial problems that could impede the supply of equipment and materials for the mechanization program should have been solved. None of these preconditions had been satisfied before the people arrived.

The effect was an emigration of settlers in search of new farming opportunities elsewhere. In 1968 it was found that 60% of the original settlers had moved out [*Taylor*, this volume]. The trend has only recently been reversed by a positive and more effective approach to land acquisition and distribution. Under the new approach, 177,259 ha (438,000 acres) are being acquired around the 52 settlements. One-quarter of this land is being distributed in 0.8- to 1.6-ha (2- to 4-acre) subsistence plots to adult male and entitled female settlers and host farmers. The remaining three-quarters are to be developed as commercial farms after appropriate trials to establish optimum farming conditions. Good progress has been made in the subsistence plot distribution, which is expected to be completed in 1971. The effect of this new approach is that practically all the emigrated settlers do rush back to receive and clear their land as soon as they know that the plots are ready for distribution (C. A. Dadey and G. W. Amarteifio, personal communication, 1971). Thus the emigration of 60% is likely to be only temporary. In that case the incursion into the settlements of nonsettling people (amounting to some 28% of the original settling population) and the gradual concentration of other rural development programs in the settlements (as observed by *Taylor* [this volume]) might gradually change the settlements into the centers of economic activity that they were expected to be.

Timing. One can hardly discuss the problem of resettlement, especially in the context of the creation of an artificial lake, without discussing the problem of timing and phasing. Effective work on resettlement started in May 1962 against a lake-fill start of mid-1962. The construction of the dam was started in September 1961 and completed in February 1965. The diversion tunnel stop logs were closed in May 1964, and the Volta Lake started to form. By the end of 1964 the lake had risen 47 meters (153 feet) to reach an elevation of 60 meters (198 feet); by this time some 19% of the 809,400 ha (2 million acres) to be flooded had been covered. But since most of the settlements lay alongside the edges of the river, 484 villages (constituting 66% of the total number of villages and containing 10,174 households with 55,000 people, or 70% of the total of 80,000 people) had been flooded out and evacuated. The balance of 25,000 people, who were situated farther away, was evacuated more gradually at an annual rate varying between 6000 and 3000 people a year over the following 4 years as the lake gradually reached its peak elevation of 83.1 meters (272.7 feet) in 1968.

The problem of the physical delineation of the floodland from which people were to be removed and the properties to be compensated for, the referencing and evaluation of individual properties, the identification and detailed survey of the population, and the actual selection of the alternative locations for the people were activities that had been envisaged as being completed before the start of dam construction. But as things turned out, it was not until the middle of 1962 that these activities were seriously started. Thus a bare 2-year period was left to survey, plan, and provide facilities for the people to be moved. In sum, not enough time had been allowed for the planning and implementation of resettlement.

Nevertheless, the relocation of the affected people was based on certain concepts of rural development. First, fewer townships of larger population units were established to exploit more economically the social and physical infrastructure. Second, an attempt was made to provide the settlers with improved conditions of living, such as better housing, better health centers, and educational facilities. Third, a more systematic attempt to improve agriculture was undertaken by the provision of a more secure access to land for rational use, by the transfer of new technology under public assistance, and by the commercialization of farming.

There are, of course, other instruments for rural development created in the basin. These are the opportunities for developing new industries made possible by the lake.

Industries

The legislation that established the Volta project defined its functions or objectives as electricity production, flood control, development of the lake area for the health and well-being of the lakeside residents, and provision as far as practicable of facilities and assistance for development of the lake as a fishery and for transportation [*Government of Ghana*, 1961]. These objectives were not defined in terms of income redistribution or regional economic growth, although surely the creation of the lake was bound to have consequences in these terms.

In pursuing these objectives the authority was required to safeguard the health and safety of the lakeside dwellers and to aim at making a profit. For the authority to pursue these objectives, it had to have control over the use of the water in the reservoir. To this end it was vested with powers to control such uses and was thus placed in a position to draw up a unified plan for the multiple uses and to ensure a more efficient technical and economic management of the reservoir water.

It is interesting to note, however, that, although the authority has control of the planning of the use of the water in relation to fisheries development and transportation, such planning according to the Volta River Development Act is optional. In the case of irrigation development, there is in fact no specific mention in the act, although a broad interpretation of 'the development of the lakeside area' would and should embrace this activity and other relevant activities. Consequently, the systematic exploitation of the new industrial conditions created by the lake has somewhat lagged. A brief examination of these industries follows.

Agriculture. Apart from the settlement farming program involving 177,259 ha (438,000 acres), agricultural development directly connected with the lake has two aspects: (1) the introduction of irrigation in the Accra plains in the south and in the northern plains, and (2) drawdown agriculture.

Irrigation agriculture: The total area of the Accra plains that is irrigable and suitable for mechanized agriculture has been estimated as 178,068 ha (440,000 acres) out of 335,092 ha (828,000 acres) of land. The types and properties of the soils have been determined, and the economic potential of the area has been found to be very high. Since the population of the Accra-Tema commercial region is growing very fast, the demand for food is rising very rapidly. The country spends N₵55 million in foreign exchange on food imports, and increased production on the Accra and northern savannas will make a significant contribution toward closing the gap.

The crops selected as being suitable for the soils and climate as well as for meeting the demand are rice, sugar cane, cotton, grain, vegetables, tree crops, pineapples, and grass and legume mixtures to support the cattle industry. The plains alone are capable of supplying almost all the country's present needs in these commodities. The maximum investment required was estimated at £G28 million in 10 years (US$78.4 million at 1965 prices). The economic feasibility of irrigating the Accra plains, as measured by benefit-cost ratios, varies during the 31- to 53-year development period proposed by a study by Kaiser Engineers (unpublished data). The benefit-cost ratio would reach a value of 1 : 1 by the seventh year to the ninth year of development, would rise to 2 : 1 between the fifteenth and eighteenth years depending on the rate of development, and would maintain this rate or better thereafter. For this small area of Ghana, such proportions are not insignificant.

The northern plains, the other area to be irrigated, has not received the same systematic study, but professional opinion seems to indicate that the potential there is even greater. If so, the failure to introduce irrigated agriculture must represent a considerable reduction in the pace of rural development attainable. This situation exists in part because of the high investment cost of irrigation itself and in part because irrigation technology is entirely new to the country and the organization needed to extend the knowledge is practically nonexistent.

Drawdown agriculture: An important development in agriculture associated with the lake is farming on the land exposed by fluctuations in the lake level. This development has started on the initiative of the local lakeside dwellers, but research work has been concerned mainly with the soils and cropping patterns.

The annual fluctuation in the level of the lake varies between 1.8 and 4.3 meters (6 and 14 feet). It has been estimated that, at 3.0 meters (10 feet), some 80,940 ha (200,000 acres) would be exposed around the 4828 km (3000 miles) of the lake boundary and that an average of about 183 meters (200 yards) could be used for farming. The soils in the drawdown area are mostly sandy and well drained. The eastern and southern banks are steep and expose only a narrow area. Wider stretches occur on the northern banks where population density is low. The northern bank of the Afram and the western bank of the main lake also expose moderately wide areas.

At present, only small portions of the drawdown area, those adjacent to the areas of high density, are cropped, mainly with vegetables such as tomatoes, okra, peppers, garden eggs, and maize. Some problems encountered include drought conditions and insects.

Crop trials are being carried out to determine the cropping system to be encouraged in the area (G. F. Richardson, unpublished data). It is thought that, in the area immediately above the maximum flood level where the water table is high, main crops of cassava and possibly cotton could be planted in the October and November season and garden crops of groundnuts, okra, peppers, and garden eggs could be planted as secondary crops. In the areas exposed up to February, groundnuts and tomatoes could be grown as main crops, and okra, peppers, garden eggs, maize, and sweet potatoes could be grown as secondary crops. For areas exposed from late February to the end of April, maize and sorghum could be grown. Rice can also be grown, and it has been estimated that at current low yields of 896 kg/ha (800 lb/acre) at least 30% of the country's rice imports can be produced.

Fishing. One of the most significant developments on Volta Lake has been its emergence as a major fishery. Using statistical sampling techniques, *Bazigos* [1970, 1971; *Food and Agriculture Organization,* 1971] estimated that in 1969 the lake produced at an annual rate of 61,783 metric tons (60,000 tons). Although this estimate is only a preliminary one derived from limited data, the order of magnitude is still very impressive. When the annual rate of 61,783 metric tons (60,000 tons) of fish from Volta Lake is compared with an estimated 117,251 metric tons of domestic marine fish catch in 1969, the importance of Volta Lake as a fishery emerges very clearly.

The fishing activity is carried out by 12,500 professional fishermen living in over 1000 villages built by themselves on the shores of the lake (P. Westaway, unpublished data, 1970). Including the families, aides, and others the fishing population numbers 60,000, and they own 12,000 canoes. Most of the fishing villages are accessible only by water and have no services provided for them. As is characteristic of villages of migrant people, males exceed females, and there are few people above the age of 50.

The boats used for fishing are mostly home-built wooden canoes without mechanical propulsion, and these limit the range of fishing operations. The fishermen use multifilament gill nets of various mesh sizes, hooks, lines, and traps (F. Denyoh, unpublished data, 1970). Monofilament gill nets have been tried and found to be of greater catching capacity. Wide use of these nets not only will increase catch per fishing effort but also will enable the fishermen to produce more effectively throughout the year and thus to reduce the instability in their incomes. (Details concerning the fishermen and their fishing gear and operations are given by *Butcher* [this volume].)

The characteristic way of processing and preserving the fish is by smoking and salting. Smoking is done in earthen ovens. As there are no icing facilities, the fish is normally smoked or sun dried. There are three major fish-landing and marketing centers (namely, Kpandu, Abotoase, and Yeji) and 12 smaller ones around the 4828-km (3000-mile) boundary. Marketing is done either by women from the fishing village, who take the processed fish to market centers at road heads, or by fish traders from the cities, who travel in transport launches to collect processed fish from the fishermen.

For proper management of the fishery, studies of the fish stocks are being carried out (W. A. Evans and J. Vanderpuye, unpublished data, 1970). Preliminary observations show that the lake is probably being underharvested, and no controls have been applied on expansion of the fishing activity. However, recent tentative estimates [*Bazigos*, 1971] indicate that the catch of 61,783 metric tons for 1969 dropped to 39,903 metric tons in 1970. In 1971 the catch appears to have risen slightly to 45,000 metric tons according to the Volta River Authority's annual report for 1971. This drop from the catch of 1969 poses the question of whether the stocks have reached their peak. To monitor whether optimum levels are being reached, a warning system has been established involving observations of fish composition, mean size, catches in relation to effort, mortality rates, and so on.

The most abundant fish in Volta Lake are the small pelagic fish clupeids that represent about one-quarter of the biomass, but the fish that dominate commercial catches are the big three of the large fish, namely, *Tilapia* spp., *Lates niloticus*, and *Labeo* spp. Apparently, there have been some changes in the fish population of the lake. Those preferring lake conditions seem to be dominating, and those preferring riverine conditions appear to be restricting themselves to the tributary areas. W. A. Evans and J. Vanderpuye (unpublished data, 1970) concluded that only certain elements of the existing fish population are being moderately exploited whereas others are not touched at all. Present fishing takes place in the shallow inshore waters, but sizable fish stocks that are not being used are available in deeper inshore waters as well as in offshore waters. Improvement of gear and fishing techniques would be required to harvest these fish, especially as yield per fishing effort reportedly drops as the water becomes clearer.

Ghana has a high demand for fish that continues to rise. In 1969, the country's per capita fish consumption was 20 kg, a 42% increase over 1968. Since the country imported 18,700 metric tons of fish and fish products valued at N₵5,872,000, or US$5,754,700, in 1969 to supplement marine and freshwater harvests, maintenance and expansion of Volta fishery operations will make an important contribution to the country.

Wildlife and tourism. A survey carried out by G. S. Child and C. K. Manu (unpublished data, 1970) has confirmed that the area between the Sene and the Obosum on the western bank holds or did hold a wide variety of game species. Plans are therefore being made for the government to establish a game reserve there. The proposal is to allow a buildup of large herbivores to help in a gradual buildup of carnivores by protecting the animals from slaughter and by removing hunting villages. The game reserve linked with sport fishing, the beauty of the lake, and the dam itself could offer a package of complementary attractions for the tourist.

Lake transport. Volta Lake lies in the center of Ghana. It stretches 402 km (250 miles) from the southeast in a westerly direction right in the center of the country. It has arms and tributary rivers running to the northeast, the direct north, and the northwest. This position makes the lake accessible to the eastern region and the whole northern region of Ghana excluding only the forested southwestern portion, which also is the mining region. The lake is thus in a position to join the industrial and commercial region of Accra-Tema to the agricultural north and east.

The expected traffic on the lake is at the moment unknown because of uncertainties in the effects of development plans for the country. These plans include rural development, improvement of roads and the rail system, and even improvement in air transport. Moreover, these development programs compete with water transport for funds and traffic.

Meanwhile, local dugout canoes are being used by the local people to transport goods and passengers across the lake. This practice is very unsafe, as Volta Lake is a large water body and develops billows that are sometimes as high as 2.43 meters (8 feet).

In spite of the uncertainties in traffic forecasts, a program has been prepared to develop the lake transport resource on a modest level initially and to expand this resource as the traffic builds up and as the people become accustomed to the use of lake transport. A small port is being constructed at Akosombo 97 km (60 miles) from Tema, another one at Kete Krachi halfway up to the north, and a third at Yapei 56 km (35 miles) from the northern capital of Tamale. A fish-landing port is being established at Kpandu on the eastern side of the lake. Although the lake was not cleared of trees, the waterway along the old river courses is navigable for boats with a draught of up to 2.43 meters (8 feet). Part of the waterway has been buoyed already, and buoys and beacons are now being placed in the northern portions.

A company has been established to purchase and run modern transport vessels on the lake and to develop the traffic potential. Some of the vessels are already being assembled. It is expected that when the traffic level reaches a quarter of a million tons and 100,000 passengers per year around 1975, the cost per ton mile will be 3.0 NP, and the cost per passenger mile will be 0.8 NP; the investment level will be N₵3 million in vessels and handling facilities and N₵6.7 million in landings and sailing lines (Volta Joint Venture, unpublished data, 1969).

PROBLEMS OF THE LAKE

Although the above discussion has focused on new economic opportunities, there are major problems also related to the lake. Of these, public health and the growth of aquatic weeds are the most important.

Public health. Volta Lake has had significant effects on the public health situation. From the work by *Paperna* [1969, 1970] and later by C. R. Jones (unpublished data, 1970) it would appear that bilharzia (urinary schistosomiasis) transmission occurred widely during the 1968–1969 period around the lake but that the transmission rate slowed down in 1970, probably because the fish stocks have approached near-equilibrium with the aquatic weed on which the snail vectors feed. But the prevalence rate is high in places and, on the western banks, approaches 90% among children in particular localities.

The breeding places of the *Simulium damnosum*, the vector of onchocerciasis (river blindness), on the river have been wiped out by the lake. However, the incidence is still heavy downstream of the dam on the Senchi Kpong rapids and in the settlements located on the Asukawkaw, a tributary of the lake. In these places the prevalence rate is about 90% among people over 15 years of age. Local control has been effective at Kpong by a combination of dosing with DDT and flushing the breeding grounds by spilling.

The lake has flooded out the riverine forests, breeding places of *Glossina palpalis*, a species of tsetse fly that is the vector of sleeping sickness. Surveillance continues on the remaining breeding grounds, the fly population, and the incidence of clinical cases.

In general, some improvement has taken place in the health situation of the settlers because the settlements are now large enough for health posts to be established in some of them, and the settlements now have easier access to health facilities outside the lake areas. But the 60,000 fishermen who live mostly in isolated villages around the lake are exposed to riverine diseases, and thus their situation is worsened.

Aquatic weeds. As can be expected of a tropical lake, Volta Lake has developed a large number of aquatic and semiaquatic plants. These weeds, which serve as food source and shelter for fish, cover only a limited portion of the lake. The weed areas are generally outside the transport route. On the other hand, the weeds have provided favorable habitats for a number of disease vectors, notably the *Bulinus* snail, the vector of urinary schistosomiasis (bilharzia), and the *Mansona africana* mosquito, the vector of the yellow fever virus. The problem of aquatic weeds therefore arises from the health point of view. Although the weeds have been identified and labeled, no effective control measures have as yet been found.

MANAGEMENT

As has been indicated earlier, our concern is to operate and manage Volta Lake in such a way as to maximize its benefits and minimize the difficulties. The lake has existing or potential uses for power generation, transportation, irrigation and agriculture, fishing, health control, weed control, and flood control. Although each of these uses places its own peculiar requirements on the water, all the uses together impose a management problem of a much more complex character.

Primarily the lake is managed by the authority for power. Since there is no surplus water in the reservoir for anything other than power, there is an economic problem of managing the reservoir water so that the best benefits could be determined if any other use, such as irrigation, were to arise.

Another management problem created by the lake is in the area of flood control. Hydrologic data on the Volta, and therefore our forecasting capabilities, are limited. It is difficult to anticipate flood flushes accurately and to take preventive measures or send warning signals early enough to prevent flood damages downstream of the dam. Even where reasonable forecasts are made and advance warnings given, the reaction of people downstream must be considered because they may be quite unable to appreciate or grasp the full impact of the problem. For example, in 1967, the people downstream ignored the warnings to move away from the flood area; and the result was that eventually their farms and properties were affected.

There is also a periodic need to release water to flush out the breeding grounds of the *Simulium* fly downstream of the dam. This need may occur when, for power purposes, the lake level must be kept up instead of reduced. The slow drawdown of the water also creates favorable conditions for disease vectors like snails and mosquitoes and also for weeds and agricultural pests to develop. There is therefore the problem of how to vary the water levels in the lake to minimize these problems and enhance the opportunities in the secondary uses without detracting from power uses.

The changes taking place in the types and habits of the fish also pose problems that require solutions. Techniques need to be developed for harvesting the fish in the bottom water, which at present are not in the commercial harvests. Also, the use of nets of certain sizes must be encouraged.

By changing the scenery, the lake has created an environment that can be consciously shaped by means of parks and facilities for preservation of wildlife as well as sport fishing and tourist facilities to encourage tourism, which can serve as an economic resource for the lakeside dwellers.

EVALUATIONS

I have tried in this paper to examine Volta Lake as one of the major instruments for transforming the economy of Ghana. In so doing, I have considered certain specific industries. It would seem appropriate to assess Ghana's record in exploiting the developmental opportunities.

It is customary to evaluate economic resources in terms of water development in relation to the flow of net benefits over time. Another way is in terms of efficiency and equity. In general terms, equity refers to the degree to which the distribution of opportunities within a community approaches some state that the community holds to be ideal. But since the size of the cake will depend on how efficiently the resources are exploited, we shall concentrate on the concept of efficiency.

The economist sees two kinds of efficiency, static and dynamic. What a community can achieve at any time depends on the state of knowledge regarding production possibilities and technologies available to the community. These possibilities define the economic opportunities that are open to the community. Static efficiency refers to the ability of the community to exploit effectively its economic opportunities with the existing input resources and technology. Dynamic efficiency is the ability of the community to add to its stock of technologic knowledge so as to exploit its economic opportunities more effectively over time. Naturally the transformation and growth of the economy critically depend on these efficiencies.

In our case, Volta Lake has created a new set of production possibilities, but the account above has shown that we have not been able to exploit the new opportunities. Consider, for example, resettlement, which, as we have said, can be viewed as a major exercise in rural development. The essence of the program was to provide the people with improved living conditions and the necessary incentives for productive effort. However, our failure to complete the land acquisition arrangements and the necessary land clearing prior to relocation and the lack of extension and other supporting services meant that the people could not even operate at their old production level; we have mentioned the initial emigration that resulted from this failure. Thus development was clearly hampered by the tension of displacement and unrealized expectations.

Another major instance of failure to capture the advantages of new opportunities was in the area of irrigation. The opportunity that irrigation offers for transforming traditional agriculture for increasing commodity production over time has not been in doubt. However, our failure to introduce irrigation has denied us the realization of the higher productive possibility attainable. The same observations could be made about the development of lake fisheries, lake transport, and wildlife and tourism.

Why have we failed to take advantage of new possibilities? This is an intriguing question whose full examination would take us beyond the scope of this paper. The account above suggests some possible explanations: our inexperience, defective planning and implementation, and lack of enterprise. This is the challenge that we face.

Acknowledgments. In preparing this paper I have drawn on material from the Volta Lake Research Project and on discussions with several of my colleagues in the Volta River Authority. I am grateful to Dr. John A. Dadson of the Department of Agricultural Economics, University of Ghana, Accra, for his criticism and assistance.

REFERENCES

Afriyie, E. K., Resettlement agriculture: An experiment in innovation, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Bazigos, G., Sampling techniques in inland fisheries with special reference to Volta Lake, *U. N. Develop. Program Volta Lake Res. Proj. Statist. Stud. F10:SF/GHA/10 St. S/1*, 44 pp., Food and Agr. Organ., Rome, 1970.

Bazigos, G., Yield indices in inland fisheries with special reference to Volta Lake, *U. N. Develop. Program Volta Lake Res. Proj. Statist. Stud. F10:SF/GHA/10 St. S/3*, 25 pp., Food and Agr. Organ., Rome, 1971.

Butcher, D. A. P., Sociologic aspects of fishery development on Volta Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Davies, O., Special exhibition of archaeological findings from the Volta River basin, report, 3 pp., State Publ. Corp., Accra, 1965.

Davies, O., The archaeology of the flooded Volta River basin, *Occas. Pap. Archaeol. 1*, Univ. of Ghana, Accra, 1971.

Food and Agriculture Organization, Volta Lake research, interim report, 58 pp., Rome, 1971.

Government of Ghana, Volta River Development Act of 1961, *Act 46*, Government Printer, Accra, 1961.

Obeng, L. E., Volta Lake: Physical and biological aspects, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Paperna, I., Snail vectors of human schistosomiasis in the newly formed Volta Lake, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, Ghana Universities Press, Accra, 1969.

Paperna, I., Study of the outbreak of schistosomiasis in the newly formed Volta Lake, *Z. Tropenmed. Parasitol., 21*, 411, 1970.

Taylor, People in a rapidly changing environment: The first six years at Volta Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Volta Lake: Physical and Biological Aspects

LETITIA E. OBENG
Institute of Aquatic Biology, Council for Scientific and Industrial Research
Achimota, Ghana

In 1924 the idea of a Volta River project was born. Before 1952, Ghana's Volta River project was a dream. In 1962 the project became a reality with the beginning of the construction of the dam. By 1964, Volta Lake was forming. In 1965, after a number of earlier desultory and halting starts, Volta Lake research made a significant breakthrough to gain recognition as an essential part of Volta Lake management: an institute for hydrobiological studies on a long-term basis, the Institute of Aquatic Biology, was established by the Council for Scientific and Industrial Research of Ghana, and scientists, mostly Ghanaian nationals from various government-sponsored organizations, embarked on various aspects of Volta Lake research.

Three years later in January 1968 the national research effort was reinforced by the launching of the Volta Lake Research Project jointly by the government of Ghana and the United Nations Development Program (UNDP). Primarily designed for the production of hydroelectric power for the electrification of the countryside of Ghana and the establishment of industrialization schemes, the Volta River project was also conceived as a multipurpose project to provide, among other things, facilities for lake transportation, a fishery industry, agriculture, and recreation.

Associated with the creation of the lake were expected as well as unpredicted far-reaching effects. Apart from the physical removal of people from their traditional homes and their resettlement in unfamiliar environments, there have been other aspects of the project indicating that certain factors should receive intensive attention and study well in advance of the actual construction of dams and that engineers, designers, biologists, and other appropriate persons should work in close cooperation even at the planning stage.

The Volta River project from this aspect is perhaps exemplary in that its planning received much study prior to its launching. The preparatory commission (1946) believed the scheme 'to be soundly conceived,' but its magnitude was such that the commission thought that 'it should not be embarked upon without every assurance that it could be carried through to a successful conclusion.'

The project was successfully launched. The Volta River was dammed. Volta Lake was formed. This lake is the largest man-made lake in Africa, having an area of 8300 km^2, a length of 402 km, a maximum depth of 905 meters, and a shoreline of >6400 km and enclosing several million cubic meters of water.

Ghana's inland water system is extensive and forms a close-knit network over the whole country. Volta Lake, being the focal point of this extensive water system, is literally in touch with almost all parts of the country.

Worthington [1966] gives a good resume of what one might expect with the creation of a major impoundment of this kind. Certainly, the Volta experience has established most of these possibilities as hard facts. Much land has been lost, possibly land with minerals. The ecological revolution that accompanied the inundation, the effect of the change and the new environment on the people, and the obvious economic potentialities of Volta Lake earned it a place as a project deserving national attention.

VOLTA LAKE IN THE GHANA SETTING

Ghana has an area of 238,699 km^2, a north-south length of 675 km, and a coastline with a maximum width of 553 km. The physiography of Ghana has interesting characteristics that undoubtedly contributed to the feasibility of the creation of Volta Lake. The landscape, on the whole, shows wide plains, a number of gentle slopes, and a limited series of hilly ranges with isolated peaks. The Afadjato in the Volta region, which is the highest point in Ghana, is only 910 meters above sea level.

The most easily noticeable feature in the relief is the Kwahu scarp (the Voltaian escarpment), which originates somewhere around Wenchi in the midwestern part of the country, crosses the country toward the southeast, and passes through the Ashanti-Mampong area and Mpraeso to the south where, with the Akwapim range, it forms the southernmost boundary of the Volta River basin. From the eastern side the highland area of the Volta region joins the Voltaian escarpment to form a link and to constitute a raised boundary around a well-protected basin of low-lying plains into which the lake water collected when the dam was built across the lower part of the Volta River.

On the western side the raised edge has its steep side facing away from the lake, so there is generally a stretch of low-lying shore. On the eastern side the steep side of the Volta region highlands, including the Buem range, faces the lake. Thus the shoreline on the eastern side has a different character from that on the western side.

Source of lake water. The Voltaian escarpment provides in the southwestern region of the country a clear demarcation of the catchment area of the Volta River and its tributaries. The Voltaian drainage system covered well over two-thirds of the country before the formation of the lake [*Wills*, 1962]. All minor rivers and streams north of the Voltaian escarpment and east of the Volta region highlands now drain into Volta Lake. South of the scarp a few large rivers (the Ankobra, Tano, Pra, Kakum, Amissah, Nokwa, Ayensu, and Densu) discharge directly into the Atlantic Ocean.

Contribution to the Volta Lake water from the north comes through the Red Volta, which has its source outside Ghana in the Upper Volta; the White Volta, which also rises from outside Ghana and receives large rivers including the Kulpwan and the Nassia within Ghana; and the Black Volta, the most important of the three Voltas, which has tributaries in Upper Volta but travels a long distance between Ghana and Ivory Coast and forms the boundary between the two countries in the west before turning sharply into Ghana and crossing it north of Wenchi to join the other two Voltas. In addition to the Voltas, from the western side of the country, the Pru, Sene, Obosum, Dwija, Afram, and Pawmpawm together with their numerous tributaries drain into the lake. From the eastern side the Oti, Daka, Asukawkaw, and Dayi rising from the Volta region highlands also take water to the lake. The country is very well watered with rivers and streams that are either intermittent or permanent in their flow. Although the Voltas originate outside Ghana, the bulk of the water collected in the lake comes from water sources entirely within Ghana.

Geologic background. From limnological considerations, the geologic character of the basin is relevantly interesting. *Bates* [1962] considers the Volta River system to be ancient and to have been in existence at the beginning of the Paleozoic age. The Ghana Geological Survey defines the term Voltaian as applicable to rocks consisting of 'a series of shales, mudstones, sandstones, arkoses, conglomerate, tillite and limestone.'

The Sene plain has arkoses, the Obosom has sandstone, and the Oti Valley has mudstone. *Bates* [1962] records also that, to understand the geologic nature, the value of data on stratigraphic classification is reduced because there are lithographic variations in the various parts of the Voltaian basin that make generalization and composite description of the areas inaccurate. However, from vertical sections and borehole samples, analyses give some basic information on the chemical composition of shale, sandstone, and limestone material from the Voltaian area.

Climate. A peculiar feature about the Ghanaian climate is the harmattan. The air masses that cause this state traverse the Sahara Desert before reaching Ghana. They are dry, have a relatively low humidity, and therefore give a general feeling of low temperature from November to February when they blow over most of Ghana. On the other hand, another set of air masses that comes from the sea during other parts of the year is, in general, cool and moist.

Prior to the formation of the lake, temperatures taken in the shade about 4 meters above ground varied only slightly from year to year (on the order of about 2°–3°F) [*Walker*, 1962]. The average maximum temperature reaches the highest level from February to April generally in the south and from April to May in the north. The annual mean temperature as recorded by *Walker* [1962] prior to the formation of the lake showed a low variation for the whole country when the temperatures were adjusted for altitude.

Rainfall has an effect on the character of water content in the basin. *Walker* [1962] considered the pattern to be significantly important not only because of its seasonality but also because of its variability from year to year. He distinguished four patterns of rainfall that varied from north to south but graded into each other so well that they were not clearly demarcated on the basis of their areas and periods of occurrence. He has recorded that, in general, January is a dry month but that there is much variation in the period of onset, extent, and duration of the rainy season. He believes Ghana to receive, on the average, the same amount of rain expected in a typical tropical area. The highest rainfalls were 218 cm in the Ahanta–Nzima region in the west and 71 cm around Accra.

Volta Lake appears to have received a favorable endowment in its choice of location and supply of water and an interesting basis for its chemical character. All these factors are relevant to the design of the studies required to support its full use and exploitation.

VOLTA LAKE RESEARCH

Organization. In a case study of Volta Lake research, it is not out of place to comment on its organization, since it is the infrastructure on which the success or failure of the research depends.

Ghana, fortunately, awoke to the importance of full-time scientific research in the use of natural resources for national development very early in her postindependence history. Statutory recognition was given to research in the late fifties when the National Research Council was established. This body has metamorphosed through the Ghana Academy of Sciences into the Council for Scientific and Industrial Research, which has nine full-time research institutes studying the country's soils, cocoa, crops, forests, inland water system, food, buildings and roads, industries, and animals. It is an extensive organization that has been given by an act of Parliament the responsibility for conducting research of national importance.

The institute for the inland water system has concentrated much effort on Volta Lake not only because it is the physical focal point of the inland water system but also because of its challenging nature and the national expectations from its creation. The research staff of the institute and their supporting technical and field staff are temporarily assigned to the Volta Lake Research Project, which was initiated in 1968 to augment existing lake research. This project is jointly sponsored by the government of Ghana and the UNDP. Some staff from the University of Ghana, the Volta River Authority, the Ministry of Agriculture, and the Ministry of Health are also assigned to the project. This national staff of more than 30 people is joined by a United Nations staff of up to 10 people, and they are supported by a turnover of more than 70 junior local staff.

Administratively, the Food and Agriculture Organization is the executing agency on behalf of UNDP, and the project manager is its representative. The Volta River Authority is the cooperating agency on behalf of the government of Ghana, and there is also a Ghanaian co-manager.

The United Nations Special Fund contributed US$1,336,000 for a period of 3 years toward the project, and this amount was matched by an equivalent contribution in cash and kind by the government of Ghana. The purpose of the project was to assist Ghana in strengthening research on fisheries and hydrobiology, public health, and the resettlement of the peoples displaced by Volta Lake.

The project has laboratories at Akosombo, the damsite of the lake, which has adequate facilities but is unfortunately not the most convenient place for a research headquarters because of its location at the southernmost end of the 402-km-long lake. Because of the transportation and communication problems of this isolation, it was decided at the beginning that the project should also use outside facilities at the universities and the Council for Scientific and Industrial Research.

Program. The design of the Volta Lake research program makes it possible to consider almost all aspects of hydrobiological research in terms of their practical application to development. The major sections are limnology, fish biology, fish technology, aquatic weeds, public health, agriculture, and game and wildlife. These sections take into account, on an immediate as well as a long-term basis, managing the lake with a view toward developing fisheries, guarding against pollution in various forms to ensure a safe level of health, and eventually providing facilities for recreation. Although these items may appear unrelated, the conduct of the studies is so organized as to encourage maximum coordination of the various activities undertaken by the project.

In detail the Volta research program covers limnological studies involving the physical and chemical characteristics of the medium, plankton, periphyton, bacteria, algae, and invertebrate fauna and their relationship to fish production. Studies on fisheries take into account the diversity of fish species; their population and distribution; and their feeding, growth, health, breeding, spawning, and migration habits. There are also sections on determining, as far as possible, the turnover both in fish productivity and in catch. Studies on gear technology and fish processing, preservation, and marketing have been included as an essential part of the program.

These sections of the program bring the field staff into direct contact with the fisherfolk on whom the eventual establishment of a viable fishing industry will depend. Since the vigor and zeal with which the fishermen carry out their work are closely linked with their state of health, the presence of any disease-causing organisms and parasite-supporting agents likely to threaten the health and virility of the fishermen becomes of vital concern. Public health implications associated with such an artificial impoundment therefore are a major factor in the research program. Invertebrates of medical importance (especially the schistosome-supporting mollusks, mosquitoes, tsetse flies, and others) receive attention. The mollusks are associated with aquatic weeds that invariably become established when impoundments are made, and the study of these weeds also becomes an unavoidable part of the research even though the weeds themselves do not constitute serious physical obstructions, as they do in some other lakes.

Other aspects of the research program include shoreline soil studies for future afforestation and agriculture and the establishment of game and wildlife parks for recreational and educational purposes. Attention has also been given to rehabilitation of the resettled people, investigations of their social problems, and apportionment of land to them for agriculture.

Volta Lake research is scientific in approach, but first and foremost it is mission oriented to aid the use of the potentialities of Volta Lake. The research program incorporates a reasonable amount of basic investigation and therefore provides a refreshing opportunity for practicing the operational interdependence of basic and nonbasic research and for applying this research to the various faunal relationships and levels of productivity in the lake to economic advantage.

The program covers almost all the problems being tackled by the other man-made lakes in Africa. It combines research into fisheries being conducted at Kariba, Kainji, and Jinja with research on the use of lake water for domestic and agricultural problems. Volta Lake shares public health problems with Kainji Lake and Lake Nasser, has the nuisance of aquatic weeds in common with Lake Kariba, has passed through a phase similar to Kariba's 'Operation Noah,' and like Lake Nasser and Kainji Lake entertains the hope of using lake water for irrigation. In addition to these similarities, in the Ghana setting, Volta Lake promises great hopes for transportation and recreational activities.

In another sense, Volta presents an interesting feature for study by the fact that it traverses a countryside that varies from conditions of savannah land to forest. Unlike Nasser, Kariba, and Kainji, Volta has an emphatic dendritic form that links it with hilly regions as well as plains and that spreads its associated riverine connections well over two-thirds of the whole of Ghana. In comparison with the other lakes, Volta stands shoulder high in its proportionate size to the country that owns her. The position of Volta Lake in the country makes inland fisheries for Ghana very important. Above all it is so conveniently located in west Africa that it is able to share its benefits with neighboring countries. From an economic point of view it is a veritable gold mine whose treasures are being worked according to a comprehensive, multidisciplinary, mission-oriented, and well-coordinated research program.

These salient features of Volta research, together with the close cooperation between non-Ghanaian staff from four continents of the world working on a complex research program with a group of Ghanaian scientists from the fifth continent to achieve the aspirations of a developing country in the management and use of the benefits from one of the largest man-made lakes in the world, give Volta Lake research a uniqueness that makes it almost a blueprint for the approach to research on man-made lakes in developing countries.

VOLTA LAKE RESEARCH 1964–1970: METHODS, OBSERVATIONS, AND COMMENTS

Limnology

In the early stages of work on Volta Lake, more as a result of necessity than as a result of desire, unsophisticated but effective methods were employed in studies of the rapidly altering medium; however, as the water increased and the lake extended its width, the need for adequate sampling methods became real. Stations were selected in parts of the lake for regular sampling. In the account presented it must be constantly borne in mind that, for a lake of the size of Volta, normal sampling methods can hardly be expected to give results that yield easily to generalization.

Oxygen pattern. Soon after the completion of the dam in 1964 the oxygen distribution in the lake was closely followed. *Ewer* [1966] reported that immediately after the dam closure a 300% surface oxygen saturation was recorded in midstream about a mile north of the dam. This record had dropped within 4 weeks to 16% oxygen saturation in surface layers, and an absence of oxygen was reported at the 10-meter depth.

Entz [1969] found an obvious increase in dissolved oxygen between 1967 and 1969. Oxygen was present down to the bed of the lake at the Afram confluence, some 20 miles from the dam. In mid-1969, A. E. Kpekata (personal communication, 1970) reported oxygen to be present at 30 meters at Ajena in May, detectable on the bed in August, and at 5% saturation on the bed in September. A survey in the northwest along the Black Volta and White Volta showed 27–55% oxygen saturation down to the bed, and the surface layers in all the other riverine arms were well oxygenated. This change very much favored productivity at various levels and affected fish and invertebrate distribution.

Stratification. As the lake conditions changed, tendencies toward stratification, as normally interpreted, were also watched with much interest. *Beauchamp* [1969] records Lake Tanganyika, an old natural African lake, to be permanently stratified. It has large deposits of organic matter and little outflow of water.

Volta Lake had comparatively few organic deposits during its initial period of formation; it had a good inflow system and little temperature variation with depth, and stratification (as conventionally understood) was not expected to be an important feature of this tropical lake.

However, *Viner* [1969] reported that, on September 4–5, 1965, he recognized three distinct layers: an upper oxygenated layer at about 5 meters, a middle moderately oxygenated layer, and a very clearly marked anaerobic layer, slight but certain at the Afram confluence and strongly marked at Krachi. In 1966, *Entz* [1969] recorded a downward gradient of dissolved oxygen that he interpreted as a factor of a stratification pattern near Akosombo, but he also observed, as had *Biswas* [1969] earlier, that the delineation was destroyed by a number of factors (including wave and wind action, the rainy season, and the harmattan) that caused a mixing and turnover of the water.

Biswas made an early study of temperature changes, and his account gives an interesting pattern of the variations that took place up to 1966 between the bottom and surface layers. It would seem that the temperature variation with depth is now virtually negligible.

Turbidity. Observations so far describe a definite decreasing gradient of maximum turbidity from the northern region southward toward Kpandu. This decrease appears to be related also to the rainy season, which brings an influx of organic materials from the rivers into the lake. During August and September 1970, areas north of the Daka confluence were the most turbid, the transparency ranging between only 9 and 10 cm. It seems likely that the variations in turbidity also affect the spatial distribution of fish.

Chemical studies. A good deal of chemical analysis has been made over the period of study to follow the pattern of distribution and concentration of certain ions. From 1966–1969, *Entz* [1969] compiled much data from analyses carried out both in the field and the laboratory.

An interesting feature that emerged from the chemical studies is the distribution of some of the chemical factors. In 1968, for instance, the Pawmpawm arm had a higher chloride content than anywhere else in the lake. Phosphate ion concentration was also higher in the lake water above the Oti than below it. Temperature, dissolved O_2, and pH decreased with depth; CO_2,

H_2S, NH_4^+, Fe^{++}, and PO_4^{---} increased, whereas Ca^{++}, Na^+, Cl^-, K^+, and SiO_3^{---} did not seem to show any definite pattern of distribution.

Entz reports measuring quite high values of Fe^{++} at the surface of a section of the lake water at one time and explains this finding to be probably the result of settled laterite dust on the surface layers. Down to 10 cm the value was low, but at greater depths where O_2 and *p*H values were low the Fe^{++} values could be extremely high. In the main, chemical analyses made over the 6-year period by various persons show much similarity in results. Studies to interpret the data so far collected in terms of productivity are in progress.

Plankton and Algae

With limnophysical and chemical data as background, studies of phytoplankton production in relation to availability or unavailability of certain chemicals can be seen in a useful light. Oxygen, light penetration, and the influence of the degree of turbidity on phytoplankton development and distribution have a direct relation to plankton-feeding fish and their growth, abundance, and distribution. Observations made in 1966 by *Rajagopal* [1969] show a correlation between these factors. It is also interesting that he recorded in 1966, as was reported from 1964–1965 by *Proszynska* [1969], that the southern section of the lake was unsuitable for plankton formation and that cladocerans and copepods were absent. The Afram region near Ampem provided a better habitat for their development.

Proszynska also recorded an interesting case of recurrent mass death of crustacean plankton in the early months of the formation of the lake near Ajena and suggested that this occurrence was probably due to the unfavorable chemical changes in the lake environment. The areas affected later became repopulated probably by plankton brought in by the current from more satisfactory areas.

Later, in January 1969, by using a bolting silk no. 25 net, vertical hauls were made at some places and at different depths down to 15 meters from the damsite to Mpaha in the north [*Rajagopal*, 1970]. *Cyclops* spp., *Bosmina* sp., *Moina* sp., *Ceriodaphnia* sp., *Rotifera, Filinia* sp., *Trichocerca* sp., and *Keratela* sp. appear to have been the main organisms in the samples. Rajagopal recorded total zooplankton at the time to range from 1620 to 15,300 organisms per cubic meter column of water. Later in the year, plankton was recorded from the surface down to 65 meters at the Afram confluence, but the irregular distribution of the plankton at different depths in the column of water during the period of study was again a clear indication of the mixing of the waters.

When we compare the results over the 5-year period, it appears that the plankton population fluctuated not only in distribution but also in size over the months of the year. The Afram wing, once rich in zooplankton (at least around Ampem), was reported in 1969–1970 to have a lower number of zooplankton than the northern parts of the lake.

Proszynska, who had the opportunity to observe the Cladocera and Copepoda from 1964–1965 and to make qualitative studies of them during the first 18 months after the lake began to form, writes, '. . . there is no one common feature which can be generalized for the whole period of investigation.'

Blooms of *Microcystis* were not uncommon between 1966 and 1967. Rajagopal also reports a large proportion of *Gymnodinium* near the shore at Mpaha in 1969 and a bloom of *Synedra* there and also near Kete Krachi. At the Afram confluence, *Volvox* was abundant. From the surface to 65 meters, colonies per cubic meter ranged from 4000 to 350,000 in number.

The plankton pattern in 1970 is still variable. A longer period of study is needed for a clear picture to emerge, but generally it appears that, during favorable periods, zooplankton is abundant and shows a decreasing gradient from the north of the lake southward. The phytoplankton picture is even less clear. The zooplankton distribution also appears to follow the vertical oxygen gradient; at the Afram confluence zooplankton was present, on a day of continuous study, from 5 meters down to the bottom, and the water was habitable for fish. Where there was deoxygenation and high turbidity, the adverse effect on the distribution of the organisms was also apparent.

Algal collections made directly from the water have been mostly *Spirogyra* and *Oscillatoria*, but it appears that various objects in the water support more species of algae. Again, it would not be prudent to generalize at this stage of our knowledge and the present state of the lake on the plankton and algal picture and the significance of their occurrence in the overall pattern of study.

Bacteria. Studies made in 1965 and subsequently by *Biswas* [1969, also unpublished report, 1970] and *Ofori* [1970] have shown that bacteria do not cause any major concern at this stage. It is likely that bacteria may require attention as shore areas become contaminated by settlers.

Periphyton. Limited studies on periphyton production were undertaken by *Entz* [1968]. Glass slides were stuck in 2.54-cm nylon fish nets that were hung vertically near the damsite for different lengths of time. The periphyton developed over these different lengths of time after which their density was calculated.

Invertebrate fauna. Bottom fauna has been studied over a period of time, and accounts have been documented. Record was also made in 1965–1966, during the initial stages of formation, of the lake invertebrate fauna associated with aquatic weeds that had then developed [*Obeng*, 1969*a*]. Subsequent collections have shown an increase in the variety of the species of invertebrates then present. Most of these, especially the chironomid larvae, form food for fish.

Fish Studies

Species and population studies. Unfortunately, before the dam was closed, very little had been recorded of the fish in the Volta River. After the closure of the dam, between 1964 and 1966, *Denyoh* [1969] recorded a number of species of fish that had then been identified. The fish had been caught with limited facilities near Akosombo and Kpandu. Since then, others, including *Adiase* [1969], have recorded other species belonging to other genera (also see *Evans and Vanderpuye* [this volume]).

Adiase [1968] reported a pattern of distribution that, although it was not definite, gave a rough idea of the occurrence of certain species. It appears that almost all the species then recorded occurred throughout the entire length of the lake. The tilapias were numerous in the south and near Ampem in the Afram region where plankton had also been found to be abundant. Near the dam where plankton had been reported to be scanty in the upper layers of the water, few specimens of tilapia could be caught. *Lates niloticus*, one of the most highly priced species in the lake, appeared to be present in all areas.

The fish population pattern has also changed over the period under observation. From catches made from 5 months after lake formation to 1966 it was reported that some species became reduced in numbers as the lake formed. *Chrysichthys* spp. occurred in small quantities in 1964 near Akosombo but became the predominant species in 1966. *Lates niloticus*, on the other hand, had been caught in reasonable numbers both at Akosombo and Kpandu, but it had increased considerably near Kpandu and decreased in the Akosombo area by 1966. *Ctenopoma* spp. also gradually became rare.

With the continued stabilization of lake conditions and increased favorable distribution of dissolved oxygen and food, a variety of fish began to form the basis of what could become a prosperous fishing industry. Bottom feeders like *Labeo* spp. and *Synodontis* spp. and the carnivorous *Hydrocyon* spp. and *Lates niloticus* have increased in size and number.

It has not been necessary to stock the lake with fish. There was a boom in the fish population after the initial adverse ecological changes that affected some fish. It has, however, been necessary to assess the present fish stock and the unit catch effort in the interest of successful management, although, when one deals with a lake the size of Volta, one has to recognize that it is nearly impossible to be categorical about quantities.

Fish biology. The usefulness of results from catch assessment in terms of fishing management is incomplete without relevant information on which to determine fish productivity. Information obtained by studying fish species and their population structure, food and feeding habits (and the availability of such food), distribution pattern, growth rate, size and maturation cycle, spawning habits, and seasonal migratory activities are essential parameters that will determine the stock turnover for a period of years. *Adiase* [1969] studied the feeding habits and food preferences of a number of species.

Maturation of species under natural conditions can be related to size ranges, and studies are being made to establish a relation between the availability of food and spawning patterns. It is likely that most of the fish, having been riverine originally, still migrate to the many arms of the lake to spawn. Certainly, juvenile species of *Alestes* that occur in the lake have been taken in samples from the Nassia River in northern Ghana, which also flows into the lake. The spawning habits of the fish and the factors likely to affect the successful replacement of fish are receiving attention. However, investigations into migratory activities of fish are difficult because there are still substantial areas of the lake with fully or partly submerged trees that make passage from the lake to the rivers that join it difficult.

Fish technology. The physical changes of Volta from a river to a lake have made the fisherman's gear almost obsolete. In place of a river he is now faced with a deep inland sea. Part of the research program has covered experiments to determine suitable mesh sizes, net lengths and widths, and net setting techniques. The monofilament type of net has been tested scientifically against the traditional multifilament net and has proved more effective. Plans are afoot to introduce mesh sizes from 12.7 cm upward into the market for use by the fishermen. But since the present fish stock has not been established with any certainty, care is being taken in the use of these nets to avoid catching juvenile fish.

The old wooden canoes previously in use on the Volta River are no longer quite safe, especially in storms, on this large inland sea. New designs have been made, and prototypes are being tried before they are introduced to the fishermen.

From as far back as one can trace, Volta fish have been processed in two ways, by smoking and by salting and drying. Studies into the causes of spoilage and the problems of preservation have been conducted as part of the research program. In the laboratory, J. K. Agbley (unpublished report, 1969) has made preliminary biochemical analyses to ascertain the relationship between the fish fat content and deterioration under certain conditions, and J. C. Ofori (unpublished report, 1969) has been studying through culture the bacteria forms occurring on the fresh and smoked fish that contribute to spoilage. Information obtained will be useful background to the proposed scheme to establish a pilot center for processing, preservation, and marketing of fish at Kpandu-Tokor.

Public Health

The range of invertebrate fauna recorded from vegetation and the bottom has increased during the years following 1966. The appearance and establishment of mollusks as part of the fauna and the possible threat of schistosomiasis were not unexpected, especially since *Bulinus* snails had been previously recorded in some regions that were subsequently inundated by the formation of the lake.

Schistosomiasis. From 1964–1968, studies on the schistosomiasis problem were concentrated on the establishment of the presence of the snail intermediate hosts, their distribution and habitats, and their association with aquatic plants. Investigations into the medical aspect of the problem were not started until the arrival of the epidemiologist and the medical biologist from the World Health Organization (WHO) in December 1969. Since that time the scientists from WHO together with the national staff have jointly tackled the problem from both the medical and the biological angles.

Early reports have shown *Bulinus truncatus rohlfsi* to be the only proven urinary schistosomiasis host associated with Volta Lake. Other snails like *B. forskalii* sp., *Pila africana, Lymnea* sp., *Anisus coretus,* and *Potadoma* sp., recorded as present in 1965, continue to occur [*Obeng,* 1969*a*]. In addition to these, *Odei* [1970] has reported other mollusks, including *Caelatura* sp., *Mutela* sp., *B. (Physopsis) globosus, Gyraulus costulatus,* and *Ferrissia* sp. No *Biomphalaria* species have been found.

B. truncatus rohlfsi has so far proved to be the most common schistosoma host snail on the lake, and *Odei* [1970] reports that this snail has been collected with an infection of *Schistosoma haematobium* in the field. He observed also that the population density of this snail seems to fluctuate with different habitats and areas on the lake. He recorded densities ranging from 0 to 140 snails per man-hour from various habitats and areas and field infection rates of 70–50% in the Afram region.

It has been considered desirable to establish with some degree of certainty the infective sites of the disease. This observation makes it pretty certain that, although in some areas the snails may breed in water bodies near villages situated on the lakeshore, the lake itself constitutes the main site of infection.

B. truncatus rohlfsi is the host snail for the *S. haematobium* 'strain' [*McCullough,* 1959] from which the Battor fishermen from the south Volta floodplains normally suffer. M. A. Odei (personal communication, 1971) has recorded that this snail breeds in the lower reaches of the Obosom River where it is found to be infected with *S. haematobium.*

B. (Physopsis) globosus is also a snail host for *S. haematobium* elsewhere in the country, although it is a poor one for the *S. haemotobium* strain that afflicts the Battor fishermen. Odei has recorded a high density rate of 74 snails per man-hour of this species in the upper reaches of the Obosom, but it has not been collected in the field in an infected condition. The breeding of this species in large numbers in the Obosom is interesting and, with further studies, may prove to be a fact of decisive importance.

Two interesting questions emerge from this discussion. First, Does the presence of the snail in the Obosom at this time indicate the tail end of a declining population or is it the beginning of a new establishment? If the latter, what ecologic changes could have initiated this new population? Second, Odei noticed that there appears to be a demarcation in the distribution of the two *Bulinus* species on the Obosom River. In the lower reaches of the river where *B. truncatus rohlfsi* occurs, there is infection among the Battor fishermen. In the upper section on the same river where *B. (Physopsis) globosus* alone breeds, there is also a low rate of infection among the people, although there is no infection among the snails. It is still to be established whether the infection is of local origin or due to the migration of persons from downstream; in either case, is it likely that *B. (Physopsis) globosus* will eventually adapt itself to become an effective host in the area? Laboratory studies are testing the susceptibility of the snail to infection with the *S. haemotobium* strain of Battor presently found on the Obosom. Also, a close study is being made of possible field infection of *B. (Physopsis) globosus* with the schistosome.

The medical investigations on the problem are also interesting. C. R. Jones (unpublished report, 1970) reports that, in the Afram area on the western side, for instance, urinary schistosomiasis in children under 10 years of age has risen to as high as 90% since the lake formation. On the eastern side the incidence is much lower. The density of the snail host is also less, and this low density is suspected to be related to the steep nature of the shore, which does not encourage a dense growth of weeds. However, with an increase in the spread of the creeping *Alternanthera* sp. and *Vossia* sp., as well as the presence of sheltered coves and bays, the snail population may increase. It would seem that snail hosts are not limited to weeds but may be found on other convenient substrata, including mud, or may be collected browsing on rocks. The bilharzia problem is receiving serious attention.

Trypanosomiasis. Although trypanosomiasis does not pose as serious a threat as schistosomiasis, the possible increase in incidence of trypanosomiasis (sleeping sickness) in the lake basin has not been overlooked, and studies have been initiated and maintained on tsetse flies. F. A. S. Kuzoe (unpublished report, 1970) records the Daka Valley to be one of the most important foci for trypanosomiasis in Ghana. It is also the sole source of water supply in a dry savannah area, and tsetse growth is associated with its tributaries. Flies that have been caught on field trips have been dissected for infections with *Trypanosoma* sp. However, the flies *Glossina palpalis* and *G. tachinoides* dissected within the April–June quarter of 1970 showed only one infection with *T. vivax* out of 36 flies examined.

Guinea worm. An interesting recent development is a record by C. R. Jones (personal communication, 1971) of guinea worm infection in an area north of Krachi. The incidence, although it is localized, is high, and, even though the infective site is outside the lake, the situation is being carefully watched.

Onchocerciasis. *Simulium* species were breeding widely in the Volta River before the formation of the lake. As had been expected, the formation of the lake eliminated the breeding sites above the dam in the area flooded, but *Simulium* species other than *S. damnosum*, vector of onchocerciasis (river blindness), were still present around the lake in a defined area investigated in 1966 [*Obeng*, 1969*b*]. A number of rivers farther north of the area examined have now shown large populations of *Simulium* species including *S. damnosum*, especially around Jasikan where in September 1970 the flies were actively biting. The incidence of a high rate of onchocercal parasite infection in the area has been reported [*Jones*, 1970]. Both the direct and indirect association of this high incidence with the lake has necessitated an intensification of biological studies on the *Simulium* larval life cycle, seasonal abundance in relation to stream ecology, and infection rates and the collection of other relevant information to facilitate the design of an effective control program.

Aquatic plants. An impressive list of common aquatic plants occurring in Volta Lake has been compiled. They include *Pistia stratiotes, Salvinia nymphellula, Azolla africana, Lemna* sp., *Cyperus distans, Eclipta prostrata, Jussiaea repens, Spirodela, polyrhiza, Utricularia inflexa, Vossia cuspidata, Cyperus* spp., and *Ceratophyllum demersum.* The situation at Kariba is unlike the one at Volta: these weeds in Volta Lake have been considered problems mainly because of their association with public health and parasitic infection problems and their nuisance in connection with fishing.

Submerged *Ceratophyllum demersum,* as well as floating *Pistia stratiotes*, and some other littoral plant forms have been found to provide attachment for snails and other intermediate hosts of parasites [*Obeng,* 1969*b*]. Other plants (including *Alternanthera* sp., *Polygonum* sp., and *Jussiae repens*) recorded earlier in the Volta basin [*Hall et al.,* 1969] have become serious marginal plants. Conventional chemical control methods tried on a small scale were unsuccessful, and other methods, including biological control, are being investigated.

Agriculture and Wildlife

Perhaps one of the most interesting and rewarding sections of Volta Lake studies has been in agriculture. As has been stated elsewhere, farming continues to be an active occupation around the lake. Even the fisherfolk alternate periods of lean fishing with farming. This alternation gives great encouragement to drawdown and lake vicinity agriculture. The project has carried out studies and set up experimental plots in parts of the drawdown area. Three experimental stations have been established at Asantekrom in the southern part of the lake, Makongo in the north, and Vakpo near the middle. (See other details by *Kalitsi* [this volume], *Taylor* [this volume], and *Butcher* [this volume].)

The extent of the drawdown area has not been calculated with certainty, but it is hoped that a definition will be possible after the planned aerial photography. Whatever its extent, a good proportion of the lakeshore holds the promise of potential use for agriculture.

Ghana cannot hope to compete with Kenya in the field of attractive wildlife, but, as part of the use of lake potentialities, a wildlife and game reserve is being established on part of the lakeshore. It is intended that this reserve will be used for recreation, education, and sport.

CONCLUSION

I have attempted to present as balanced a picture as possible of the results of environmental changes, both desirable and undesirable, that have been produced by the creation of Volta Lake. The study of these ecologic changes is to be employed toward using the existing potentialities in purposeful development and toward curtailing and controlling the unsatisfactory possibilities to prevent any undesired drawbacks.

In the course of collating the data, it has been necessary to analyze and compare various man-made lake research programs. There is an almost stereotype plan of research being followed on all the African man-made lakes. The plan is well designed and comprehensive. According to the degree of seriousness of problems, each lake puts stress on certain sections of the program.

However, taking an overall view of man-made lakes with respect to what is expected of them by way of development of fisheries, it would seem that the need of a developing nation lies with investigations that will reasonably ensure the maintenance of a desirable level of yield.

In the present plan of research, much emphasis is being placed on stock assessment, processing, preservation, and so on. This emphasis, presumably, is desirable. Stock assessment, for instance, will give an estimation of stocks and will help to devise a plan for wise exploitation of the resource.

But we do not merely want to exploit resources. Although the word exploitation is quite respectable, I cannot help but feel that in this respect it has a certain connotation of irreparable destruction. I believe we should use the potentialities of the resource rather than exploit them. To do this, we need the foresight to consider solutions to problems on a long-term basis. Whereas it is necessary to know what stocks we have, I feel it is even more important, at this stage, to initiate and encourage investigations into how to maintain the stocks.

In this circumstance, man-made lakes appear to me to be in a peculiar situation. It may be possible to restock a lake with new fish should yields fall. But restocking would be only half the solution. The vital problem is how to maintain a sufficiently relevant concentration of nutrient material at the lower levels of the food chains so that the food cycles can work satisfactorily.

Fish ponds can have their basic nutrient matter replenished by the addition of various materials, chemical and otherwise, to the medium. Natural lakes of long standing have deposits that serve as reserves. Our man-made lakes are too new to have such reserves, and they are generally too large (true of Volta) to be treated as a fish pond. By the time the initial postinundation boom in the fish yield declines, the lake would probably not have enough bottom reserve to maintain a satisfactory supply of nutrient material. Even if new fish are introduced as a means of stepping up the yield, the new population will need nutrient materials.

How then do we augment and maintain a satisfactory level of nutrient matter to sustain our yields? We have started to investigate the quantity of matter brought in by the riverine areas. We are also investigating possibilities of certain physiological studies, but it is an exercise that needs to be done on a wide basis.

For Volta Lake, fishing is not a sport. It is a means of obtaining valuable protein. It provides an occupation on which about 20,000 people depend. A decline in fish production is a serious matter. Preventing a continuous decline is vital. Replacing and maintaining a satisfactory level of nutrient material appear difficult, but such a level is important and should receive conscientious and urgent attention.

To find a breakthrough, we shall have to identify the key factors on which the productivity of the microflora and microfauna depends. We shall have to understand physiology and energy absorption at that level. This search for knowledge may entail a large amount of basic or what is often called pure research, but it will not only be pure in research, it will also be pure in its intention in that it will seek to contribute a solution to a pressing problem, i.e., maintaining a satisfactory level of basic nutrients.

Do we have to try chemical fertilizers? On the scale of Volta, such fertilizing will need careful consideration and planning. Do we rear ducks? How? Or do we use our aquatic weeds? There are possible avenues that we might explore.

The important thing now, as I see it, is to begin. Hopefully, by jointly studying the basic requirements, we can find a solution for the replacement and maintenance of the nutrient materials in man-made lakes to help them out during the critical periods.

Insofar as Volta is concerned, it must be said on a comparative basis that the ecological nature of the new environment and its impact on the people and their various occupations have, on the whole, not been unsatisfactory. The contribution of the lake to national development shows high promise. How events go in the future with the maturation of the lake will depend on our foresight and planning at the present time.

REFERENCES

Adiase, M. K., Fish population distribution and fishing habits, in *Annual Report 1967–1968*, pp. 14–16, Institute of Aquatic Biology, Achimota, Ghana, 1968.

Adiase, M. K., A preliminary report on the food of fish in Volta Lake, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, pp. 235–237, Ghana Universities Press, Accra, 1969.

Bates, D. A., Geology, in *Agriculture and Land Use in Ghana*, edited by J. B. Wills, chap. 3, pp. 51–61, Oxford University Press, London, 1962.

Beauchamp, R. S. A., Hydrobiological factors affecting biological productivity: A comparison between the great lakes in Africa and the new man-made lakes, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, pp. 91–93, Ghana Universities Press, Accra, 1969.

Biswas, S., Thermal changes in the Volta Lake at Ajena, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, pp. 103–109, Ghana Universities Press, Accra, 1969.

Butcher, D. A. P., Sociologic aspects of fishery development on Volta Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Denyoh, F. M. K., Changes in fish population and gear selectivity in the Volta Lake, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, pp. 206–211, Ghana Universities Press, Accra, 1969.

Entz, B. A. G., Limnology—Chemical and physical studies, in *Annual Report 1967–1968*, pp. 2–6, Institute of Aquatic Biology, Achimota, Ghana, 1968.

Entz, B. A. G., Observation on limnochemical conditions on Volta Lake, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, pp. 110–115, Ghana Universities Press, Accra, 1969.

Evans, W. A., and J. Vanderpuye, Early development of the fish populations and fisheries of Volta Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Ewer, D. W., Biological investigations of the Volta Lake, May 1964 to May 1965, in *Man-Made Lakes*, edited by R. H. Lowe-McConnell, pp. 21–30, Academic, London, 1966.

Hall, J. B., et al., Observations on aquatic weeds in the Volta basin, in *Man-Made Lakes, The Accra Symposium*, edited by L. E. Obeng, pp. 331–336, Ghana Universities Press, Accra, 1969.

Kalitsi, E. A. K., Volta Lake in relation to the human population and some issues in economics and management, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

McCullough, F. S., The susceptibility and resistance of *Bulinus (Physopsis) globosus* and *Bulinus (Bulinus) truncatus rohlfsi* to two strains of *Schistosoma* *haematobium* in Ghana, *Bull. WHO, 20,* 75–85, 1959.

Obeng, L. E., Invertebrate fauna of aquatic plants of the Volta Lake in relation to the spread of helminth parasites, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 320–330, Ghana Universities Press, Accra, 1969*a*.

Obeng, L. E., The effect of inundation on the Simuliidae of the Volta basin, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 361–365, Ghana Universities Press, Accra, 1969*b*.

Odei, M. A. Schistosomiasis, in *Annual Report 1969–1970,* pp. 55–58, Institute of Aquatic Biology, Achimota, Ghana, 1970.

Ofori, J. C., Studies on fish spoilage and preservation, in *Annual Report 1969–1970,* pp. 43–46, Institute of Aquatic Biology, Achimota, Ghana, 1970.

Proszynska, M., A preliminary study on the quantitative study of the Cladocera and Copepoda in the Volta Lake 1964–1965, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 127–132, Ghana Universities Press, Accra, 1969.

Rajagopal, P. K., Preliminary observations on the vertical distribution of plankton in different areas of the Volta Lake, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 123–126, Ghana Universities Press, Accra, 1969.

Rajagopal, P. K., Plankton and algae, in *Annual Report 1969–1970,* pp. 22–26, Institute of Aquatic Biology, Achimota, Ghana, 1970.

Taylor, B. W., People in a rapidly changing environment: The first six years of Volta Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Viner, A. B., Observation of the hydrobiology of the Volta Lake, April 1965–April 1966, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 133–143, Ghana Universities Press, Accra, 1969.

Walker, H. O., Weather and climate, in *Agriculture and Land Use in Ghana,* edited by J. B. Wills, chap. 2, pp. 7–50, Oxford University Press, London, 1962.

Wills, J. B. (Ed.), *Agriculture and Land Use in Ghana,* 504 pp., Oxford University Press, London, 1962.

Worthington, E. B., Introductory survey, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 3–6, Academic, London, 1966.

People in a Rapidly Changing Environment: The First Six Years of Volta Lake

B. W. TAYLOR

Volta Lake Research Project, Akosombo, Ghana

VOLTA RIVER PROJECT

The formation of Volta Lake occurred as a by-product of the Volta River project. This project aimed at using Ghana's hydroelectric and bauxite resources both for the establishment of an aluminium industry and for the general industrialization of the country. The project has a long history and was first conceived in the early years of this century. Very detailed studies and proposals were made by the *Volta River Preparatory Commission* [1956] in the years 1952–1956. A reassessment of these proposals was made by Kaiser Engineers Inc. (unpublished data, 1959).

There were considerable difficulties in arranging finance. As a result the final decision to dam the Volta River was not made until 1961, and the actual construction commenced in the same year. By May 1964 the dam was closed, and construction was completed in February 1965. The first electricity was generated in September 1965, and, by April 1966, all the initial units were in operation with a capacity of 589 Mw. It is planned that this capacity will be raised in 1971 to its final figure of 833 Mw.

Although the project was justified economically solely on the basis of power generation, the planning authorities, particularly the preparatory commission, were very conscious of the many possible effects of the formation of a large dam and lake. Their studies covered the problems of the people to be displaced by the lake, public health, transport, the fishing industry, and the effects on the river downstream of the dam. This paper gives a brief description of the features of the lake, the predicted changes that were expected from the lake's formation, and the reactions of the people to the changing conditions in the years 1964–1970.

LAKE ENVIRONMENT

Probably the most striking feature of Volta Lake is its great surface area of 8500 km^2, the largest of any man-made lake (Figures 1, 2, and 3). Similarly, it has a very long shoreline that exceeds 4800 km in length (P. Westaway, unpublished data, 1969). The lake is relatively shallow and averages a little less than 20 meters. However, its large surface still gives it a reservoir capacity of 165 km^3, and thus it is one of the larger reservoirs of the world. In contrast to that of other reservoirs of similar capacity, the mean annual inflow of Volta Lake is low; it averages only 44 km^3 for the period 1936–1964. This inflow is very variable; total annual flows recorded have ranged from 14 to 108 km^3, and mean monthly flow rates have ranged from <30 to >14,000 m^3/sec. Despite this great variation the reservoir capacity is so large that, when the dam is in full power production, it is expected that spilling will occur only in occasional peak flood years.

The lake has a dendritic shape with many arms, and it extends 400 km north of the dam. This area is largely in the Guinea savanna zone of west Africa, but small areas of forest have been flooded near the south and east banks of the main lake. The topography of the surrounding area is flat to gently rolling, and there are a few steep slopes near the south and east banks. Soils are typically sandy loams of low fertility. This area has a markedly seasonal rainfall (the annual means ranging from 1100 to >1600 mm) and a farming season from May to October.

Before impoundment the lake-fill area had a population of 80,000 people (D. A. P. Butcher and G. W. Amarteifio, unpublished data, 1967). These people were largely from farming communities that practiced shifting cultivation in over 700 villages and one small town. There were

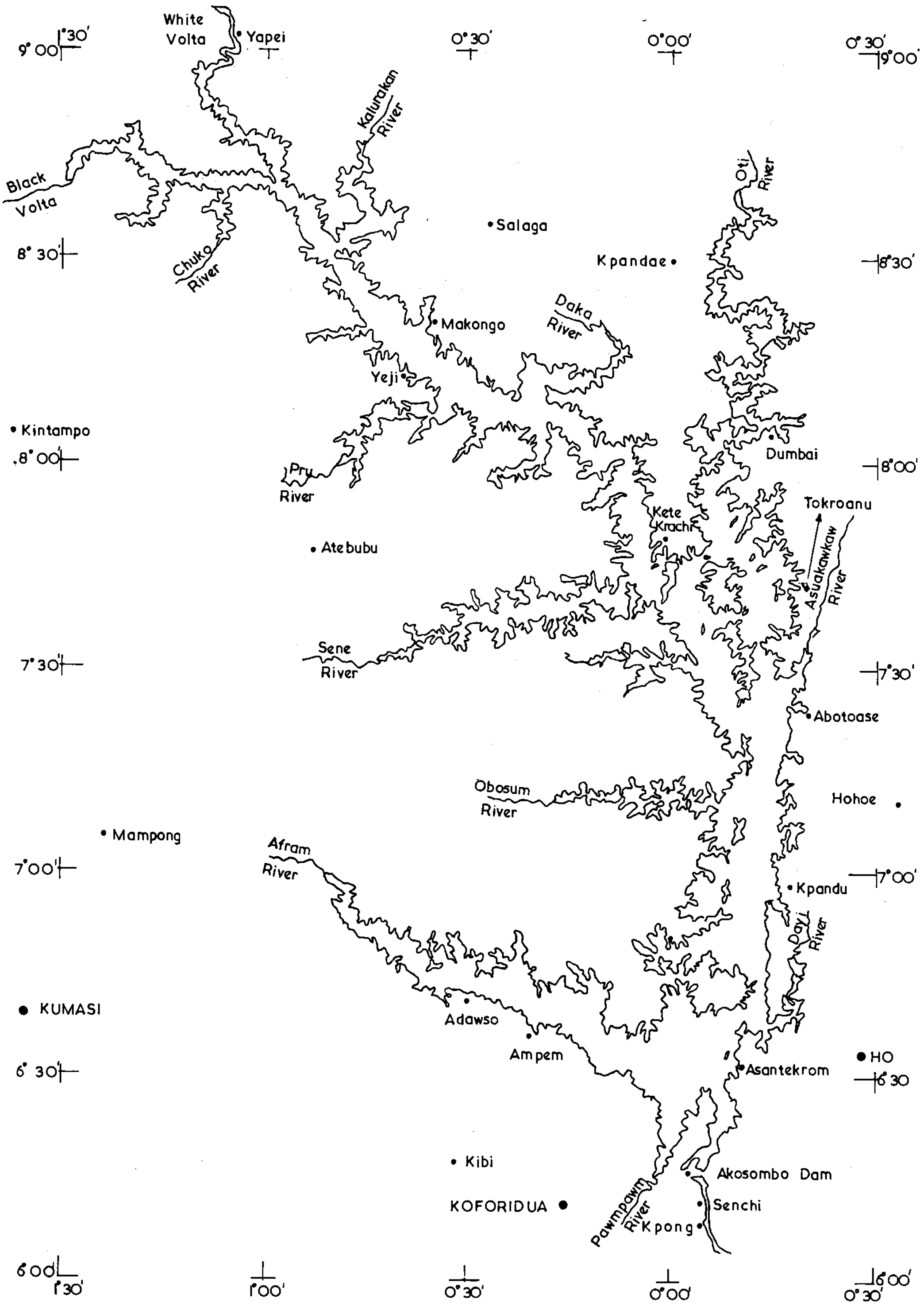
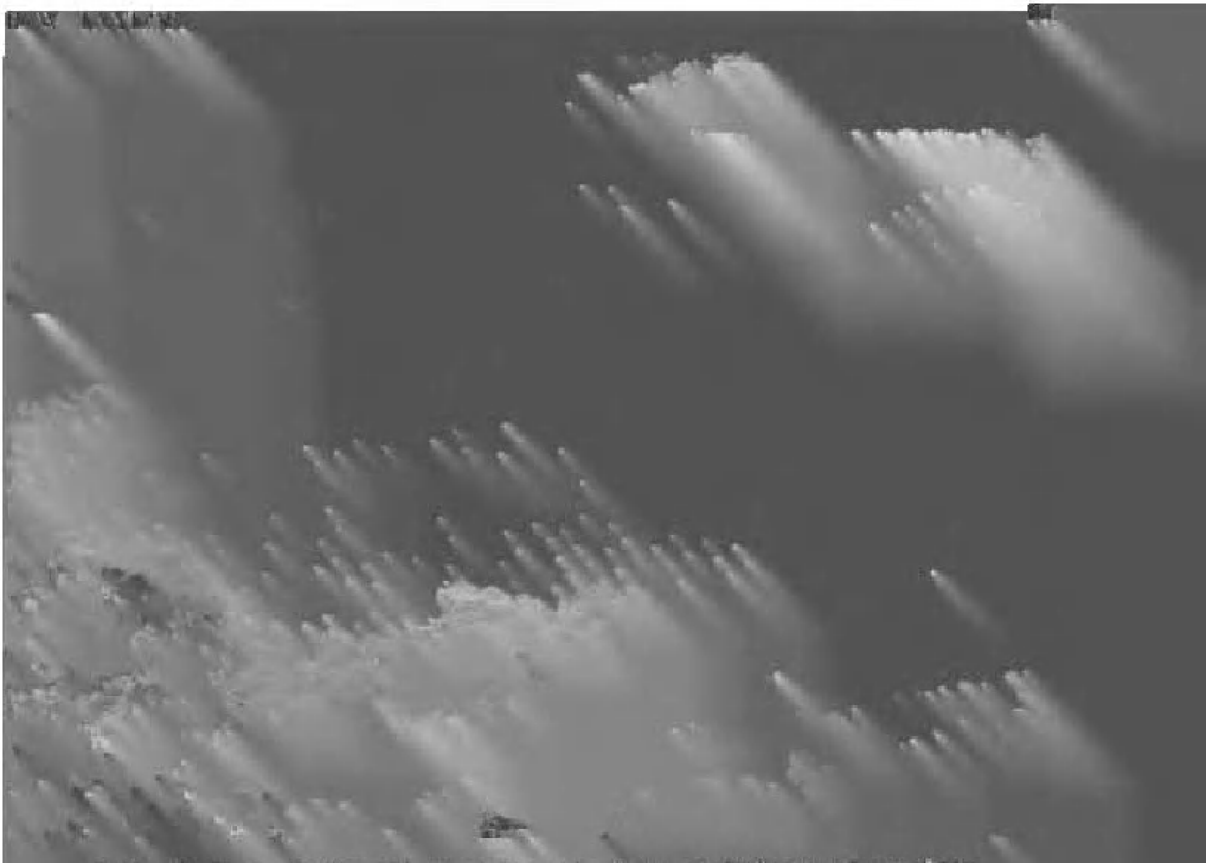


Fig. 1. Map of Volta Lake, Ghana.



[illegible]

[illegible]

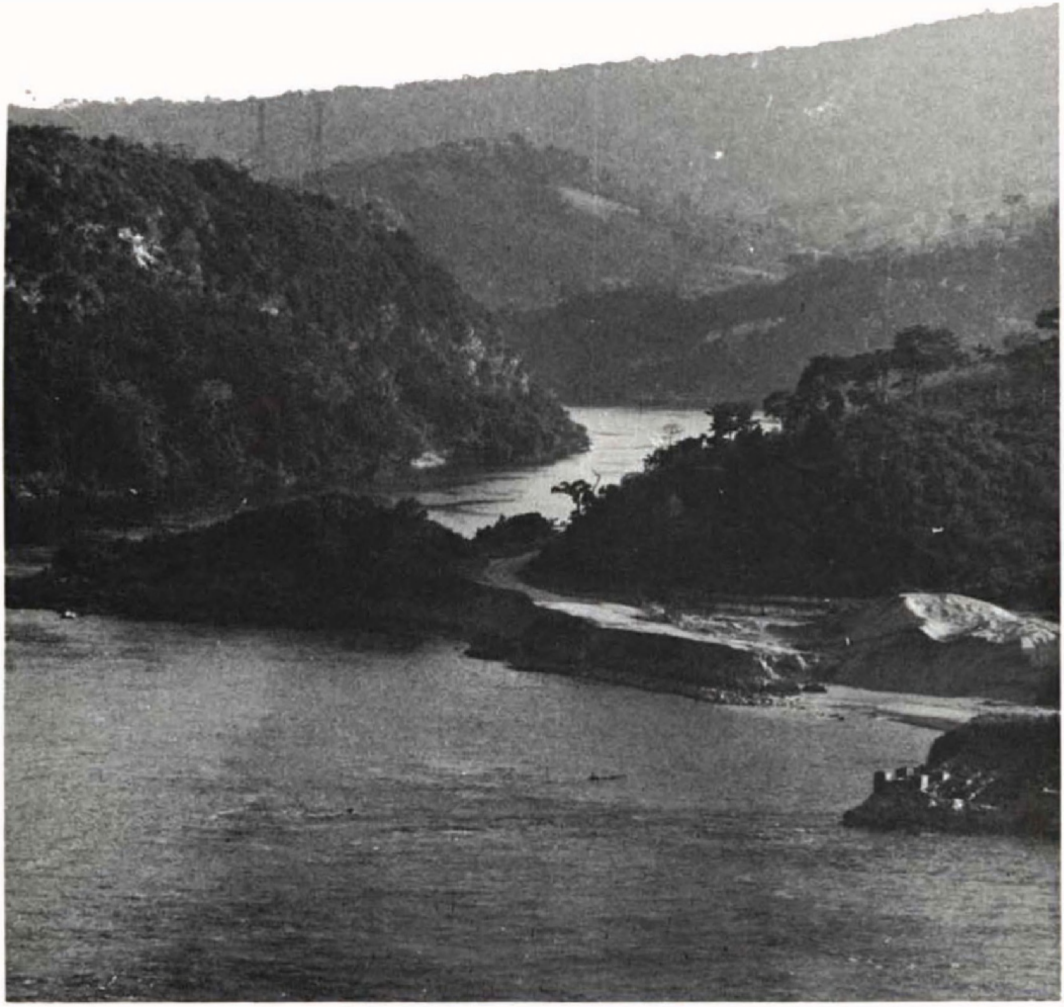


Fig. 3. Volta River immediately below the spillway. Photograph by Peyton Johnson (FAO).

for each settlement. Moreover, roads were built to each site so that, even where a public health assistant could not be stationed in a particular settlement, there would still be reasonable access to regional public health facilities.

Concern was felt for other public health problems. The movements of people could be expected to bring communities into new health environments that could result in outbreaks of various diseases. In particular it was expected that the lake would increase the breeding of the vector snails of bilharzia and thus increase the incidence of this disease. In contrast it was believed that the incidence of river blindness would probably drop because of the flooding of most of the rapids on the Volta River. These rapids were the breeding grounds of the vector fly *Simulium damnosum*. It was expected that remaining breeding sites below the dam could be controlled by the use of insecticides.

Concern was expressed for the fishing industry below the dam. This industry is largely based on creeks and lagoons filled during the annual floods. When the river was dammed, these floods would no longer occur. Another aspect of the industry on the lower river was the production of up to 4000 metric tons per year of the freshwater clam *Egeria radiata*. It was thought that the low flow of 150 m³/sec that would be maintained during the construction and early filling period would permit salt water to enter the river and that this salt water might kill the clams.

On the other hand it was believed that the fishing industry on the new lake would be a major industry. The optimum production from the lake was estimated to exceed 20,000 metric tons of fish. It was also expected that such a production level would require far more fishermen than would be available for a very long period.

ACTUAL CHANGES

When the dam was closed, the water level rose rapidly and started a whole series of hydrobiological changes. These continued well after the lake reached full size in the 1968 flood season. These changes naturally included an explosion of aquatic plants, fish, and other aquatic organisms. Water conditions have also continually changed. Initially, rotting vegetation on the lake bottom caused large deoxygenated layers that extended up close to the lake surface. With succeeding years these layers have become very much smaller (C. Czernin-Chudenitz, unpublished data, 1970).

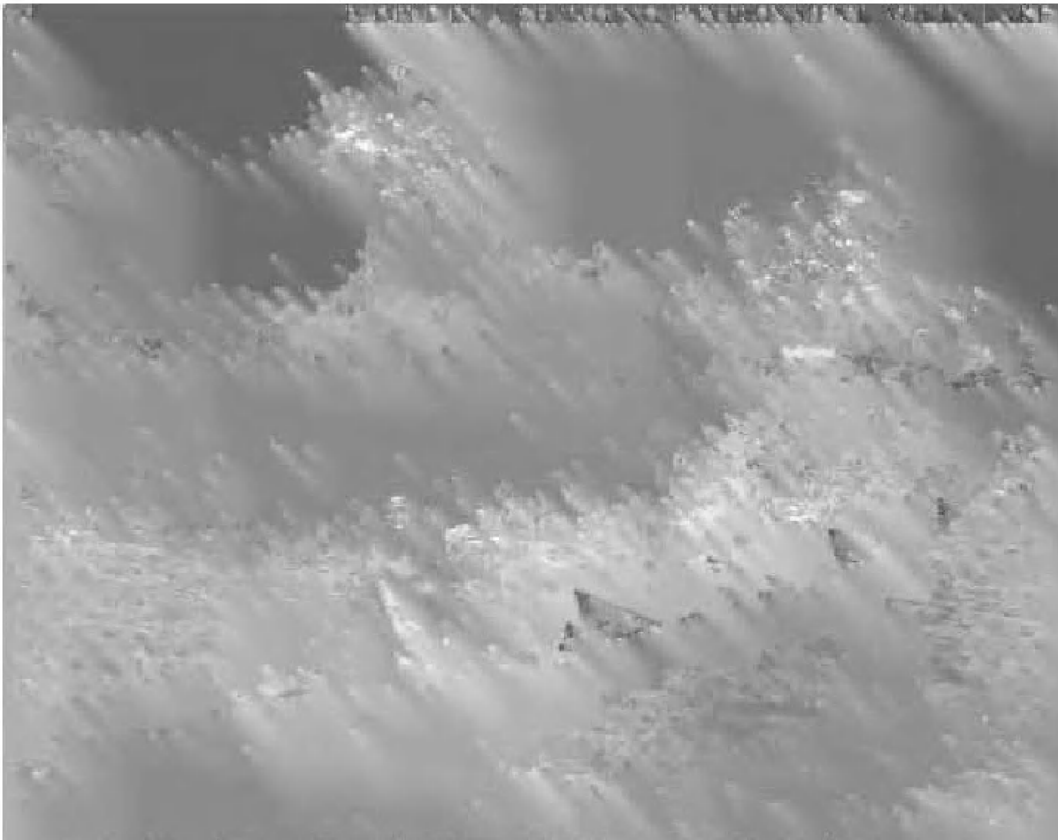
In the first years, floating aquatic weeds became abundant in some localized areas. These weeds caused concern because of their possible future increase, but in subsequent years the floating weed populations have become slightly reduced. Similarly, submerged weeds quickly became abundant, and in the initial years these weeds carried heavy populations of the vector snail of bilharzia. However, since 1968, there has been a decline in the abundance of submerged weeds and a large drop in the snail population. There have been continued changes and an increase in the production of weeds growing on the drawdown area exposed by the annual fluctuation in lake level.

Production of benthic organisms is relatively low, and there is a tendency for this level to decrease. Phytoplankton populations were originally very low. They have undergone very rapid increases but are still at somewhat low levels. Fish stocks have undergone many modifications with the changeover to more lacustrine conditions. Some of the more striking changes have been the buildup of large populations of small pelagic fish and of an important population of the predator *Lates niloticus*. Of the 120 species originally recorded from the Volta River (T. Robert, unpublished data, 1966), some 60 species are now entering the commercial catch, but 50% of the weight of these are the herbivorus *Tilapia* spp.

Contrary to expectations the fish catch very rapidly exceeded 20,000 metric tons (Figures 4, 5, and 6). A detailed study (P. Westaway, unpublished data, 1970) carried out in 1969–1970 located over 950 fishing villages, mostly newly established, along the shore of the lake. From these villages, some 12,500 fishing canoes and approximately 20,000 fishermen were operating, and the total population of the fishing communities was estimated as approximately 60,000 people. In the period from May 1969 to April 1970 a statistical survey of the fish catch of these fishermen gave a point estimate of 61,000 metric tons fresh weight equivalent (G. Bazigos, unpublished data, 1970).

As was expected, the creek fishing in the lower Volta has suffered, but the towns and villages of this area have had a wave of prosperity. Many people from this area have migrated to the lakeshore fishing villages and have spent some of their savings in their hometowns. New studies have shown that, contrary to being killed by saltwater inflow, the clams need at least a small salt content for breeding [*Pople and Rogoyska,* 1969]. Since the river now has a relatively constant flow, the zone of saltwater influence and therefore of the clam's breeding grounds is now far smaller. The clam industry is therefore declining but will not be wiped out.

In the settlements, events did not always go as planned. In all, 67,000 people elected to go to the official settlements, and the remainder opted for cash compensation. The physical movement of this very large number of people and their possessions was successfully carried out, owing in no small measure to a very effective social program. However, by 1968 a new socioeconomic survey (D. A. P. Butcher and E. K. Afriyie, unpublished data, 1970) showed that only 25,000 of the original settlers remained in the settlements. However, another 18,000 people were living in the settlements; these were newcomers or children born since settlement. The major cause of the exodus of the missing 42,000 settlers was the failure of the agricultural program; secondary causes were the movement of the relatively few fishermen settlers to the lakeshore and departures of those dissatisfied with the small number of rooms even in the completed settlement houses. Naturally, a small



[illegible]

[illegible]

[illegible]

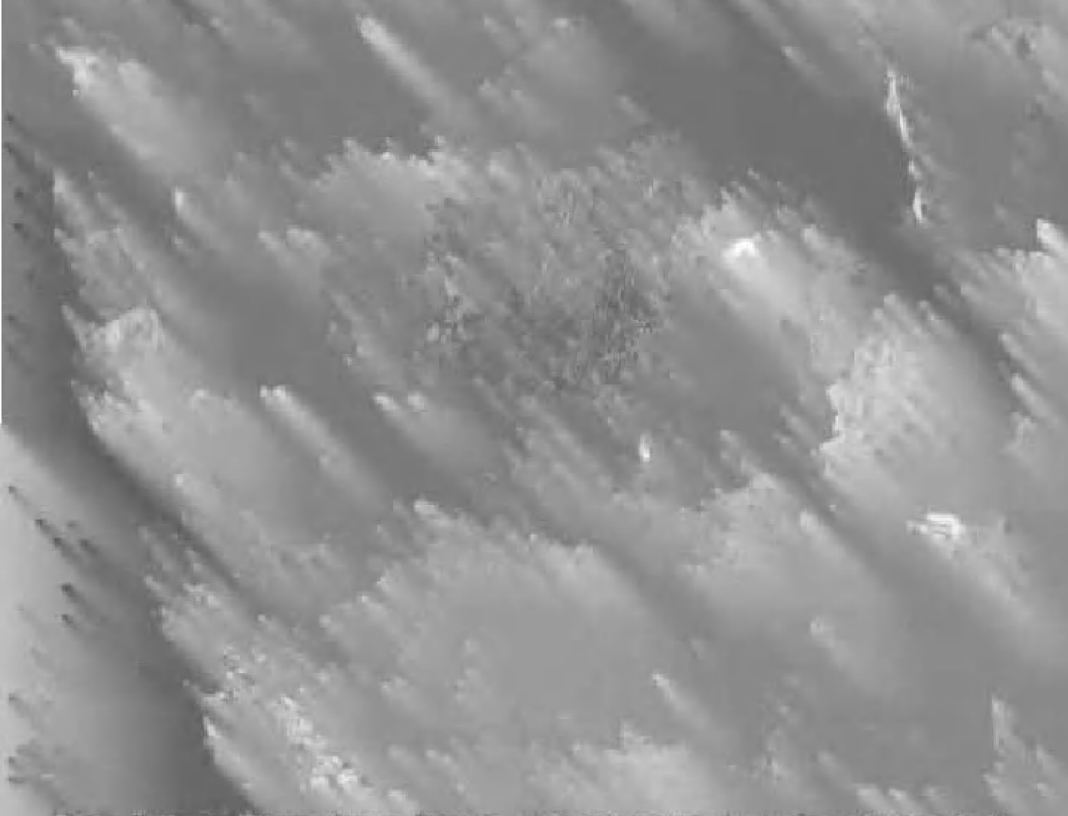
[illegible]

[illegible]

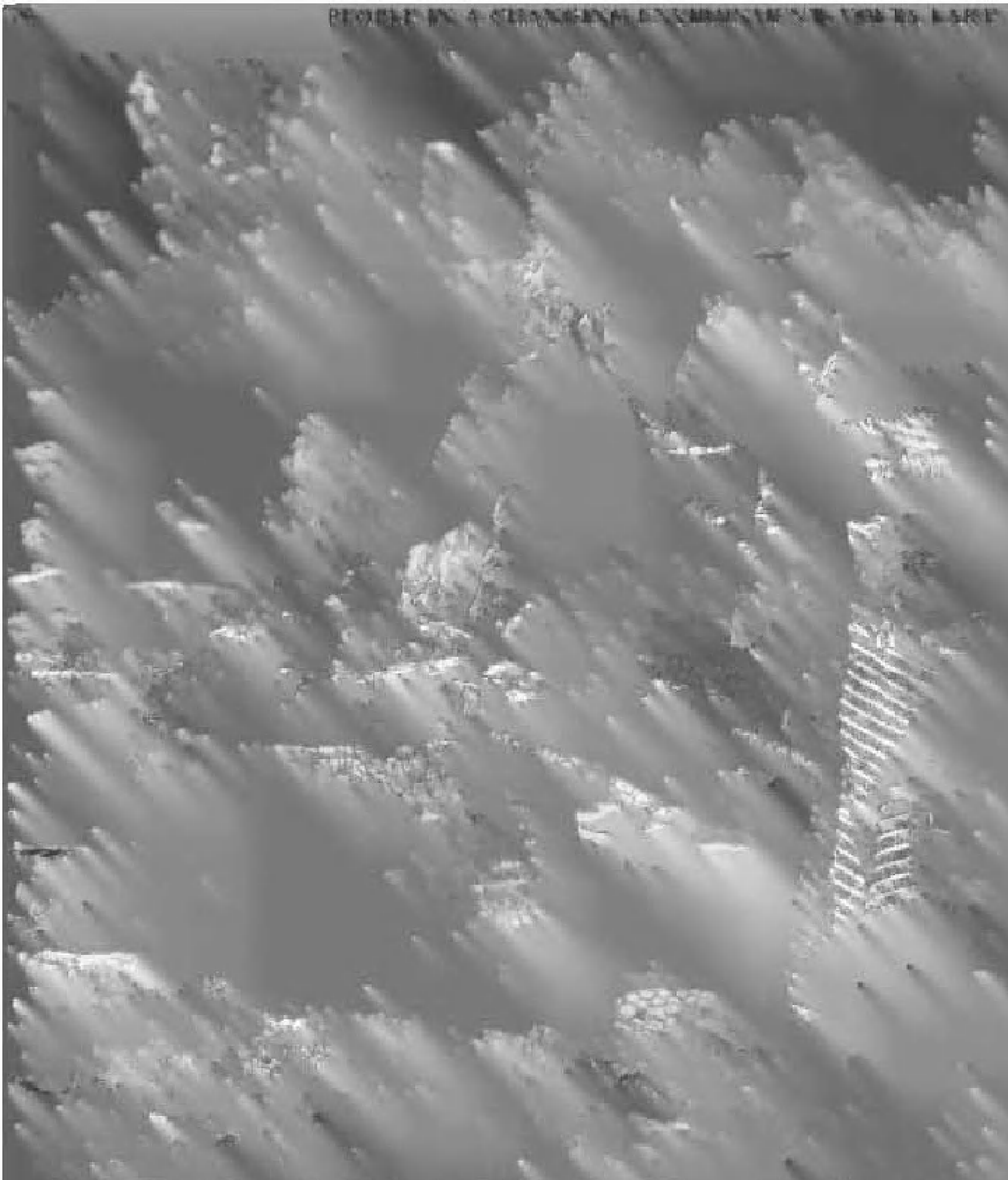
[illegible]

[illegible]

[illegible]



[illegible]



[illegible]

[illegible]

tiveness under Ghanaian conditions of the cash return from the fish catch. This return is estimated to be about N₵400 (N₵1 = US$0.98) per man employed in actual fishing. This category includes not only the master fishermen but also their assistants. Even after allowance is made for costs of fishing gear, this return is high under Ghanaian conditions. As a result, many traditional fishermen who had previously abandoned fishing and gone to work in towns or who had taken up farming have returned to their traditional activity. Such men included even many skilled tradesmen and school teachers.

In summary it can be said that the benefits of Volta Lake to Ghana have been increased and its disadvantages have been reduced by intensive preimpoundment planning. However, this planning would have been more effective if more stress had been given not only to the various physical and biological factors but also to the interrelationships of these factors with changing social and economic conditions.

REFERENCES

Pople, W., and H. S. Rogoyska, Salinity penetration up the Volta River during the building of the Akosombo Dam, *Ghana J. Sci., 8*,(1/2), 16, 1969.

Volta River Preparatory Commission, *Volta River Project, Report of the Preparatory Commission,* vol. 1 and 2, Her Majesty's Stationery Office, London, 1956.

Sociologic Aspects of Fishery Development on Volta Lake

D. A. P. BUTCHER
Volta Lake Research Project, Accra, Ghana

The Volta Lake fishery in the first few years after impoundment developed quickly, mainly owing to the efforts of the local fishermen. In a matter of 4 years the new lake covered more than 3% of the surface of Ghana, and a new and important fishery had been created.

The intention in this paper is to outline how a sociologist, using what might be termed a 'systems' approach, can set about understanding the working of a complex set of interrelationships between people, nature, technology, and money. In this case a fishery is the subject of study. It is hoped that in the attempt to isolate the essential elements an oversimplification has not resulted and that the basis for the prediction made on possible future changes in the system is sound.

The aim of the work program of the Volta Lake Research Project, of which this study forms a part, is to find methods of raising fish production to the maximum sustainable level. The important objective of raising the fishermen's standard of living is also desirable. With these objectives in view, little 'pure' research was embarked on, and in fact the scale of the job and the time available permitted study of only those sociologic aspects of direct relevance to the problem. One of the greatest challenges in this effort has been to discern and focus on that which is most immediately relevant.

VOLTA LAKE FISHERY

Volta Lake is large, having an area of 841,764 ha (3250 mi^2) and an estimated shoreline length of 4800 km (3000 miles). Details of its characteristics and history are given elsewhere in this volume. Except for a small proportion of land near the dam at Akosombo and some areas in the Afram arm, there was no tree or bush clearing in preparation for the filling of the lake. This lack of clearing has subsequently prohibited the use of moving fishing gear, and the principal gear has become multifilament nylon gill nets. However, long lines are also extensively used to catch the lungfish (*Protopterus annectens*) along the beaches and the Nile perch (*Lates niloticus*) in deep water. Traps are used in conjunction with palm branch leads (fences) in some areas, and cast nets are used mainly to catch live bait for the long lines.

The fishing unit is a master fisherman, or adela, in a flat-bottomed board canoe that is 6–9 meters (20–30 feet) long and that is usually measured by the number of 3.66-meter × 30.48-cm × 2.45-cm (12-foot × 12-inch) boards used in its construction. Nine boards is the mode, and the average cost of this type of canoe is N₵40 (in 1970 1 new cedi, N₵1, equaled US$1.40). However, for open water work, 13-board canoes are used, and the average cost of such a canoe is N₵75. The canoes can be paddled for short journeys of 5–15 km (3–10 miles) to fishing grounds by one man. The narrowness of the canoe (90 cm, or 3 feet) enables the fishermen to penetrate the dead trees where most nets and other gear are set. One fisherman in two has an assistant, or adegbovi, and one in seven has a junior assistant, or wudomevi, whose main task is bailing water.

A fisherman owns an average of 17 multifilament nylon gill nets totaling 30 units of 92.9 m^2 (1000 ft^2), although only rarely are all set at the same time (G. T. Taylor, personal communication). The most common manner of setting the nets is to tie the ends of the head rope between the emergent branches of two dead inundated trees. As the head rope is thus stretched, it is made shorter than the foot rope to avoid distortion of the net. Each net is usually supported by a single bamboo float in the center.

Before impoundment, some 1200 fishermen lived along the old Volta River and its tributaries, some of which are now covered by the lake. These fishermen were of the Ewe subtribe, known as Tongus, from the lower Volta. Their principal gear was traps, hooks, cast nets, and seines. According to one estimate the value of their annual catch was US$125,000 (P. Westaway, unpublished data, 1970).

By 1970, there were about 12,500 fishermen living with at least part of their families in more than 1000 villages built by the people themselves around the lake. The estimated population in these villages is >60,000 people owning about 12,000 canoes. The annual rate of catch by 1969 had risen to an estimated 60,000 metric tons valued at US$8,000,000 (G. Bazigos, unpublished data, 1970). The dominant tribal group is still Tongu, although there are a large number of Adangbwe and some Anlo Ewe and Hausa. The report of the *Volta River Preparatory Commission* [1956] estimated that the fish production would reach at least 6 metric tons per 2.59 km^2 (6 tons/mi^2) but that it would not reach this figure for some time, since production would be limited by the number of Tongus available for fishing. The 1969 rate of catch as given above exceeds 7 metric tons per square kilometer.

The Tongu fishermen nearly all have the ambition to build a fine house in their hometown with cement block walls and a sheet aluminum roof. Secondary ambitions are to save capital to open a shop and to give their children a good education. There is, of course, a tendency to buy transistor radios, sewing machines, and other manufactured goods, but it is the former more costly venture that provides the incentive for fishermen to keep working after their simple needs have been met.

FISHERMEN

Recruitment of land-owning fishermen to the fishery is of two main types: (1) young men working as adegbovis use their share of the profits to set up on their own; or (2) people working as employees on cocoa farms, as labor on building jobs, or as clerical workers save enough capital to start fishing. In mid-1970, there was a significant number of former school teachers and clerical workers who had returned to the traditional type of work of their forebearers because the financial rewards of fishing on the lake had become so attractive. The importance of this return to village life of such educated people will in the long run have far-reaching consequences for the development of the country.

In some of the fishing villages, ex-teachers have started classes in literacy for adults and children and incidentally pass on some of the ideas and values gained from life in cities; thus, in the early years of socialization, some village children will gain more modern values and ideas than heretofore. Instead of village homes' perpetuating traditional values, many of which are incompatible with development and which formal education does not later change easily, a feedback loop is established. Should educated men and women continue to return to the villages, then the chain of traditionalism would be broken, and a dynamic type of social change would arrive. The value would not necessarily be in the injection of new ideas per se but would be in the inculcation of the concept of change itself, which in turn produces a new type of self-awareness and the possibility of the objective evaluation of new ideas and the initiation of change by the people themselves. Such a trend is far more important to the development of a country than the introduction of any number of factories or industrial techniques in my view.

The same 60,000 people directly connected with the fishery have built some 1000 villages around the lakeshore. Carrying their belongings with them in their canoes, they have settled in all areas of the lake. Using the corrugated metal roofing sheets brought with them (56%) together with local grasses to build their houses and mud to make fish-smoking ovens, the communities are entirely self-supporting and in addition earn a relatively good income estimated at N₵700 a year on an average per canoe. The vast majority of the villages are accessible only by water and have no public or other outside services provided; nevertheless, the people appear on the whole to be strong and healthy.

The houses are quite small, having an average of 2.15 rooms and an open kitchen; more than half of them have a porch or shelter where people sit, talk, and mend nets. A characteristic of Tongu villages is the scattered form of the village layout; there is a distance of 50–100 meters between each compound. The people's explanation of this layout is that there would be quarrels and conversations would be overheard by neighbors if the houses were built closer together. This individualism appears to be typical of the Tongu ethos and is carried into economic activity as well.

Each compound houses an average of 5.88 people, usually a man and his wife or wives, his children, and perhaps a young brother (an adegbovi). The overall sex ratio is 1 man to 1.34

women and, in the 15–50 age group, 21% of the men are surplus above the number of women of the same age group. In addition, only 4.7% of the population are over the age of 50. Villages tend to be dominated by people from the same hometown, and most of them are related to one another.

Tongu society cannot be said to be synonymous with the society of the lakeside villages. The lake Tongus are a part of the wider society with its heartland in the Tongu traditional area in the lower Volta. The absence of the elderly and the preponderance of males indicate an active population at the lakeside, most adults having an active work role in the fishery.

DIVISION OF LABOR

The method of operation and the division of labor are fairly standard. Most of the fishing is carried out by the men. An adela goes out at about dawn in his canoe with his adegbovi to visit the nets. Depending on the distance away, the number of nets set, and the number of fish caught, this trip takes from 2 to 6 hours. On his return to the canoe beach of the village or fishing camp, the fish are scaled and gutted and taken to the house where the wife puts them in the smoking oven or prepares them for sun drying. At present, menfolk spend an average of 8 hours a day on activities directly connected with fishing and 1.2 hours a day on farming.

Tongu fishermen have a clear concept of the various roles crucial to the industry. The term adela for the master means hunter, and adegbovi means hunter's assistant. The use of the same term for a fisherman reflects the confidence in knowing where to set nets; thus it is possible to say that the fishermen are 'stalking' the fish rather than setting nets randomly.

The processing and selling of fish are also distinct roles. A married fisherman assigns the roles to his wife, but a single man may hand the fish to his mother, a sister, or a friend to cure for him. Adegbovis are usually unmarried and have neither the money nor the status to have a wife; casual liaisons with women are one of the great attractions of visits to local markets.

The various roles are rewarded according to variation on a basic principle. When a woman is processing the fish for an adela and adegbovi, the running expenses of food, gear, and boat are paid for out of fish caught. Some fish are consumed, and others are bartered for food crops, milk, cigarettes, and so on. Money from the fish sold pays for new gear and mending twine. In all, about 1.8 kg of fish per adult per day is sufficient for running expenses.

At agreed intervals (i.e., half-yearly, yearly, or on the departure of an adegbovi), a reckoning is made, and the profits over and above running expenses are shared. The profits are often divided into shares for the adela, adegbovi, and woman on a 4 : 2 : 1 basis. Since there are no hard and fast rules, there is considerable variation. Sometimes the woman is given a lump sum and not a share as such. In other instances the shares are on the basis of one for the canoe, one for the gear, and one for the adegbovi.

A common practice among the Tongus with more than one wife is for one woman to process and sell all the fish for 1 year. The same wife will cook and generally look to the domestic needs of the fisherman and his assistant(s). On receiving her share of the profits, the woman is free to travel about and then usually trades in fish, clothes, or provisions. It is not uncommon for the husband to provide a canoe to assist the wife in trading, although he may want a share of the profits. During the woman's absence a second wife carries on the role of cook, fish processor, and seller for 1 year. A man with only one wife naturally keeps her with him all the time.

The fishing conditions at present (1969–1970) vary greatly according to the time of year, the best season being from August to February when the rains bring turbid water, nutrients, and other matter into the lake. There is also a monthly cycle in which most fish caught by multifilament gill nets are on dark nights but not on bright moonlight ones, especially when the water is clear.

Although there are varying demands on time and labor with seasonal peak periods, there is still time each month for farming, which becomes more important when the fish catch goes down. Profits from farming are much lower than those from fishing, but farming is a more profitable use of time than setting nets when the catch rate is very low. Farming can be looked on as a buffer activity that occupies surplus labor at slack times and also gives the fishermen an income for a small investment in labor and seed.

SYSTEM AND THE DIRECTION OF CHANGE

The system shown in the diagram (Figure 1) is an open one. The demand for fish in the various

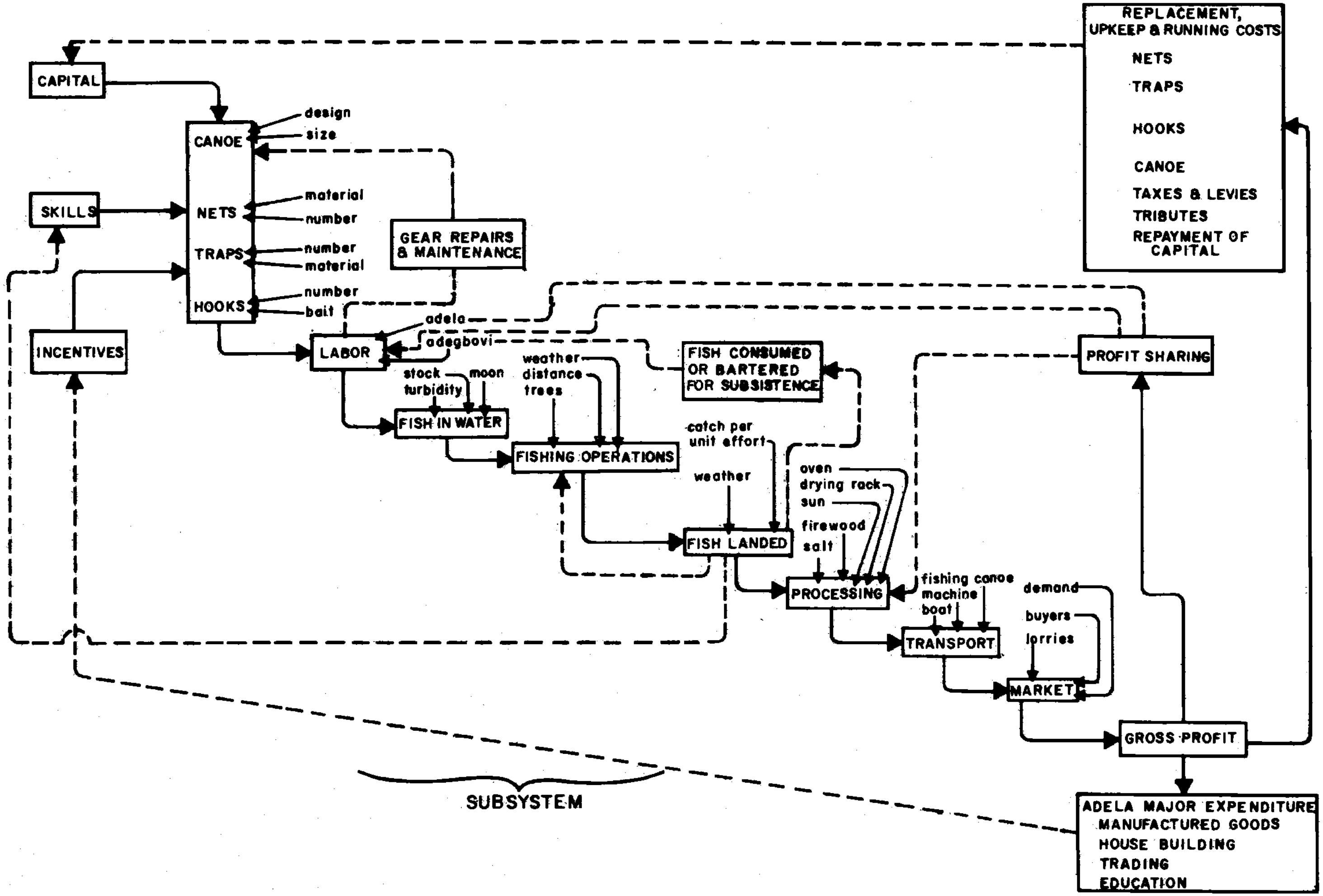


Fig. 1. Model of fishing 'system' on Volta Lake.

urban centers, the supply from the marine fishery, and the imported fish will have an effect, since they are all part of a more general and wider system. Similarly, the hazard of ill health and accidents can affect the system directly. In the boxes are the various inputs, events, and activities (unlike a Pert diagram) that are parts of a system of operations leading to the production of fish and the maintenance of the system. The small arrows entering the boxes indicate key variables affecting the contents of each box, many of which are not under the direct control of the fisherman but are instead the constraints imposed on him by nature or technology. The dotted lines indicate feedback loops, both short and long term. (For example, a fisherman has the long-term goal of making enough money to build a house, educate his children, and so on. However, this goal is dependent on several short-term loops such as the upkeep of gear and the size of the fish landings.)

The fishery system is truly self-governing, and changes in the quantity of fish landed produce new points of equilibrium mainly through changes in organization [*Emery,* 1969]. For example, the subsystem that maintains the adela, the adegbovi, and the woman is easily maintained when there is a surplus of fish caught and sold. But during the 3-month period before the heavy rains the catches are so small that it is neither advantageous to the adela to keep his adegbovi nor advantageous to the latter to stay on since he is not saving any money and is only existing.

To raise the productivity of the work team is not even a question of buying more nets or other gear. The quantity of gear is limited by the energy and time required for the tasks of setting, removing fish, removing gear from the water, and repairing and cleaning nets. Extra hands are required but can neither be attracted to the work nor paid when the catch rate is low. In the early days of the lake's formation, one adela could have up to six adegbovis and three canoes. But as catch rates dropped, the burden of the additional boats, gear, and labor could not be maintained.

The problem of increasing the productivity of the fisherman hinges on the catch per unit of effort whether the gear is gill nets, traps, or hooks and long lines; increasing the number of gear in use when catch rates are low will not increase productivity. Although traps made of chicken wire catch more than those made of bamboo, the difference is perhaps not great enough to offset the cost of wire. The limitation on the number of long lines is catching enough live bait. The use of an outboard motor cannot be justified with the size of the present canoes, the amount of gear used, and the catch rate, especially since fishermen usually live immediately adjacent to the fishing grounds. Some fish are lost through spoilage in the nets on occasions when the water is too rough for the canoes to be used to visit them, and a more seaworthy boat would be desirable. However, such a boat is likely to be heavier and to require more people to propel it, and the same problem of rewards and profits arises.

The most effective way of increasing production is to increase the catch per unit effort by using new types of gear, as the fishermen's actual techniques are considered to be very good. So far, project trials have proved that monofilament nylon gill nets catch at least twice as much fish as the multifilament nylon of the same area. (The Volta Lake Research Project carried out experimental field trials of monofilament nets during May–August 1970 and used multifilament nylon as the control. All fishing was done by local fishermen according to their normal practices. The net was so successful that some of the remaining project stock of monofilament nets were stolen and sold for 5 times their value.) The advantage of the monofilament net is not merely that it catches twice as much as the gear in general use but that it catches consistently all the time. As a result, seasonal variations in the fish landings due to the presence of turbid water in the rainy season accompanied by a relatively high catch rate and clear water conditions and a low catch rate in the dry season will disappear. Similarly, the variation in catch over the lunar cycle is smoothed, and in fact the monofilament nets appear to catch more on bright moonlit nights than on dark nights.

EFFECTS OF CHANGE

The general use of monofilament nets could enable the fishermen to approach the maximum sustainable catch by organizational changes with no direct costs to government. As a result the following would be expected:

1. More fishermen will take an adegbovi.
2. Fishermen will be able to keep the services of their adegbovis over the whole year, and in turn the adegbovi's share of the profits will enable him to set up on his own more easily.

3. The use of larger, more seaworthy boats operated by more men will become an economic proposition, or, alternatively, one man with a small outboard will be able to tow a number of the canoes and drop them at different points (this system is already being used by one man in the north where catch rates with multifilament are comparatively high).

4. When the flow of fish to the markets is steadied, the prices will become more stable, and the fishermen will be less at the mercy of the wholesale fish traders.

The effects of increased fishing efficiency could be far reaching. More cement block houses might be built (the desirability of which is questionable). More money would be spent on the education of children, some of whom would return to fishing and would speed up the process of 'detraditionalism' as already discussed.

The danger that traders will supply boats and nets to fishermen paid as labor is not likely to become widespread, owing to the individualism of the Tongu Ewe and the need for owner-operator supervision. The possibility of local councils and chiefs putting high taxes on boats and sales of fish may in fact make operations difficult for the fishermen but will not stop them from fishing.

CONCLUSION

If the fish-producing capacity of Volta Lake does not become a limiting factor, the general use of monofilament nets could theoretically double the annual weight of the catch. This theoretical prediction is not made on the assumption that every fisherman (adela) will double his catch or that the number of masters, or adelas, will increase. Monofilament webbing, with its high catch rate, could enable one adela to use his skill and knowledge to direct more adegbovis, or apprentices, on where to set nets. In addition to more assistants being employed generally, more young men will in fact be under training in the art of fishing.

A secondary effect of increased fishing efficiency could be a decline in the importance of farming (the buffer activity) by fishermen and an increase in the demand for food crops produced by other men at present not supplying the fishermen with food. A further secondary effect might take place in the cooperatives that have been formed in a number of places. These cooperatives are barely viable with existing catch rates, because one man can do better on his own than he can as a member of a group since not all the members may be as skillful or hardworking as he. No undue difficulty in processing an increased catch is foreseen, as more of the female Tongu will move to the fishing villages. This move may perhaps regularize the ratio of men to women.

REFERENCES

Emery, F. E. (Ed.), *Systems Thinking, Penguin Modern Management Readings,* Penguin, Baltimore, Md.. 1969.

Volta River Preparatory Commission, *The Volta River Project,* vol. 2, *Appendices to the Report of the Preparatory Commission,* p. 228, Her Majesty's Stationery Office, London, 1956.

Early Development of the Fish Populations and Fisheries of Volta Lake

WILLIS A. EVANS AND JOHN VANDERPUYE
Volta Lake Research Project, Akosombo, Ghana

DESCRIPTION OF VOLTA LAKE AND ITS FISHERY

Volta Lake, Ghana, was formed as a result of the closure of the dam on the Volta River in May 1964 that produced a water body with a surface area of 8482 km^2 (3275 mi^2), a storage capacity of 164.8 km^3 (120 million acre-feet), a shoreline length of 4828 km (3000 miles), a maximum depth of 70 meters (230 feet), a mean depth of 19 meters (63 feet), and an annual fluctuation in level between 2 and 4 meters. The basin was not cleared of bush or trees before flooding, and their presence has had considerable influence on the limnology and fishery of the lake.

The transformation of the former river into a lake and the concomitant expansion in the fish population have offered occupational opportunities to a large number of people in the lake region. It has been estimated that as many as 20,000 people were engaged in fishing in 1970.

Owing to the presence of the flooded trees and brush, the main fishing gear is static; gill nets are by far the most important, but traps, cast nets, and lines are also used. More than 900 fishing villages have been recorded, well scattered around the lake. The principal fishing craft is the plank canoe, of which there were an estimated 13,000 in 1969 (G. Bazigos, unpublished data, 1969). To prevent spoilage, which can occur rapidly, the fish are mainly dried or smoked, and some are salted. After preserving they are transported to several major market ports by large canoes and are then loaded on trucks and distributed to towns within a 160-km (100-mile) radius of the lake. Catches consist principally of *Tilapia* spp., Nile perch (*Lates niloticus*) and *Labeo* spp. being of secondary importance. Fishing activities are continuous all year, but the largest quantity of fish is taken during the wet season of heavy runoff and turbid waters (April–October). The estimated total catch of fish for the year 1969 was about 60,000 metric tons, which yielded about $6,000,000 (G. Bazigos, unpublished data, 1969).

RESEARCH METHODS EMPLOYED

An initial question was whether the fish stocks were being overfished or underfished. After a brief reconnaissance survey of the lake and an examination of the limited data available, it was concluded that Volta Lake was not being overfished; this conclusion has not been changed by subsequent information (W. A. Evans, unpublished data, 1969). Factors considered were the environment, the fishery, the species composition of the commercial catch, and the biological characteristics of the principal species, *Tilapia*.

The main evidences used to support the premise that overfishing was not occurring were the following.

1. The lake is very large, and there was light fishing intensity per unit area. The fishery was largely limited to waters within 1000 meters of shore, and the fishing intensity was estimated to be eight fishermen and four canoes per 1.6 km (1 mile) of shoreline.
2. The extensive littoral zone had a varied fish fauna, some species of which were little exploited.
3. The fishery was based on individual fishing effort with gear of low efficiency. Efficient moving gear such as seines and trawls could not have been feasibly employed at the time of the survey.
4. The large-mesh gill nets in common use were selecting mainly adult fish, which have normally spawned several times prior to capture. When the lake was first formed, the most common gill net mesh size was 8-cm (3-inch) stretched mesh. The principal mesh size in use steadily increased until 14 cm (5½ inches) had become the most common by 1969.

5. Abundant submerged trees inhibited the harvest of fish. To avoid damage and loss of gill nets from unseen submerged trees, fishermen mainly used waters of <5 meters deep. Thus an extensive area of 'fish refuge' existed.

6. *Tilapia,* the principal species in the catch, became unavailable to the prevalent methods of fishing for approximately half of each year. The *Tilapia* catch underwent a decided decline and became so poor that some fishermen discontinued fishing. It is believed that the *Tilapia* at this season move offshore into deeper water and are thus not readily available.

It was concluded early that the conventional methods of stock assessment as outlined by *Gulland* [1969] were not applicable to the conditions existing in Volta Lake; direct estimation of the size of the fish stocks was not deemed to be feasible. Efforts were therefore made to determine the level at which the fish stocks could be safely harvested (W. A. Evans and J. Vanderpuye, unpublished data, 1969) without knowledge of the total size of the stocks. The conclusion reached was to encourage expansion of the fishery, inevitably a slow process. At the same time it was planned to acquire base line data from which to gage the changes that might take place in the stocks as the fishery developed and as the environment changed. By this means it was believed that maximum use under existing circumstances could be realized and that at the same time a warning system could be established to monitor whether optimum levels were being reached and not exceeded. This system involved close observation of changes in size frequency distribution of the fish caught (by species) in the different mesh sizes of the gill nets, catch in relation to effort, and species composition. To implement this system, both the fish population and the commercial harvest were, and would continue to be, sampled on a quarterly basis. Under such a surveillance system, many warning indicators would have to be ignored over a period of several years before any serious damage to the stocks from overfishing would occur.

Paralleling stock assessment operations, a catch record system was also established for the commercial fishery. By the combination of data from the two sources the emergence of adequate guidelines was anticipated for proper management of the fishery. Although only 2 years have transpired in this effort, valuable experience and information were gained.

The fish stock–sampling plan involved the use of gill nets, mainly monofilament, of various mesh sizes because, as was indicated previously, the submerged trees and brush precluded the use of other types of gear. The lake was divided into eight areas, and sampling stations were established in each (Figure 1). Normally, in each area, one station was located on each side of the lake inshore, and one station was located offshore in deep open water. At planned intervals a battery of 45 gill nets was fished for one night at each inshore station, and a battery of 30 nets was fished at the offshore station. One area in the northern half of the lake and one in the southern half were chosen for more detailed sampling. Here the number of stations was doubled, and each station was sampled for two nights instead of one.

To sample each of the 30 stations (a complete round of the lake) required approximately six boat trips of 7–10 days each. Thus a round of the lake could be completed once every 3–4 months. The large research vessel normally took a team of three crew members, three fishermen to set the nets, a technician to assist in recording the data, and a senior fishery scientist.

The gill nets used were 30.5 meters (100 feet) long but of three different depths: 1.5 meters (5 feet), 3 meters (10 feet), and 9.1 meters (30 feet). All nets were hung on a 50% basis. Each size group comprised 15 nets ranging from 14-mm (½-inch) stretched mesh to 203 mm (8 inches) at 14-mm (½-inch) intervals. Each group of nets at an inshore station was fished from surface to bottom in waters corresponding to the net depth. Thus one line of nets was fished in 1.5 meters of water, another in 3 meters, and the third in 9.1 meters. In offshore areas, nets were fished at the surface only. All nets were set in the afternoon and recovered the following morning. The catch of each net was placed in separate sacks and brought to the research vessel for recording of species, length, weight, sex, and stage of sexual maturity.

By October 1970 the preliminary survey and three sampling rounds of the lake had been completed, and the data for preliminary survey and first round had been analyzed (W. A. Evans and J. Vanderpuye, unpublished data, 1969, 1970). In addition the total catch figures from the survey of the commercial fishery were available at this time (G. Bazigos, unpublished data, 1970).

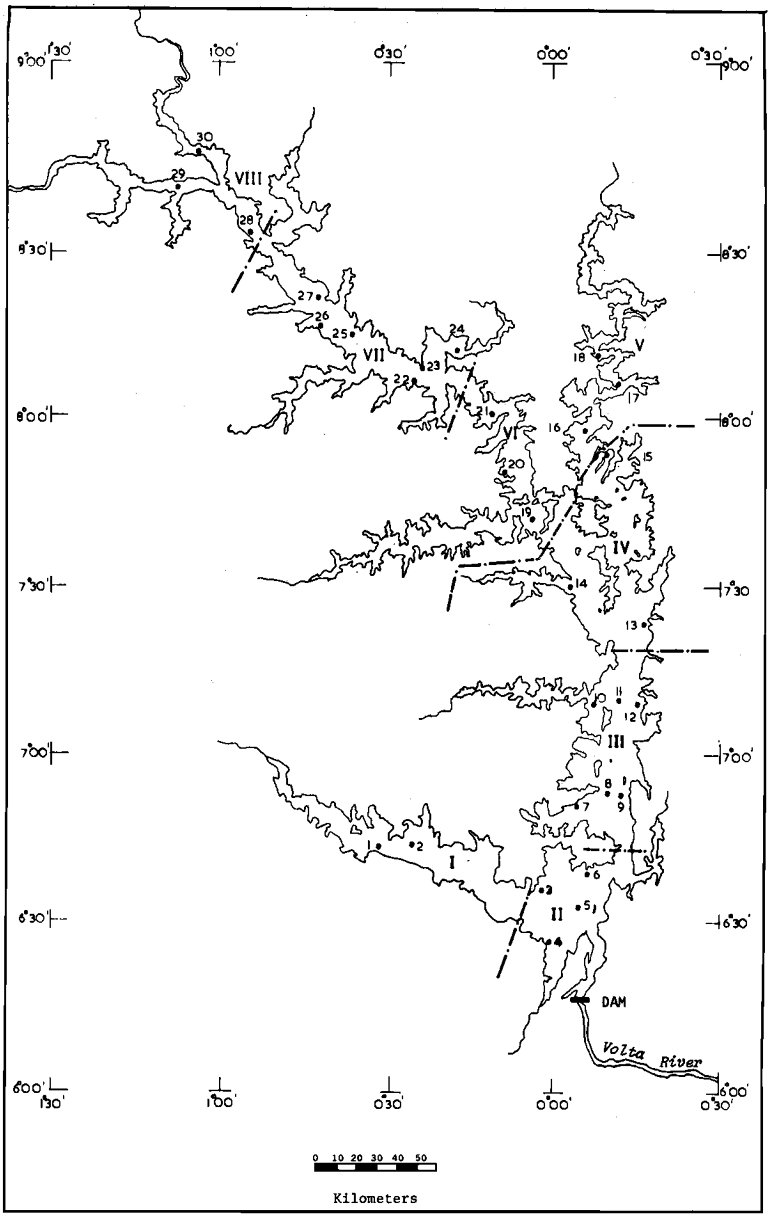


Fig. 1. Fish population sampling stations, Volta Lake, 1969–1970. The roman numerals indicate the eight stock assessment areas. The dots numbered by arabic numerals mark the experimental fishing stations for stock assessment.

RESULTS

Changes in the fish stocks. Changes in the fish populations were noticed from the beginning of the lake. The rainy season, which immediately followed the closure of the dam in May 1964, saw the creation of the initial impoundment. With the decay of the flooded vegetation, expected fish kills, which were associated with oxygen depletion, occurred. A variety of fish was affected, especially *Chrysichthys* spp., which proved to be very sensitive to oxygen depletion [*Petr,* 1968]. Since then the dissolved oxygen situation has steadily improved to the point where 79% of the water mass was suitable for fish life in 1970 (C.

TABLE 1. Comparison of the Clupeid Population with That of All Other Fish in Volta Lake Based on Catch per Standard Gill Net Unit

	Number	%	Weight, kg	%
	May to Oct. 1969 (Wet Season)			
Clupeids	823,980	96	1169.480	44
Other fish	37,297	4	1485.340	56
Total	861,277	100	2654.820	100
	Dec. 1969 to May 1970 (Dry Season)			
Clupeids	145,122	73.01	261.409	17.31
Other fish	53,638	26.99	1248.358	82.69
Total	198,760	100.00	1509.767	100.00
	July to Sept. 1970 (Wet Season)			
Clupeids	240,994	84.8	454.732	24.5
Other fish	43,072	15.1	1399.210	75.4
Total	284,066	99.9	1853.942	99.9

W. Czernin-Chudenitz, unpublished data, 1970).

The year following initial impoundment saw further changes and reflected the shift from riverine to lacustrine habitats. Certain species (such as those of the genera *Labeo* and *Chrysichthys* and *Alestes nurse*) were originally quite abundant in the southern part of the lake; they soon became greatly reduced in this area but continued to be abundant in the northern part of the lake, where riverine influence persisted. Their place in the southern part was largely taken by *Tilapia galilaea*, which thrives in lacustrine environments. Perhaps an even more spectacular change was the initial lake-wide expansion of the mormyrids during the first few years, followed by their near disappearance even from the northern part of the lake. Apparently, their dependence on a riverine habitat was quite specific. The open water expanses of the lake have been occupied mainly by two species of clupeids, as well as by *Eutropius niloticus* and *Physailia pellucida*. The populations of these species expanded rapidly until in 1970 they comprised the major ichthyomass of that portion of the lake sampled by gill nets. Other fish such as *Lates niloticus* and species of *Labeo* and *Distichodus* also underwent noticeable expansion.

Present species composition. By 1970 the two species of clupeids, *Cynothrissa mento* and *Pellonula afzeliusi*, were the most abundant elements of the fish fauna (Table 1). They comprised about three-fourths of the fish population by number and at least one-fourth by weight. Despite their wide distribution throughout the lake, they were little used in 1970, but they hold promise for future fishery development.

To portray the 1969–1970 fish population in as simple a manner as possible, the important elements of the fish fauna have been divided into four categories according to principal feeding habits: aufwuchs and detritus herbivores, piscivores, semipelagic omnivores, and benthic omnivores (Table 2). According to these groupings the composition of the experimental gill net catches for the first three complete rounds of the lake stations is shown in Table 3.

The most important group was the semipelagic omnivores, which consistently comprised by this sampling method about 99% of the fish population by number and approximately half of the ichthyomass. Other than the clupeids the important semipelagic forms were *Alestes* spp. and the schilbeids, all of which are mainly abundant in

TABLE 2. Classification of Common Fish of Volta Lake on the Basis of Principal Food Habits

Aufwuchs and Detritus Herbivores	Piscivores	Semipelagic Omnivores	Benthic Omnivores
Osteoglossidae	Polypteridae	Clupeidae	Mormyridae
Heterotis niloticus	*Polypterus senegalus*	*Cynothrissa mento*	*Hyperopisus bebe*
Distichodontidae	Gymnarchidae	*Pellonula afzeliusi*	*Mormyrus* spp.
Distichodus spp.	*Gymnarchus niloticus*	Mormyridae	*Gnathonemus* spp.
Citharinidae	Characidae	*Petrocephalus bovei*	Bagridae
Citharinus spp.	*Hydrocynus* spp.	Characidae	*Chrysichthys* spp.
Cyprinidae	*Hepsetus odoe*	*Alestes dentex*	*Auchenoglanis occidentalis*
Labeo spp.	Bagridae	*A. baremose*	Clariidae
Mochokidae	*Bagrus bayad*	*A. nurse*	*Clarias anguillaris*
Synodontis spp.	Centropomidae	*A. macrolepidotus*	Malapteruridae
Cichlidae	*Lates niloticus*	*A. leuciscus*	*Malapterurus electricus*
Tilapia spp.	Cichlidae	Distochodontidae	Cichlidae
Leptotilapia irvinei	*Hemichromis* spp.	*Paradistochodus dimidiatus*	*Chromidotilapia guntheri*
	Tetraodontidae	Cyprinidae	
	Tetraodon fahaka	*Barbus* spp.	
		Barilius senegalensis	
		Schilbeidae	
		Schilbe mystus	
		Eutropius niloticus	
		Physailia pellucida	
		Siluranodon auritus	

TABLE 3. Volta Lake Fish Population (Catch of Standard Net Unit of 14- to 203-Millimeter Mesh)

	Number	%	Weight, kg	%
May to Oct. 1969 (Wet Season)				
Aufwuchs and detritus herbivores	1,024	0.12	598.147	23.1
Piscivores	230	0.03	218.608	8.4
Semipelagic omnivores	859,306	99.77	1769.235	66.6
Benthic omnivores	717	0.08	68.830	2.6
Total	861,277	100.00	2654.820	100.7
Dec. 1969 to May 1970 (Dry Season)				
Aufwuchs and detritus herbivores	1,785	0.92	422.025	28.00
Piscivores	770	0.39	281.988	18.71
Semipelagic omnivores	195,174	98.15	739.111	48.85
Benthic omnivores	1,031	0.53	66.643	4.42
Total	198,760	99.99	1509.767	99.98
July to Sept. 1970 (Wet Season)				
Aufwuchs and detritus herbivores	748	0.26	349.740	18.80
Piscivores	780	0.27	372.412	20.10
Semipelagic omnivores	281,710	99.20	1058.853	57.12
Benthic omnivores	828	0.29	72.937	3.93
Total	284,066	100.02	1853.942	99.95

the northern half of the lake, apparently owing to their association with the tributary rivers and the estuarine environment of the northern part of the lake.

The herbivores, which are mainly aufwuchs and detritus feeders, formed the dominant element of the present commercial fishery. The tilapias were most important; fish of the genera *Labeo, Distichodus,* and *Citharinus* were of secondary importance. Although these fish collectively comprised about three-fourths of the commercial fishery by weight, they represented only about one-fourth of the estimated ichthyomass in the gill net population samples. Although the tilapias accounted for about half of the commercial fish landings, they represented only a little more than 10% of the ichthyomass, probably because the gill net fishery was concentrated close to the shore among the flooded trees, which are the principal habitat of the species.

The piscivores consisted primarily of the Nile perch (*Lates niloticus*) and the several species of tigerfish (*Hydrocynus*). The Nile perch was widely distributed throughout the lake, whereas the tiger fish was present mainly in the northern estuarine environment. Collectively, the piscivores represented an estimated one-fifth of the lake's ichthyomass. The benthic omnivores were relatively unimportant, consisting primarily of the bagrids of the genus *Chrysichthys* and various mormyrids.

Several additional features of the fish population are noteworthy. For example, there was an evident decline of the fish stocks from the wet season of 1969 to that of 1970 (Table 1), but the data period is insufficient to differentiate between a possible yearly fluctuation and a definite long-term trend. It is anticipated, however, that the decline will continue at least through the second dry season. Although present sampling records began only with 1969, it is possible that the population explosion, which characterizes most new reservoirs, had reached its peak somewhere in the period of 1964–1969. The subsequent 1969–1970 period may well represent the anticipated decline, after which the fish population can be expected to relatively stabilize at a new level commensurate with the normal lake regime, nutrient supply, and the rate and character of exploitation.

Also to be noted is the seasonal variation in the availability of certain species (such as those of *Tilapia*) to capture by gill nets. This variation is attributed to the peaking of activity of the fish during the wet season (April–October) as well as to increased turbidity of waters, which might render the gill nets less detectable by the fish. Conversely, during the dry season (November–March), not only is the water clearer (clear water may aid in fish avoidance of gill nets), but also there seems to be a movement of the adult *Tilapia* population into the deeper water areas. Efforts have been directed toward improving the

TABLE 4. Comparison of Commercial Catch and Relative Abundance of Fish Based on Experimental Fishing

	Estimated Total,* metric tons	Estimated Relative Abundance,† kg
May to Oct. 1969 (Wet Season)	40,449	0.778
Dec. 1969 to May 1970 (Dry Season)	21,334	0.408
June to Sept. 1970 (Wet Season)	22,500	0.336

* The estimated total is taken from the commercial catch as compiled by G. Bazigos (unpublished data, 1969, 1970).

† The abundance of the fish population is expressed as the catch per 92.9 mm^2 (1000 ft^2) of 102- to 203-mm (4- to 8-inch) mesh net.

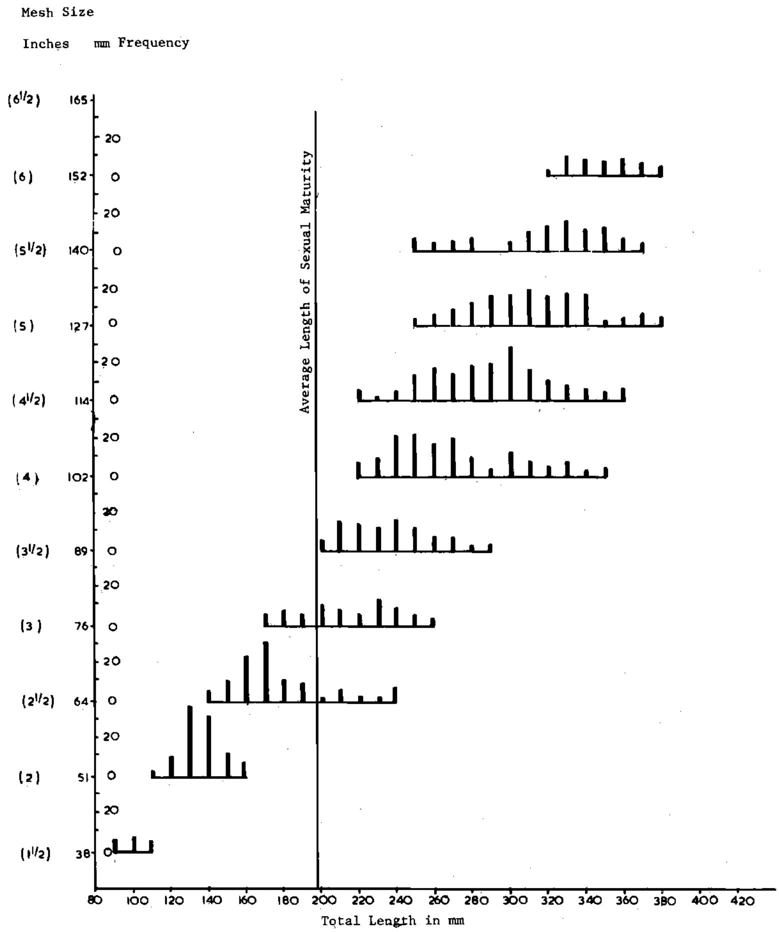


Fig 2. Length frequency distribution of *Tilapia galilaea* in Volta Lake (December 1968 to May 1970).

dry season harvest of these fish to give better year-round stability to the fishery.

Further to be noted is the constant increase of the piscivores up to about 20% of the ichthyomass (Table 3). This increase may be interpreted as the normal pattern of increased predator abundance following, with a slight time lag, the explosion of the semipelagic fish and other organisms. The same general pattern was noted in Lake Kariba, where the *Hydrocynus* stocks increased similarly (T. Scudder, personal communication, 1971).

With the foregoing evidence of a system of dynamic change in view, it becomes important that both fishermen and fishery administrators recognize that a decline in fish abundance is a natural phenomenon in the history of a reservoir and that they do not erroneously attribute such a phenomenon to overfishing of the stocks. The next few years may well carry the lake through this period of severe fluctuations and result in greater stability of the stocks for which optimal continued exploitation can be planned. Such planning, however, will need continual monitoring at least somewhat on the basis that we have established.

Relative abundance. Comparisons of the first available commercial catch data compiled by G. Bazigos (unpublished data, 1969, 1970) and our stock assessment data based on catch per unit of effort show that the abundance patterns in both sets of data are quite similar (Table 4). Both exhibit peaks in the wet season of 1969, and these peaks are followed by a drop to about half the abundance in the next wet season.

Length frequency distribution in relation to gear selectivity. Stock assessment data show that *Tilapia galilaea* comprised about 10% of the fish population but made up about half of the commercial catch. Therefore any onset of overfishing may well first be reflected by this species. Hence analysis was made of the length frequency distribution of catches of this fish by experimental gill nets of mesh sizes ranging from 13- to 203-mm (½- to 8-inch) mesh (Figure 2). This analysis indicates the presence of a high proportion of the larger sized fish in the population. If fishing pressure was very intense, only the smaller meshed gill nets would catch appreciable numbers of *Tilapia galilaea.*

G. T. Taylor and F. Denyoh (unpublished data, 1968), after extensive survey of mesh sizes then in use by the lake fishery, showed that 82% of the commercial gill nets fell within the mesh size range of 102–203 mm (4–8 inches). Our analysis has shown that the minimum size of *Tilapia galilaea* caught in these nets was 220 mm. In contrast, *Petr* [1969] reported that female *Tilapia galilaea* reach sexual maturity in Volta Lake at an average total length of 198 mm. Thus it may be deduced that most of the *Tilapia* caught by the commercial fishery have had the chance to spawn at least once, evidence of a healthy fishery.

CONCLUSIONS

From the evidence available the fish population of Volta Lake has undergone the normal evolutionary process observed in most man-made lakes. With the increased living space and nutrients following initial impoundment the fish population expanded to occupy the environment, shifts among species abundance reflecting the different ecological adaptations of the fish. This expansion has been followed by the decline in the fish stocks in 1969–1970, which may have marked the turn to a lowered but more stable level of population commensurate with the normal lake water regime, nutrient supply, and rate and character of exploitation.

Although no indication of overfishing exists, certain elements of the fish population such as *Tilapia* are more exploited than others; some species are very scarcely used. Since all of the fish of Volta Lake are acceptable as protein food, there is opportunity to increase the harvest, especially of those species that are underused.

Knowledge of absolute size of the fish stocks in bodies of water as large as Volta Lake is as yet unattainable, but, if a monitoring system such as the one that we started is followed, adequate guidelines for management decisions in the direction of optimum use of the fish stocks are attainable.

REFERENCES

Gulland, J. A., Manual of methods for stock assessment, part 1, Fish population analysis, *Manuals Fish. Sci. 4,* Food and Agr. Organ., Rome, 1969.

Petr, T., The establishment of lacustrine fish population in the Volta Lake in Ghana during 1964–1968, *Bull. Inst. Fondamental Afr. Noire, Ser. A, 1,* 1968.

Petr, T., Fish population changes in Volta Lake over the period January 1965–September 1966, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, Ghana Universities Press, Accra, 1969.

Limnological Observations during the Early Formation of Volta Lake in Ghana

S. BISWAS

Volta Lake Research Project, Akosombo, Ghana

LIMNOLOGICAL HISTORY OF THE LAKE

Biological studies started on the Volta River system with the launching of the Volta basin research project of the University of Ghana [*Lawson*, 1963]. This project included a survey of the zooplankton, phytoplankton, water chemistry, and water weeds [*Ewer*, 1966]. The tributaries were generally rich in dissolved nutrients but poor in phytoplankton [*Biswas*, 1968]. This situation was also the case with the main Volta River during the flood season (July–September 1963). After a lull in the early dry season (October–December 1963) the phytoplankton organisms started appearing in large numbers later in the dry season (January–May 1964). Diatoms appeared early in the season, and the blue green algae appeared later. The dam was closed at a time when a water bloom was declining. A close relationship was observed between the phytoplankton and dissolved oxygen immediately after the impoundment [*Biswas*, 1966]. The floodwater that filled the lake had an opalescent brown turbidity that was mainly due to colloidal iron [*Biswas*, 1969*b*]. This turbidity interfered with the photosynthetic activity of the phytoplankton and thus contributed toward the deoxygenation of the water mass.

These observations were mostly made at an offshore station at Ajena, 3.2 km (2 miles) north of the dam at Akosombo. Subsequent observations on the main stretch of the lake between Ajena and Yeji (Figure 1) revealed a general similarity of pattern in the hydrobiological conditions of the lake [*Biswas*, 1969*b*]. These data have been brought up to date in a review hydrobiological work of the Volta basin research project [*Lawson et al.*, 1969].

PRESENT OBSERVATIONS

Aims and Objectives

A number of changes took place in the water mass as the river transformed into a lake. Very little is known about such changes under purely tropical conditions. It was with this view in mind that as many data as possible were collected to follow the changes that the new lake was expected to undergo. Weekly observations have been possible at Ajena on the temperature, color, Secchi disk transparency, dissolved oxygen, and major inorganic nutrients throughout this early period of development of the lake. Data thus obtained have been calculated into monthly averages for brevity and for ease in following the major changes.

Methods

Sampling techniques. Initially it was not possible to collect samples from all parts of the lake because of transport difficulties. The station at Ajena (Figure 1) was chosen because of easy access to the lake, and it is only at this station that continuous limnological observations have been possible throughout the period of development of the lake. Samples were collected from the mid-lake region, usually in the late mornings. A closing type of water bottle was used to collect samples from the surface, bottom, and various intermediate depths. These depths were precisely determined by means of a gage fitted to the winch.

Physicochemical determinations. The temperature of water was taken by means of a precision thermometer that was read as soon as the

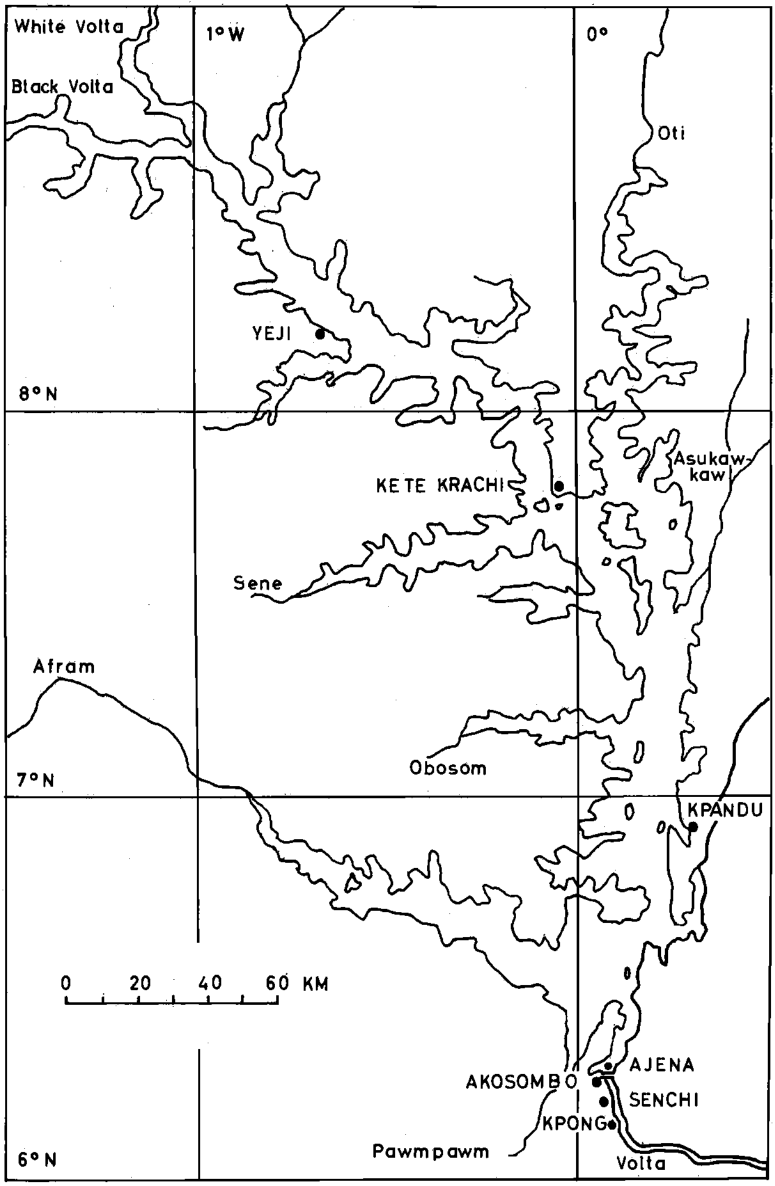


Fig. 1. Volta Lake, Ghana, showing principal towns and tributaries.

sampler was raised above the surface of the lake. Secchi disk transparency of the lake water was measured by using a glossy white disk of 20 cm in diameter. It was lowered from the shaded side of the boat by means of a graduated cable. The reading was obtained by taking the average of the depths of disappearance on lowering and of reappearance on raising the disk. Dissolved oxygen was estimated by the Winkler method and expressed as a percentage of saturation according to G. A. Truesdale, A. L. Downing, and G. F. Lowden as given by *Mackereth* [1963]. Other properties of the water were determined by the following methods: color of the water, standard colorimetric methods with a Lovibond Nesleriser; total iron, thioglycollic acid method;

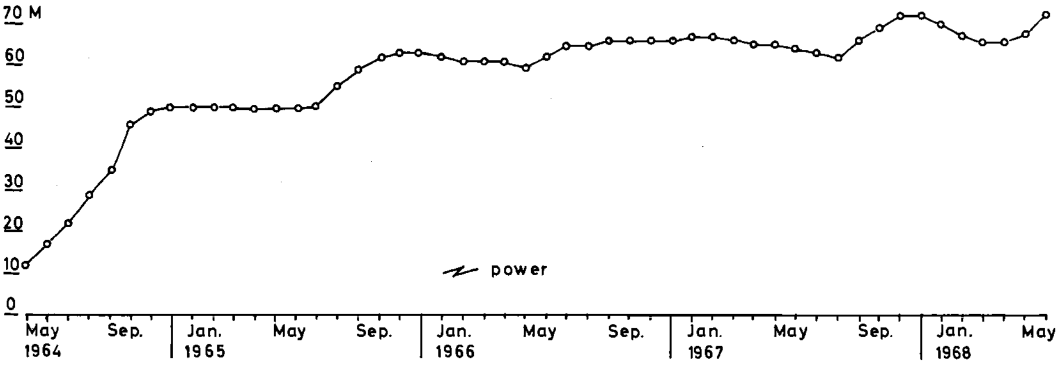


Fig. 2. Lake level at Ajena during 1964–1968.

phosphates, Denigès' method; ammonia, Nessler's method; nitrites, Griess-Illosvay's method; and sulfides, lead acetate method [*Biswas,* 1967].

Results

Changes in the lake level. The lake filled most vigorously between May and October 1964. By December the lake level rose to 50 meters above the lake bottom at Ajena and continued at that level until March 1965 (Figure 2). After a drop of 1 meter during the end of the dry season between April and June, the lake level started rising for the second time from July 1965 and gradually rose to 63 meters by November 1965. It remained at this level until December 1965 and then steadily dropped from January to May 1966. During this latter period, four hydroelectric turbines were put into operation in stages. Their operation added to the outflow of the lake and thereby caused instability of the lake level that had not occurred in the previous year. There was an even greater instability in the lake level during the third and fourth years of filling when the spillways had to be opened occasionally; the opening of the spillways caused an appreciable increase in the outflow [*Biswas,* 1972].

Temperature of water. The water mass cooled rapidly during the course of initial filling between May and August 1964, so there was very little temperature difference from top to bottom of the lake (Figure 3). Toward the end of the flood season in September 1964 the surface temperature started rising. The temperature at the lake bottom, however, continued falling until October 1964. This drop led to the widening in the temperature difference between the surface and the lake bottom. Such a difference was found to be smallest during the months of flood (July–September) and the harmattan seasons

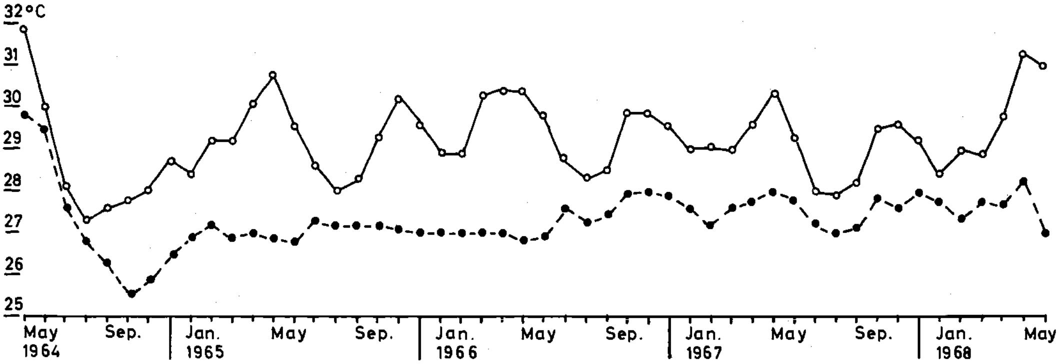


Fig. 3. Temperatures at the top (open circles) and bottom (closed circles) of the lake.

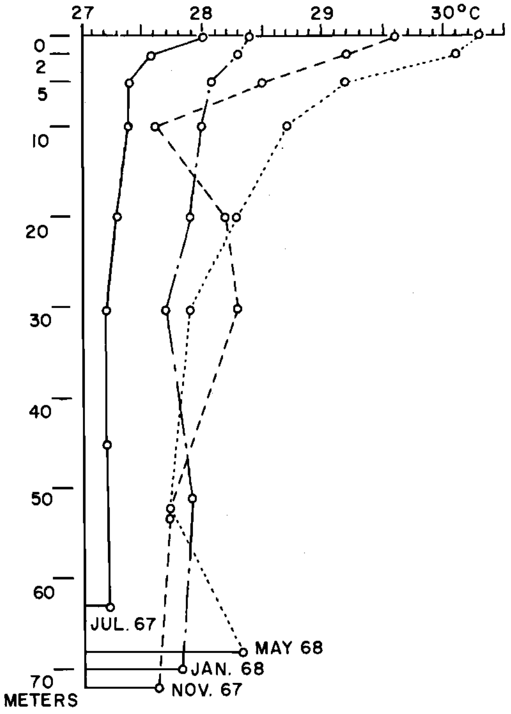


Fig. 4. Temperatures during mixing and stratification.

(December–February) each year. The temperature gradient was found to be smallest during these months, and the water mass approached a homothermal state.

In the intervening period the temperature difference widened greatly between the surface and the bottom. This widening led to the development of a metalimnion within the upper half of the lake, especially during the months of April or May and November (Figure 4). There was no evidence of a well-defined thermocline at Ajena, although a thermocline has been observed elsewhere in the lake [*Biswas,* 1969*b*]. The hypolimnion remained relatively cool during the first 2 years, after which it warmed up appreciably (Figure 5).

Secchi disk transparency. The transparency of water was very low during the first 2 years of the lake. This situation was mainly due to the turbid nature of the floodwater that filled the lake. During the second 2 years, there was an appreciable increase in the transparency through the settling of the suspended matter that caused turbidity [*Biswas,* 1969*a*]. In spite of this trend, however, the transparency decreased seasonally (Figure 6) during the months of flood and the harmattan seasons.

Dissolved oxygen. In the surface water the dissolved oxygen closely followed the Secchi disk curve (Figure 6), probably owing to the association of dissolved oxygen with the photosynthetic activity of the phytoplankton [*Biswas,* 1969*a*]. In the first 2 years the hypolimnion was deoxygenated (Figure 7). Subsequently, this region was found to be oxygenated even during the periods of thermal stratification.

Color of water. An opalescent brown color developed in the lake as it filled with the floodwater. The deepest color was observed in the surface water in November 1964, and there was no appreciable decrease until the end of the second year of development of the lake (Figures 8, 9, and 10). Even during these later years the color increased appreciably in the flood and harmattan seasons. The vertical distribution of color revealed the smallest gradient during these seasons and the largest gradient in the intervening months when the lake stratified. The deepest color was observed at the bottom of the lake on most occasions.

Major inorganic ions. Iron was measured because of its influence on the color of water

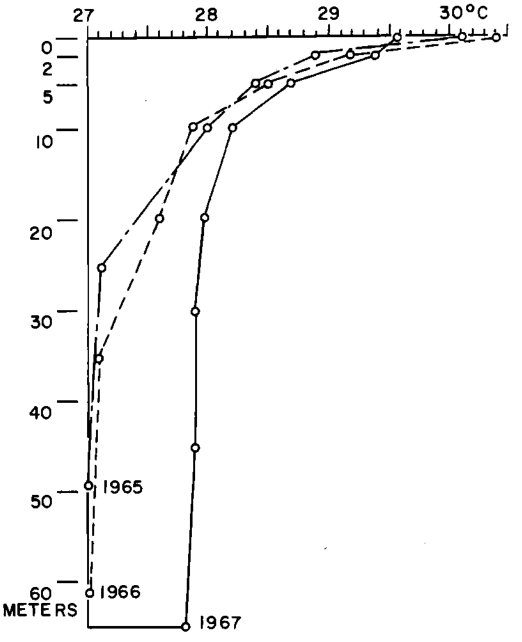


Fig. 5. Temperatures during April 1965–1967.

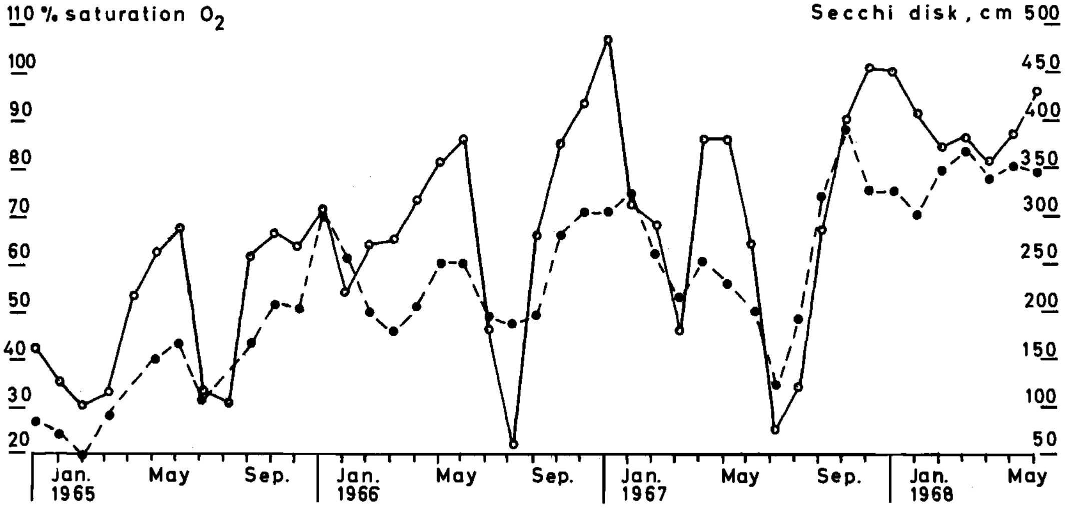


Fig. 6. Secchi disk transparency (closed circles) and surface oxygen content (open circles) during 1965–1968.

(Figure 8) and hence on the Secchi disk transparency as well as on dissolved oxygen (Figure 6). The surface water was very rich in iron during the first 2 years, after which the iron content decreased so much that its presence was not even detectable except during the months of flood and the harmattan seasons (Figure 11).

The method employed for the phosphate test enabled the determination of soluble orthophosphate only. This nutrient was present in appreciable quantities throughout the period of development of the lake. It was distributed in the entire water column during the months of flood and the harmattan seasons (Figure 12). In the intervening months it was present in large quantities in the hypolimnion but was not even detectable in the metalimnion. In this respect, this nutrient closely followed the distribution of total iron (Figure 11).

Ammonia was present throughout the water column during the months of flood and the harmattan seasons (Figure 13). There was a greater abundance of this nutrient in the former season than in the latter. In the intervening months, ammonia was present in large quantities in the hypolimnion and in much smaller quantities in the metalimnion.

Nitrite nitrogen was not always detectable, and it was present only in traces except during the months of flood and the harmattan seasons (Figure 14). During the first 2 years of deoxygenation of the lake, nitrite nitrogen was rarely detected in the water column. It is now appearing in increasing abundance, probably as a result of oxygenation of the hypolimnion. This increase was particularly evident during the harmattan months of recent years, when the increase of nitrite nitrogen was associated with a considerable decrease in ammonia.

Sulfide has been detected in appreciable quan-

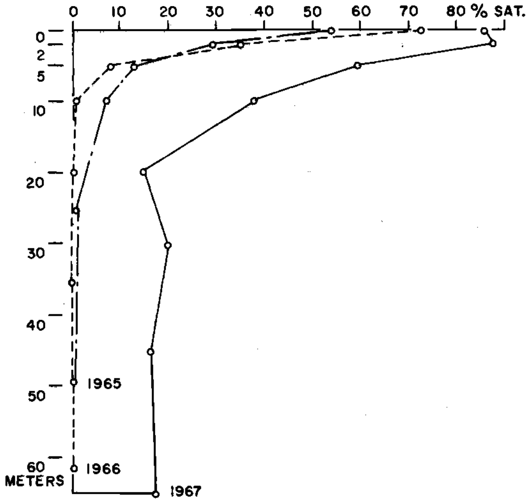


Fig. 7. Dissolved oxygen during April 1965–1967.

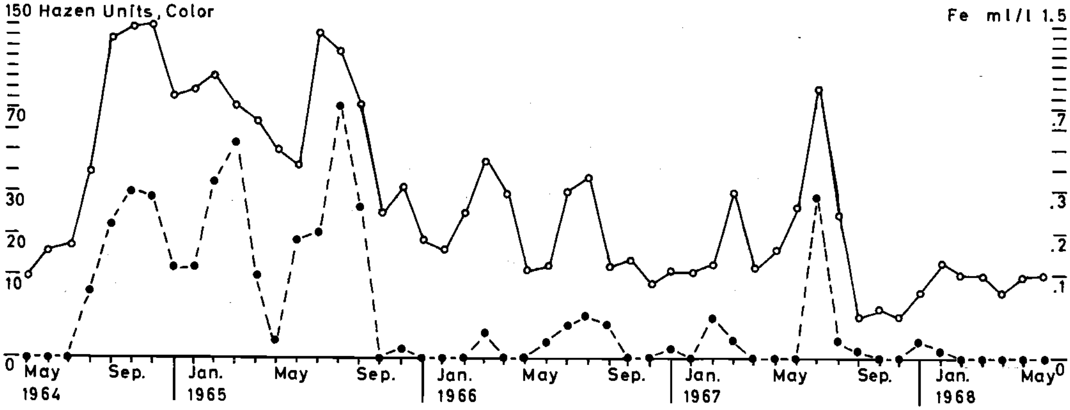


Fig. 8. Color (open circles) and total iron (closed circles) in the surface water during 1964–1968. Scales are in geometric progression.

tities during the early years of the lake. It was particularly abundant in the hypolimnion except during a major overturn as in December 1967 (Figure 15). Its distribution was comparable to that of the nitrite nitrogen (Figure 14) in many respects, probably owing to the unstable nature of both these compounds.

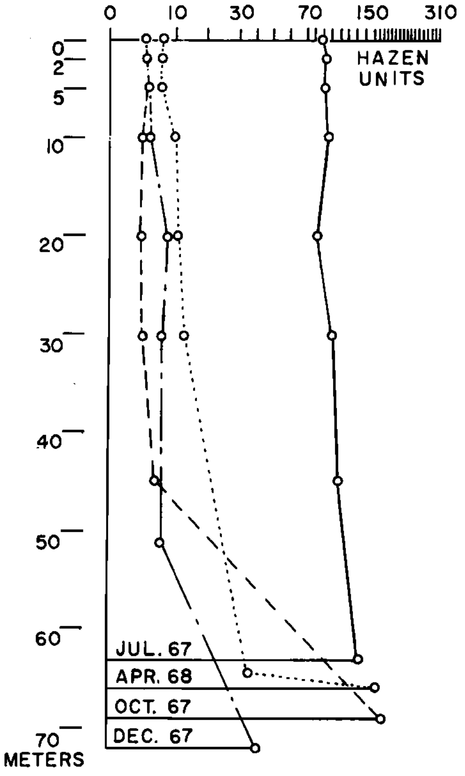


Fig. 9. Color of water during mixing and stratification.

CONCLUSIONS

Early observations on thermal changes in the lake revealed the influence of flood and the harmattan winds in overturning the lake [*Biswas,* 1969*a*]. Subsequent observations on dissolved oxygen and phytoplankton also revealed that such overturnings were due to the upwelling of the layers. In reaction to this upwelling the layers moved downward, and thereby a

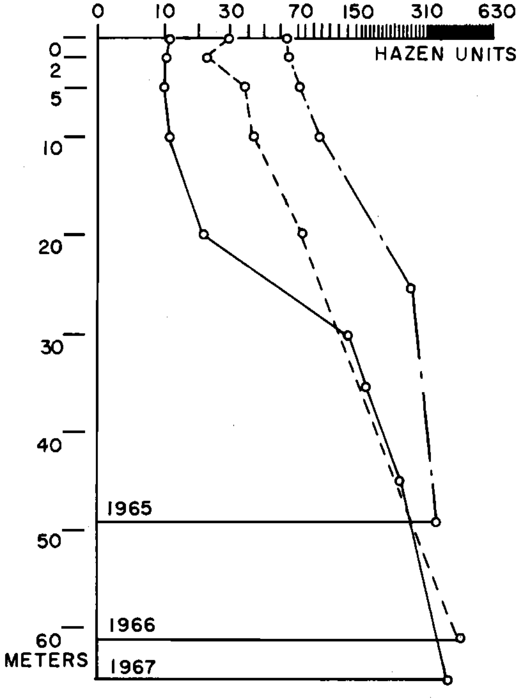


Fig. 10. Color of water during April 1965–1967.

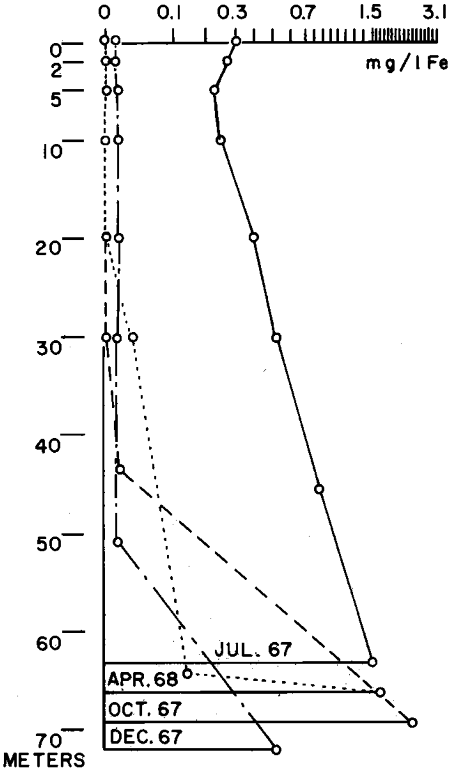


Fig. 11. Total iron during mixing and stratification.

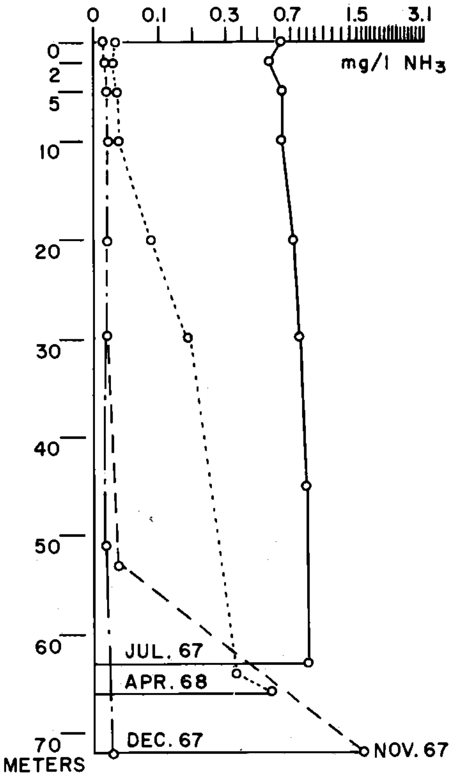


Fig. 13. Ammonia during mixing and stratification.

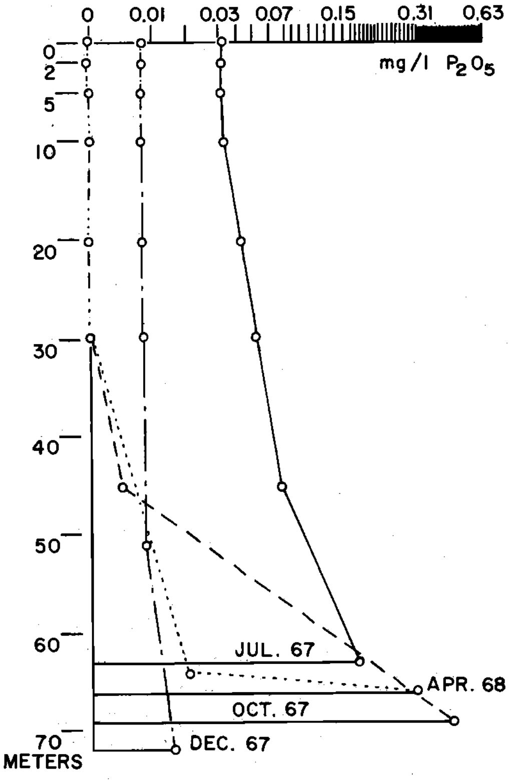


Fig. 12. Phosphates during mixing and stratification.

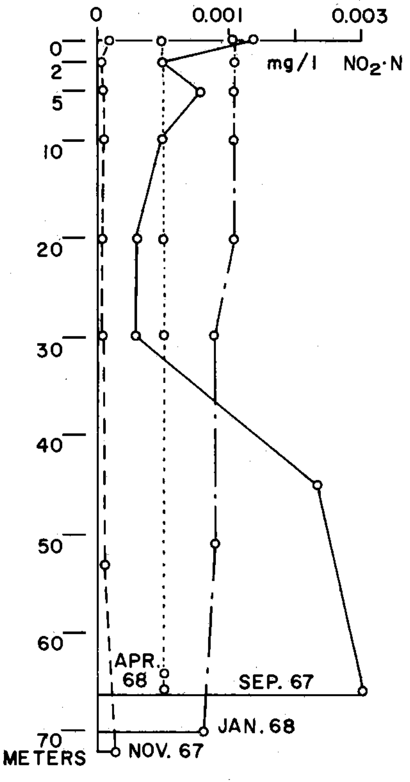


Fig. 14. Nitrites during mixing and stratification.

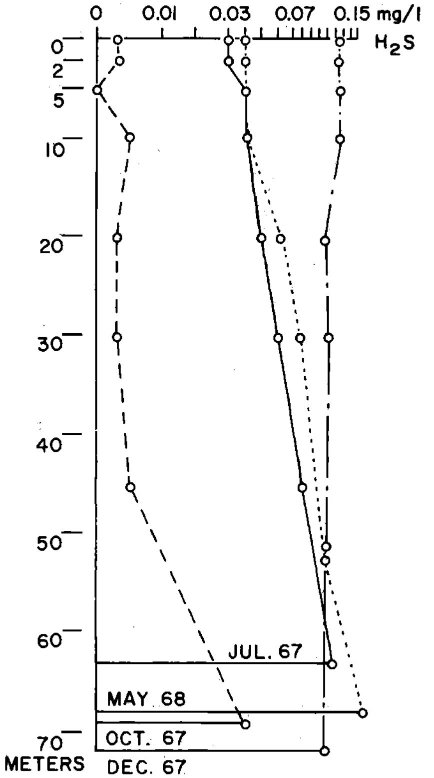


Fig. 15. Sulfides during mixing and stratification.

rhythmic movement of these layers was set up [*Biswas,* 1969*b*]. Such movements diminished in the absence of any disturbing forces, and their decline led to the stratified condition of the lake during the dry season in October–November as well as March–June.

The present series of observations revealed that, with the upward movement of the layers, inorganic nutrients spread from the hypolimnion to the metalimnion. This transfer made the nutrients available to the phytoplankton, which was found to be restricted mainly to the upper layers of the metalimnion [*Biswas,* 1969*b*]. The movement of dissolved oxygen to the hypolimnion has also enabled the oxidation of ammonia, which was evident from the presence of nitrite nitrogen. Recent observations showed that these changes are leading to a rapid increase of the phytoplankton and their spread to the hypolimnion [*Biswas,* 1970]. The operation of the hydroelectric turbines and the frequent opening of the spillways have also increased the outflow, and thereby the movement of the layers has increased to an even greater extent than in the early years of the lake.

Acknowledgments. The laboratory work was carried out in the Department of Botany, University of Ghana, and I am grateful to Professor G. W. Lawson for his cooperation. I am also grateful to the Volta River Authority for providing sampling facilities on the lake and to the FAO coordinator for allowing me to submit this paper to the Symposium on Man-Made Lakes held in Knoxville. I also take this opportunity to thank all my colleagues in the laboratory for their ready cooperation and help in the fieldwork.

REFERENCES

Biswas, S., Oxygen and phytoplankton changes in the newly forming Volta Lake in Ghana, *Nature London, 209,* 218–219, 1966.

Biswas, S., Some limnological innovations, *Tech. Rep. X19,* pp. 1–6, Volta Basin Res. Proj., Univ. of Ghana, Legon, 1967.

Biswas, S., Hydrobiology of the Volta River and some of its tributaries before the formation of the Volta Lake, *Ghana J. Sci., 8,* 152–156, 1968.

Biswas, S., Thermal changes in the Volta Lake at Ajena, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 103–109, Ghana Universities Press, Accra, 1969*a.*

Biswas, S., The Volta Lake: Some ecological observations on the phytoplankton, *Verh. Int. Ver. Limnol., 17,* 259–272, 1969*b.*

Biswas, S., Distribution of phytoplankton during the early development of the Volta Lake, *Hydrobiologia, 40,* 201–207, 1972.

Ewer, D. W., Biological investigation of the Volta Lake, May 1964 to May 1965, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 21–30, Academic, London, 1966.

Lawson, G. W., Volta basin research project, *Nature London, 199,* 858–859, 1963.

Lawson, G. W., T. Petr, S. Biswas, E. R. I. Biswas, and J. D. Reynolds, Hydrobiological work of the Volta basin research project, 1963–1968, *Bull. Inst. Fondamental Afr. Noire, Ser. A, 31,* 965–1003, 1969.

Mackereth, F. J. H., Some methods of water analysis for limnologists, *Sci. Publ. 21,* Freshwater Biol. Ass., Ambleside, England, 1963.

Entomological Aspects of Trypanosomiasis at Volta Lake

F. A. S. KUZOE

Volta Lake Research Project, Accra, Ghana

Trypanosomiasis had been endemic in some northern parts of Ghana, from where it had extended southward as sleeve epidemics along main routes of communication. One such route crosses Volta Lake at Yeji. Previous trypanosomiasis surveys in the region of the reservoir had been carried out by the medical field units. The disease occurs in districts between the Oti and the Kalurakan rivers, between the Sene and the Chuko rivers, and at the tip of the Afram wing in the Ashanti Akim north district. Incidence rates have been low. Fears have been expressed about the possibility of an increase in incidence and distribution of the disease, either by multiplication of the vector tsetse or by the lake's acting as a channel of communication down which infection could be transported southward in a manner witnessed along roads in the past. The principal aim of this paper is to discuss these fears in relation to the present knowledge of the distribution of the vectors of trypanosomiasis along the lake.

DISTRIBUTION OF THE VECTORS

In Ghana, *Glossina palpalis* is the principal vector of trypanosomiasis, *G. tachinoides* playing a minor role. Both species are riverine. Previous to the formation of the lake in 1964, the banks of the Volta River and its tributaries were covered with gallery and fringing forests, which varied in size from a few meters wide in the north to extensive forests in the south. *G. palpalis* was widespread along the Volta basin, and *G. tachinoides* was restricted to northern localities.

During the formation of the lake, these forests were drowned for almost 402 km (250 miles) upstream along the Volta and its tributaries. In the southern parts of the lake, where the forests were extensive and the river valley was narrow, parts of the forests have remained, and the lakeshore is therefore wooded in parts. In the northern parts, where the forests were narrow, they were completely drowned, and the lakeshore is open and has wide expanses of grass and widely spaced trees. As a result of these ecological changes, *G. palpalis* still occurs in vegetation along parts of the lakeshore and alongside streams in the southern parts of the lake. In the northern parts the tsetse is absent from the lakeshore. Mixed populations of *G. palpalis* and *G. tachinoides* are, however, present in vegetation along unflooded parts of tributaries and side streams. The general distribution of the tsetse along the periphery of the lake is illustrated in Figure 1.

SIGNIFICANCE OF DISTRIBUTION

From this pattern of distribution, it is evident that, in the absence of the tsetse from the lakeshore in the northern parts of the Guinea savannah, transmission of trypanosomiasis may not occur. This situation may remain so until suitable vegetation develops along the lakeshore and *G. palpalis* and *G. tachinoides* colonize it. Transmission may probably continue in the absence of effective control measures in communities along the unflooded parts of tributaries and seasonal streams, which form the main source of water supply in that northern part of the Guinea savannah. It is possible that people living along the lakeshore, where the tsetse is absent, may become infected by traveling into these transmission foci.

In the southern part of the Guinea savannah zone, contact between man and tsetse may continue along parts of the lakeshore and alongside streams, but it is doubtful whether this contact will be close or intimate, a necessary condition for trypanosomiasis transmission. In this part of the Guinea savannah, there are no severe dry seasons. Man and tsetse are never forced into the same ecological habitat, despite the former's search for water and the latter's need for shade conditions, as is the case in the northern part of

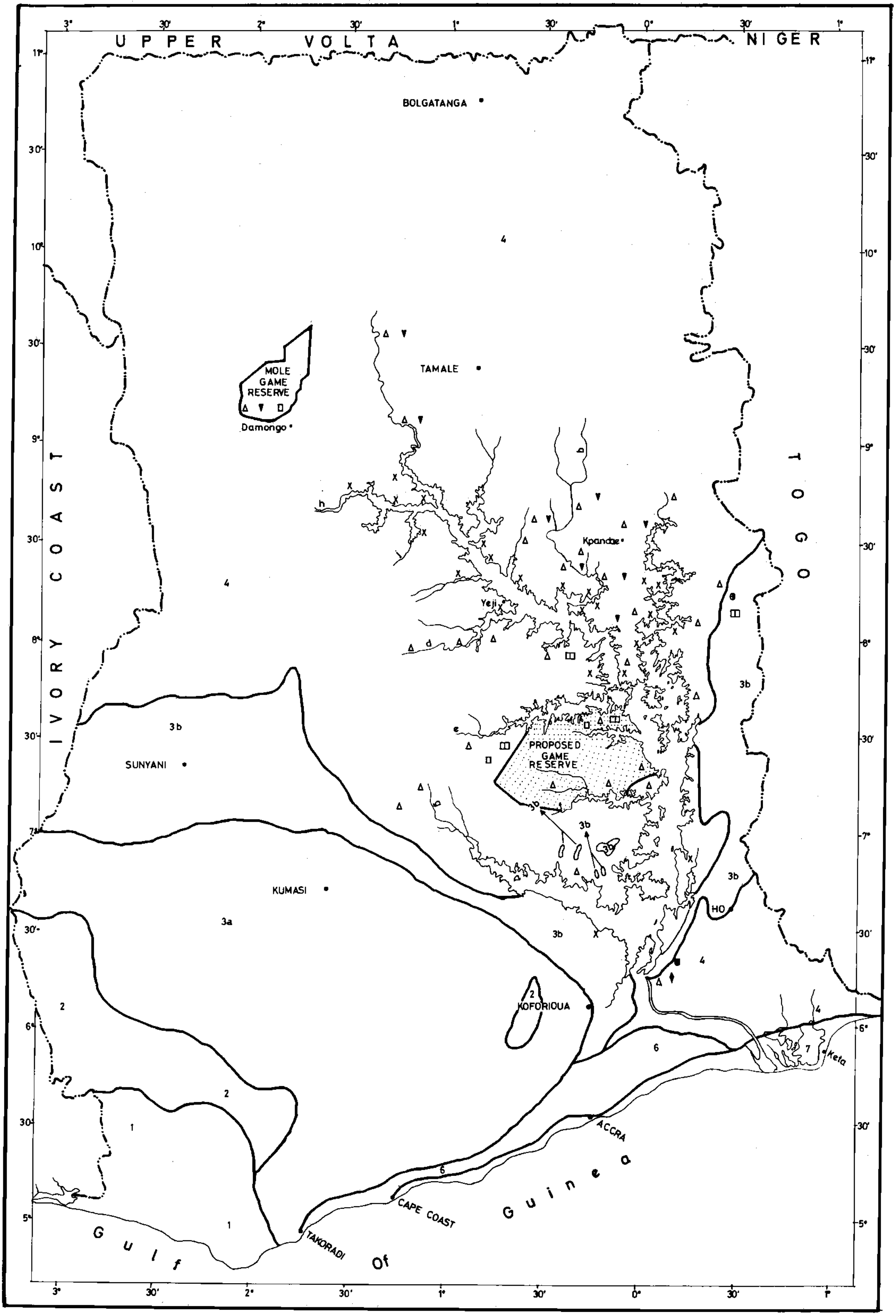


Fig. 1*a*. Map showing the distribution of *Glossina* along Volta Lake, Ghana.

VEGETATION ZONES

Rain Forest	1
Transition Zone	2
Moist Semi Deciduous Forest	(3)
Celtis-Triplorochiton Association	3a
Anitaris Chlorophora Association	3b
Guinea Savannah	4
Sudan Savannah	5
Coastal Thicket and Grassland	6
Strand and Mangrove	7

TSETSE FLIES

G. palpalis	Δ
G. tachinoides	▼
G. morsitans	□
G. longipalpis	◫
G. fusca	♦
G. tabani	⊕
Glossina free area	X

TRIBUTARIES

Oti River	a
Daka River	b
Kalurakan River	c
Pru River	d
Sene River	e
Obosum River	f
Afram River	g
Black Volta	h
White Volta	i
Chuko River	j

0 20 40 60 80 100 km

Fig. 1*b*. Legend explaining map of *Glossina* distribution along Volta Lake.

the Guinea savannah. There is a possibility of increase in tsetse populations in some southern districts around the lake, owing to the presence of numerous favorable breeding places. However, an increase in tsetse populations per se does not constitute a trypanosomiasis hazard, because it is known that the incidence of trypanosomiasis bears little or no relation to the density of tsetse infestation. A classic example has been described by *Nash* [1944]. It is therefore likely that, even if infection is introduced into the southern parts of the savannah through lake transportation and population movements, local transmission probably will not occur.

There is evidence that local transmission of trypanosomiasis occurs in the forest belts of Ashanti and Brong-Ahafo in Ghana, although the transmission is on a smaller scale than it is in the northern Guinea savannah zone [*Scott,* 1965]. There is a direct relationship between the prevalence of the disease and the proximity and importance of lines of communication, and the disease is an occupational hazard among people who spend much time in the field, e.g., farm laborers, wine tappers, and sawyers. The moist forest belts on the southwestern and eastern sides of the lake have large agrarian populations. It is possible that, if infection is introduced into these regions, local transmission may probably occur similarly to the manner in which it occurs in the forest belts of Ashanti and Brong-Ahafo. Here is probably where the lake and other new lines of communication may contribute.

CONCLUSIONS AND RECOMMENDATIONS

The creation of Volta Lake has been beneficial in drowning in certain areas the riverine forests that were tsetse habitats. It is too early to observe the effect that this reduction in tsetse habitats will have on the prevalence of trypanosomiasis in the region surrounding the lake. However, it can be said that the effect will depend on a combination of other factors, e.g., future trends in tsetse distribution, future development projects and population movements along the new communication routes, and above all the effectiveness of control measures at the known foci of infection from where the disease may spread.

In view of these considerations it is recommended that (1) the control of the disease in the known foci of infection, both by therapeutic and entomological means, must be intensified; (2) sites for future ports along the lake must be surveyed for the vector tsetse, and, where there is a likelihood of man-fly contact, protective clearing of vegetation must be undertaken; and (3) ecological studies on the vector tsetse must be carried out with the view of assessing the practicability of insecticidal control. This is one method that can be brought into operation quickly when the need arises and that does not involve the destructive and costly operation of vegetation clearing.

REFERENCES

Nash, T. A. M., A low density of tsetse flies associated with a high incidence of sleeping sickness, *Bull. Entomol. Res., 35,* 51, 1944.

Scott, D., *Epidemic Diseases in Ghana 1901–1960,* pp. 138–186, Oxford University Press, New York, 1965.

Lake Kariba: Early History and South Shore

M. I. VAN DER LINGEN
Department of National Parks and Wildlife Management
Salisbury, Southern Rhodesia

Lake Kariba, on the Zambezi River and bordered on the south by Southern Rhodesia and on the north by Zambia, lies between latitudes 16°28′S and 18°06′S and longitudes 26°40′E and 29°03′E (Figure 1). Evaporation and mean annual discharge of 40.1 km^3 through floodgates and turbines result in an annual variation in water level of about 5 meters. The catchment consists of high ground to the north, swamps in the Barotse floodplain and Chobe to the west, and a peneplain forming the Rhodesian plateau.

The meteorological year is divided into three more or less distinct seasons: a cool dry season from May to September when the lowest air temperatures may reach 10°C, a warm dry season from October to November when the air temperatures reach 40°C, and a warm rainy season from December to April with 24-hour mean temperatures of 25°C and a rainfall of 600 mm. Between April and August, cold and dry southeasterly winds blow along the lake axis. In September, variable northerlies occur.

The Zambezi flood reaches Lake Kariba in March–May; water levels rise until June or July and then drop in November when the lowest discharge occurs. The lake has five well-defined basins separated from each other by narrows or chains of islands and increasing in size from the head of the lake to the dam.

Limnologically, Lake Kariba is a monomictic lake whose physical characteristics depend greatly on the Zambezi River (upper third of the lake) and the local climate (lower half of the lake). Water temperatures range from 17° to 32°C. Homothermy occurs at 25°C during April–May in the riverine part of the lake. This homothermy results from the arrival of the massive Zambezi flood, which flushes out most of the water present at the time. In the lacustrine part, homothermy resulting from thermal phenomena occurs around 22°C during the cold season. The main metalimnion (thermal drop of $\geq 0.2°C/m$) is rarely found at a depth of >35 meters and generally involves a layer of <10 meters thick.

Usually, 50% of the incident light is absorbed within the first 3-meter layer, and the 1% relative illumination level seldom lies deeper than 20 meters. In the epilimnion the *p*H varies between 7 and 8.5, the total alkalinity averages 40 mg/l as $CaCO_3$, and the specific conductivity at 25°C is about 90 $\mu\Omega^{-1}$. Great variations exist from basin to basin: the dissolved inorganic nutrients increase from the upper basin toward the lower end of the lake but never reach very high values.

The principal morphometric data are: length, 280 km; greatest width, 40 km; mean width, 19.8 km; surface area, 5544 km^2 at 487.8 meters above sea level; volume, 160 km^3; maximum depth, 120 meters; and mean depth, 29.2 meters (30% of the area is shallower than 17 meters).

EARLY HISTORY

Lake Kariba was created by damming the Zambezi River at the Kariba Gorge in December 1958 to provide hydroelectric power for the Federation of Rhodesia and Nyasaland. It was the first of the great man-made lakes, and it was also among the first six in size of all African lakes. The possibility of damming the river at this point had been suggested for irrigation purposes as far back as 1912. The hydroelectric scheme finally approved in 1955 envisaged power stations on both banks. The first installation on the south bank has been operating at full capacity since 1963, and the second stage on the north bank is now under construction. Much of the early work and research on the lake was carried out through joint action of the three governments (Southern

Rhodesian, Northern Rhodesian, and Federal). The fishery is managed separately by Zambia and Southern Rhodesia, and both countries support research on their respective sides of the lake.

The aim of this paper is to give an account of some of the problems that have arisen, how they were dealt with, and the research activities in a variety of fields that followed the creation of the lake. Early aspects and recent work on the southern shore are described. Many of the problems were unique and included such things as the planning of new areas for settlement of the displaced population and the rescue and study of wildlife affected by the rising waters. Attention was, from an early date, focused on the potential of the fishing industry. The Lake Kariba Fisheries Research Institute at Kariba and the Nuffield Lake Kariba Research Station at Sinamwenda are centers for research on the lake.

PHASES IN LAKE DEVELOPMENT

It is convenient and valid from the viewpoint of the changes occurring in systems associated with the lake to consider the following phases: (1) a preliminary preimpoundment phase up to December 1958, (2) a period of filling until full supply level from 1959 to 1963, and (3) a period of approach to stabilization from 1963 to 1971.

Preimpoundment phase. During this period, in 1956 and 1957, studies were carried out on fish populations by the Joint Fisheries Research Organization operating from Northern Rhodesia. Planning for the movement of people from the valley and the development of new areas was well in hand, and by mid-1958 the movement was completed. A committee was set up by the federal government to examine and report on the industrial, subsistence, and recreational fishing potentialities of the lake. This committee considered expert reports on the fishery possibilities and reported to the government at the end of 1956. As a result of the committee's recommendations, plans were made and carried out in regard to bush clearing, fish stocking, and other development. This phase was characterized by bold planning and imaginative tackling of problems.

Filling phase. The closure of the dam in 1958 was the first step leading to the attainment of a peak level of 487.8 meters above sea level in September 1963. Animal rescue operations were concluded in 1963. On the south bank, commercial fishing started in 1962. Research work on the lake increased, and the annual pattern of limnological events was indicated by observations in the Sanyati basin. The Lake Kariba Coordinating Committee had been set up to coordinate research, investigate control of *Salvinia auriculata,* and arrange the stocking of *Tilapia* fingerlings. This phase was characterized by a host of extreme biological and physical phenomena, the most obvious of which were the drowning of the terrestrial vegetation, the explosive development of *Salvinia auriculata,* and the expansion of the fish populations.

Third phase. Research activities increased during this period, detailed work being carried out in selected localities. It is apparent that the last 3 or 4 years have been a period of assessment for researchers. Although the lake has not yet stabilized, it has entered a period of apparently lower productivity, and the change to lacustrine conditions is pronounced.

PHYSICAL SYSTEMS

In the inundated area the Zambezi Valley consists mainly of karoo and Cretaceous sandstones, and limestones occur in low-lying parts. *Jackson* [1961] describes the Zambezi as a typical sandbank river that has steep banks cut in the alluvium and that rises and falls rapidly in level during and after the rains. G. Bond (unpublished data, 1965) describes the development of shoreline features by the beginning of the postfilling stage. In 1963, sandy beaches were already developing extensively on soft forest sandstone. The lowering of the water level by 7.5 meters after 4 months at 480 meters above sea level provided an opportunity to examine the earliest stages of shoreline development after sudden submergence, and an attempt was made to relate erosion and shoreline features that were formed to factors such as geologic structure topography, prevailing winds, and the protective effects of sunken trees.

Perimeter leveling carried out in 1957–1958, connection of levels across the future lake floor, and establishment of accurate bench marks enabled measurements to be made of the crustal depression resulting from the weight of the water contained in the lake. Crustal depression was measurable 36 km from the lake, and *Sleigh* [1969] suggests that this depression is due to elastic bending of the strata.

A network of seismographic stations was established during the second phase, and work was

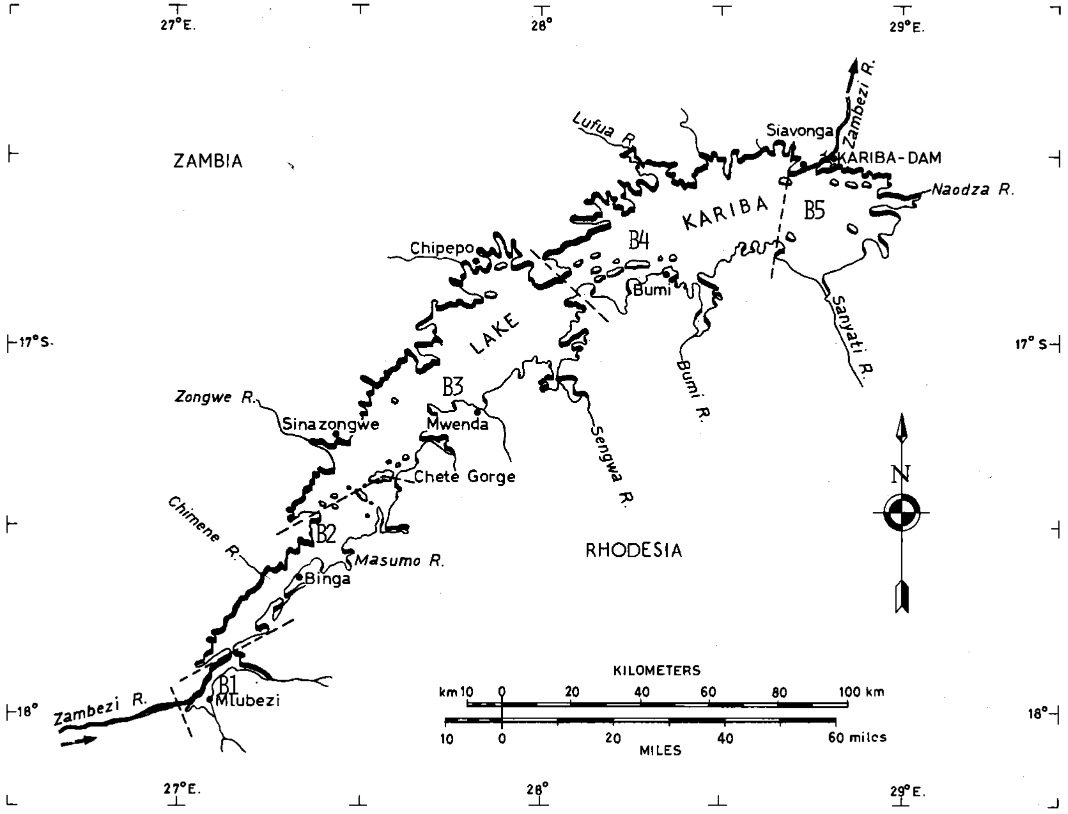


Fig. 1. Lake Kariba showing the main rivers and the division of five basins, which are identified by B1, B2, and so on.

carried out by the Department of Meteorological Services and the University of Rhodesia on seismic effects. Prior to the filling of the dam the area was nearly seismically inert, but, in 1959, shocks were measured when the water level had risen 60 meters. This weak but persistent activity continued and culminated in 1963–1964 in strong but short-lived bursts superimposed on the weaker basal activity. Available data suggest that the lake is approaching the final phase in its seismological history with occasional bursts of low-level activity [*Archer*, 1969; D. I. Gough and W. I. Gough, unpublished data, 1970]. Epicenters of tremors lie in the downfaulted rift valley of the middle Zambezi, and the lake is thought to have reactivated existing faults.

Since wave height and wind force were of importance in designing craft and harbors, these factors were investigated. A. B. Law (unpublished data, 1965) reported that wave heights of 2.7 meters would be possible as a result of sustained winds of 38 km/hr over a fetch of some 64–80 km. Winds of >45 km/hr blowing for >30 hours are known to have produced waves of 2–2.7 meters in height.

Limnograph stations have been set up at a number of points. P. A. Muncaster (unpublished data, 1965) describes the results. At Kariba a sinusoidal trace of a 12-hour period is obtained, and midway up the lake a seiche that is out of phase by half a period and that has a 30-min oscillation superimposed occurs. A dicrote seiche occurs at the western end. The magnitude of oscillation is only 0.25 meters.

Flood forecasting data required for the hydrologic management of Lake Kariba are obtained from a network of rainfall stations and telemetric flow meters in the river. Normal operating levels are between 474 and 478 meters above sea level, maximum spilling being carried out over periods that are as long as possible. It is envisaged that, with the north bank scheme in operation, retention levels will remain high and spilling will only be necessary at intervals of 3–5 years [*Allison,* 1970]. Fluctuations in water level and, in particular, the drop during summer have a profound influence on the fauna and flora of the lake.

The annual heat budget for Lake Kariba has been investigated at the Lake Kariba Fisheries Research Institute and has been found to be in the region of 13,000 cal/cm², a somewhat low figure by comparison with the heat budget of lakes in the northern hemisphere and in New Zealand in the southern hemisphere. This characteristic may be due to the shallowness of the lake and the reflection of solar energy by clear water. It may be of interest in future work on primary production to establish a correlation between heat budget and productivity [*Fish,* 1970] by comparison with other lakes.

LIMNOLOGY

Limnological observations on the newly developing lake were made by *Harding* [1966] in the period 1959–1963. These were made mainly at two stations in the vicinity of Kariba, one being in Kariba Gorge itself. Stratification was first observed in November 1959 at 10 meters, below which no oxygen occurred. Overturn took place in July 1960 at a water temperature of 23.5°C, and cooling continued until the end of August when a temperature of 21.5°C was reached. This definite pattern of stratification continued and was repeated with variation only in the timing. The period of deoxygenation, which was 8 months in 1960–1961, diminished; by 1963, hydrogen sulfide was present for only 3 months.

Begg [1970*a*] studied the lake on the Southern Rhodesian side in 1967 and established the individual behavior of the five basins (Figure 1). Circulation, or turnover, occurs in a progressive series of phases from May to July. Turnover in basins 1 and 2 results from flushing by the Zambezi floods in May, whereas basins 3–5 behave in what Begg terms a 'conventional lacustrine manner,' the turnover being temperature induced. Stratification commences in all basins in September. Hypolimnetic temperatures are a reflection of the previous winter turnover temperatures. The situation in Kariba Gorge is significantly different from that occurring in the rest of basin 5, owing to the passage of water through the turbines and spilling through the gates.

The gradual decline in the period of deoxygenation has not continued. The period depends, according to *Begg* [1969, 1970*a, b*], on locality and season. For example, at Harding's sampling station, hydrogen sulfide was present for 3 months in 1963 and 7 months in 1967, and in 1968 it was absent. Begg suggests that the production of hydrogen sulfide is related to the quantity of *Salvinia* sinking to the bottom of rivers and that here are the main sources of the hydrogen sulfide that moves along the drowned valleys.

Prior to inundation the total dissolved salts in Zambezi water in June was 26 mg/l. Just after closure this concentration rose to 65 mg/l but by December 1964 had declined to 42 mg/l. *Harding* [1966] predicted that this decline would continue until the lake water took on the character of the combined inflows. *Mitchell* [this volume, 1973*a*] points out that the trend to oligotrophy is clear but that ultimate productivity depends on the nutrient balance and the degree of recycling.

There has been a decrease in phosphate and nitrate during the last 5 years. *Caulton* [1970], working at the Lake Kariba Fisheries Research Institute, investigated nitrate and phosphate entering the lake over a short period during the rains in 1969. Nutrients from marginal runoff and small inflows are immediately available, whereas those entering via major inflows are temporarily locked in the hypolimnion. This author suggests that nitrogen entering the lake is predominantly atmospheric via rainwater whereas phosphates enter from leaching by rivers. A certain contribution is made to the nutrient supply at times of rising water from animal droppings and vegetation.

S. M. McLachlan [1969] investigated chemical properties of the muds and water and concluded that, in general, the waters investigated were similar, irrespective of the nature of the bottom. However, a close correlation existed between exchange properties of mud and parent rock, mud derived from basalts having the highest exchange properties.

The importance of rivers and 'estuaries' is recognized, and research is moving toward a closer study of these areas. *Bowmaker* [1969*a*] has made a close study of the Mwenda River mouth and the results of different rates of river flow. The rivers have been drowned to varying extents from 9 to 56% of their total lengths, and this drowning has important implications for fish breeding [*Begg,* 1969].

PLANKTON

During the reconnaissance surveys of the Joint Fisheries Research Organization, collections of Crustacea were made in flooded backwaters; two species of planktonic Cladocera and one copepod were collected [*Jackson,* 1961]. This copepod, *Tropodiaptomus kraepelini,* dominates the zooplankton at this time (1971). During the filling of the lake, extensive collections were made, but only *Thomasson* [1965] has published information based on some of Harding's collection. Subsequent work by *Begg* [1970 *a, b,* also unpublished reports, 1969] indicates that there has been a decline in the number of species since 1959–1963.

During 1967, sampling in Rhodesian waters was done by G. W. Begg, who recorded 20 species of zooplankton: Cladocera, nine species; Copepoda, two species; and Rotifera, nine species. The copepod *Bosmina longirostris* is the principal food of pelagic *Limnothrissa miodon,* the introduced Tanganyika sardine. *Limnocnida rhodesiae,* a pelagic coelenterate, occurs periodically in swarms after turnover.

In his sampling, Begg also recorded 31 species of phytoplankton: Chlorophyta, 15 species (eight common); Cyanophyta, four species (two common); Pyrrophyta, two species (two common); and Chrysophyta, 10 species (three common). *Anacystis* is the dominant phytoplankton element and increases after turnover, although not immediately. *Surirella* sp. is the most common diatom.

Using more refined techniques and a plankton pump in 1970, workers at the Lake Kariba Fisheries Research Institute recorded eight new species of phytoplankton. Plankton of the open water of the lake is, in general, a dilution of that of the richer inshore and estuary areas.

BENTHOS

A. T. McLachlan's [1969*a, b, c,* also unpublished data, 1965] study of the ecology of the bottom fauna also indicates a change from eutrophy to mesotrophy, but the tendency is reversing since the establishment of aquatic vegetation; an increase in both species and standing crop is becoming apparent. This author describes Lake Kariba as a 'polypedilum' lake, after Brundin's classification, on the basis of the dominant chironomid constituent in the mud of the profundal. After the 1964 drop in water level, trees left exposed were attacked by a terrestrial wood borer (*Xyloborus torquatus*), and a new habitat later available to aquatic larvae after a rise in level was created under the bark. Subsequently, as trees broke owing to wave action, the tree habitat was destroyed. The effect of changing water level is most important and is described by A. J. McLachlan. At static levels on gently sloping cleared areas the biomass is maximal at approximately 2 meters at 500 mg/m² dry weight and disappears at 8–12 meters; it is composed of 23 species. With advancing water level the peak occurs at 0.2 meter at 10,000 mg/m² and consists solely of *Chironomus transvaalensis* (Figure 2).

G. W. Begg (unpublished data, 1970) investigated molluscan elements in the Sanyati basin and found a greater biomass on mud bottoms but a greater variety in vegetation. He has compiled a checklist of mollusks showing the following: lamellibranchs, two species; and gasteropods, two species of Prosobranchiata and seven species of Pulmonata (three common).

VEGETATION

From 1959 to 1964 the constantly changing shoreline resulted in ephemeral fringing vegetation occupying a narrow 1-meter strip at the limit of the soak zone (A. S. Boughey, unpublished data, 1965). Permanent quadrats have been established at the Nuffield Lake Kariba Research Station to record long-term development of shoreline vegetation.

Submerged vegetation has become established since 1964 [*A. J. McLachlan,* 1969*c;* B. G.

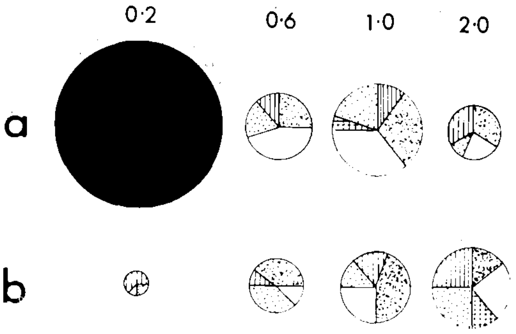


Fig. 2. Biomass and species composition of bottom fauna at Sengwa (*a*) during a rise in water level and (*b*) at static water level. The area of circles is proportional to the dry weight per square meter. Water depths in meters are indicated. The totally darkened area refers to the percentage of *Chironomus transvaalensis;* the other patterns refer to other constituent chironomids. Figure is taken from *A. J. McLachlan* [1969*b*].

Donnelly, unpublished data, 1970] and noticeably since 1967. *Potamogeton pusillus,* recorded in 1964, expanded rapidly in 1965; *Lagarosiphon ilicifolius, Ceratophyllum demersus, Potamogeton schweinfurthii,* and *Vallisneria aethiopica* have expanded since 1967; and, more recently, *Naias* sp. has increased. Since 1967 the terrestrial grass *Panicum repens* has assumed importance along some shorelines.

Donnelly [1969*a*] has given a detailed account of the importance of submerged vegetation as a nursery habitat. Bush-cleared areas provide a diversity of species and show a marked zonation.

Recent aerial surveys in 1970 by Lake Kariba Fisheries Research Institute staff have been useful in assessing the situation. The Sanyati basin is rich in vegetation, whereas, west of Sengwa, only isolated patches occur, owing to the rocky and steep coastline.

SALVINIA AURICULATA

Salvinia auriculata was first collected above the Victoria Falls in 1949; it appeared in Lake Kariba in 1959 where it exhibited explosive growth, as described by *Mitchell* [this volume, 1973*b*]. The growth of this species appears to have stabilized at about 15% of the total lake surface area and is confined mainly to creeks and protected inlets. The Lake Kariba Coordinating Committee in 1959–1960 prudently decided to investigate chemical and other methods of control. Costs of chemical spraying were, however, prohibitive.

Boughey [1963] describes the development of sudd mats on the *Salvinia.* In uncleared areas, trees trap *Salvinia,* and, between the line of *Salvinia* and the shore, *Salvinia* nursery areas occur. *Mitchell* [this volume, 1973*a*, also unpublished data, 1965] has indicated that nitrate nitrogen may be a limiting factor in the growth of the plant on Kariba. D. S. Mitchell (unpublished data, 1965) has also pointed out that *Salvinia* has retained in the lake a large amount of nutrients released on flooding that might otherwise have been lost through the release of water through gates and turbines.

Salvinia has offered some protection to young fish and has acted as a buffer when rapid water level fluctuations have destroyed other vegetation [*Bowmaker,* 1970]. Biological control of *Salvinia* is being investigated by using *Paulinia acuminata,* a grasshopper found in association with the plant in South America, as a control agent. It is thought that, although this control may result in limiting the spread of *Salvinia* rather than eradicating it, a valuable side effect would be the more rapid cycling of nutrients.

FISH POPULATIONS

Preimpoundment studies were carried out by the Joint Fisheries Research Organization in four visits in 1956 and 1957 [*Jackson,* 1961]. During the period of filling, gill-netting programs supplemented by commercial records provided data [*Harding,* 1966]. This system of data collection has continued [*Coke,* 1969; B. G. Donnelly, unpublished data, 1970, 1971] and is reinforced with detailed studies on the biology of certain species, the conditions in the vicinity of river mouths, and the problems of potamodromesis [*Bowmaker,* 1969*b*, 1970, this volume]. The time is now ripe for critical studies on certain physiological aspects.

The surveys by the Joint Fisheries Research Organization team established the occurrence of 28 species of fish (although more were known from this area), of which 20 were species that grew to >18 cm in the adult stage. *Hydrocynus* and other predators constituted 33% of the catch by numbers, whereas tilapias and other cichlids formed a very minor part. Despite the scanty information, these surveys were most valuable in providing a basis for recommendations on the future fishery.

Jackson [1960*a*] described the early period of flooding and predicted possible changes in the composition of the stocks. As a result of the more favorable environment offered to young fish, there was a high survival for subsequent age groups. The sharp break in age structure between young fish and yearlings that occurred under the old conditions was advanced a year later, and the first lake-spawned fish formed dominant year classes. Jackson predicted that, from 1961, catchable, well-grown 3-year-olds would enter the fishery. However, new factors began to emerge. Up to 1963, each flood covered new ground. After 1963, previously flooded areas, now denuded of vegetation, were inundated each year; the results of spawning by cichlids in particular were poor. This situation continued until vegetation became established and resulted in gaps in year classes spawned after 1962, so that, by 1967, only year classes of 6+ were available to the fishery. Also it must be understood that in each successive year from 1958 to 1963 the shallow areas resulting from flooding became progressively reduced owing to the morphometry of the lake basin. The reduction in habitat also reduced survival of young cichlids. In 1964, no tilapias were taken in nets of <11.5-cm (<4½-inch) mesh, but, by 1968, good recruitment was evident. The establishment of vegetation, drawdown, and the introduction of *Limnothrissa miodon* have all had far-reaching effects on the fish populations.

The distribution of species is strongly influenced by rivers and the nature of the basins. An example of this influence is the almost continuous decrease in the percentage of *Labeo* and increase in cichlids in catches from the head of the lake to the lacustrine basins near the dam (Figure 3).

Tilapia macrochir was stocked from 1959–1962 and totaled some 18 metric tons. These fish appeared sporadically in catches but have now disappeared almost entirely. They were introduced in the hope that they would populate the open water as they did in Lake Mweru. However, fish from Kafue River stocks were used for breeding; the young fish exhibited no behavior response to the predatory *Hydrocynus* and undoubtedly suffered severe reduction as a result.

Investigations of the feeding of *T. mortimeri* (previously designated *T. mossambica*) by B. G. Donnelly (unpublished data, 1970) indicate that there is little difference in the feeding habits of different sizes of this species and that these fish feed in a bottom-dredging manner instead of browsing off aufwuchs. Both dredging and browsing probably occur. *Donnelly* [1969*a*] surveyed nursery areas and found that all these occurred on or near horizontally bedded lower karoo and marly sandstones. This author also reported on the growth of tilapias [*Donnelly*, 1969*b*, also unpublished data, 1970]. He found that fish of up to 4 years old could be accurately aged by scalimetric means. Rapid growth occurred in *T. mortimeri* and *T. rendalli* (previously designated *T. melanopleura*) in the first 2 years, although the growth of the latter was much slower.

Coke [1969] has suggested that there has been a massive buildup in *Hydrocynus* since the lake has filled. He bases this suggestion on an increase in the percentage of this fish in experimental catches. However, an analysis based on numbers of fish per unit of effort in experimental nets in fact shows the reverse, i.e., a steady decline between 1960 and 1965 with a pickup in 1967 at the time that the *Alestes lateralis* population was expanding (B. G. Donnelly, unpublished data, 1971).

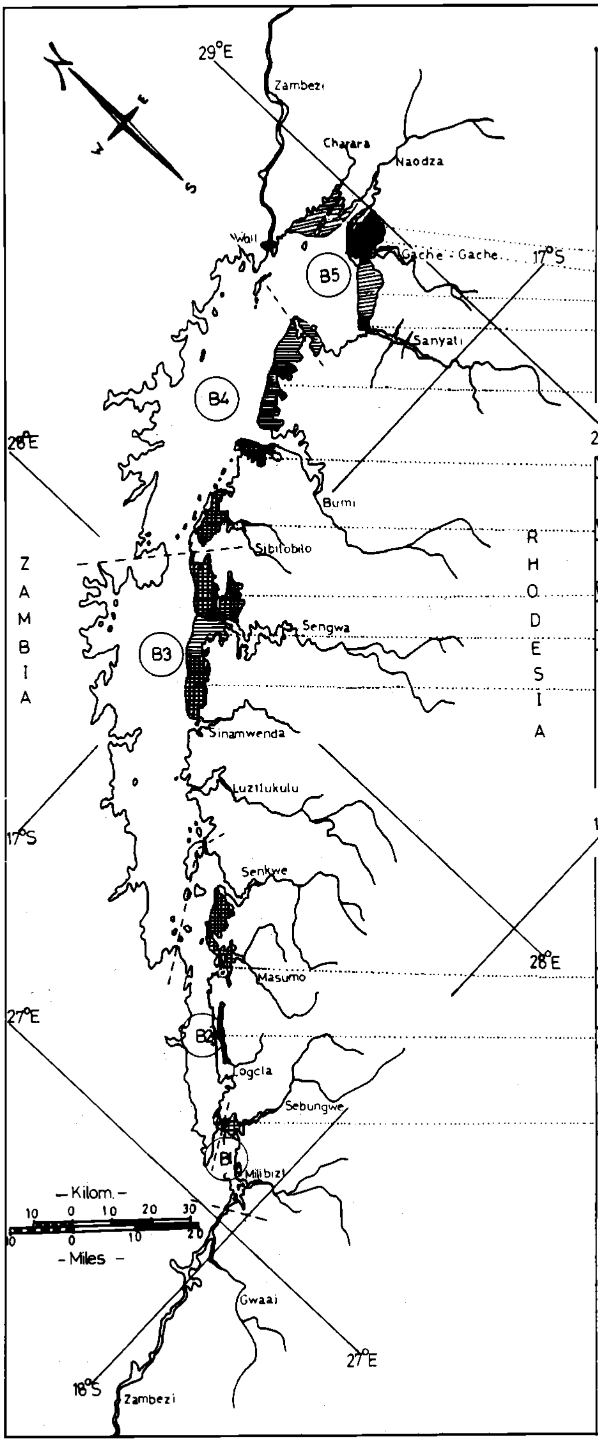
Since 1964–1965 there has been a reduction in the percentage of cichlids in the identifiable fish prey of *Hydrocynus vittatus* (B. G. Donnelly, unpublished data, 1971) and at the same time a proportionately greater drop in *Tilapia* as prey, from 20 to 8%. *Limnothrissa miodon* has now replaced *Alestes lateralis* as the major constituent of the diet of *Hydrocynus*. It thus appears that since the establishment of vegetation, despite the increasing numbers of *Tilapia*, the influence of *Hydrocynus* has declined. A high natural mortality occurs among *Hydrocynus* after these fish have reached a size of 20 cm. This occurrence strongly resembles the mortality of spawning salmonids.

The citharinids *Distichodus schenga* and *D. mossambicus* have shown a steady decline, although there are indications of a slight reversal. *Labeo altivelis*, which was a major constituent of the population, appears to have declined but in fact is still of importance in the riverine basins and occurs in the eastern end, where, because of the large mesh size used in the fishery, it forms only a minor part of the catch. *Labeo congoro*, on the other hand, is declining in the lacustrine basins, although it is still important at the western end of the lake.

Bowmaker [1969*b*, this volume] has concentrated on studies of upstream migration of fish in the Mwenda River. He suggests that there is no one factor triggering upstream spawning migrations but that a combination of physical and chemical factors is responsible.

FISH INTRODUCTIONS

The creation of new habitats as a result of dam building invariably raises the question of the introduction of additional fish species, a question that usually provokes heated argument. *Jackson* [1960*b*] mentioned some proposed introductions to Kariba, namely, *Limnothrissa*, *Stolothrissa*, *Serranochromis*, *Lates*, *Bagrus*, and *Tilapia macrochir*. At the Limnological Society of Southern Africa symposium in 1968, I discussed the possibility of the introduction of some of the Lake Malawi tilapias. The most successful introduction has been that of *Limnothrissa* by the Zambia Fisheries Department.



AREA	1968			1969			1970		
	CHARACIDAE	CYPRINIDAE	CICHLIDAE	CHARACIDAE	CYPRINIDAE	CICHLIDAE	CHARACIDAE	CYPRINIDAE	CICHLIDAE
I	4·3	0·8	80·0	0·9	0·4	84·4	1·2	0·4	90·7
II	1·4	1·9	93·8	2·6	2·2	89·4	3·6	1·8	87·3
III	4·1	0·8	78·1	2·1	0·7	66·9	3·6	1·5	84·6
IV	10·1	10·1	62·4	4·4	8·2	79·0	4·2	11·4	75·8
V	13·8	5·2	66·0	11·1	5·5	70·4	6·3	4·1	71·5
VI	2·9	8·9	84·0	1·7	7·6	85·6	1·4	5·6	86·9
VII	2·2	3·4	83·7	2·2	2·8	82·3	1·6	8·2	83·8
VIII	1·5	6·7	85·9	2·2	4·4	86·4	1·4	5·1	90·1
IX							9·2	5·8	73·9
X	3·3	12·4	64·1	1·2	6·9	88·1	0·5	1·9	96·2
XI	6·6	43·0	20·6	4·7	44·1	25·5	10·1	33·4	24·5
XII	5·2	62·1	3·6	8·6	69·2	1·6	10·4	45·4	29·2
XIII	4·2	50·0	23·8	8·4	69·2	6·4	7·0	63·1	23·2

Fig. 3. Lake Kariba showing percentage of *Labeo* and cichlids in catch at different localities along lake axis in 1968–1970. Note the general increase in *Labeo* (cyprinids) toward the head of the lake (Lake Kariba Fisheries Research Institute, unpublished data, 1970, 1971).

THE FISHERY

Early estimates of the fishery potential ranged from <9000 to 28,000 metric tons per annum. Early preparations were made for the fishing industry, and some 100,000 ha of the future basin was cleared at a total cost of about US$6 million. The area cleared represents 18% of the area of the basin and 52% of the area within the 20-meter contour. The clearing from 485 to 465 meters above sea level was done to facilitate fishing but not necessarily, as has been suggested, trawling. *Bowmaker* [1970] has suggested that in view of subsequent experience a better approach would have been to clear to canopy height (i.e., 11 meters below normal level on gentle shorelines) and to clear narrow lanes from the shoreline to a depth of 20 meters alternating with broad bands of trees.

The fishery on the Southern Rhodesian side is exploited by some 450 fishermen operating on a varying, but on the average small, scale and by an industrial concessionaire with freezing and ice works. Noncommercial fishing areas are demarcated in various parts of the lake for recreation and/or game reserves. Fish from the Sanyati basin are transported to Kariba where they are frozen, whereas from the rest of the lake the main export is in the form of dried or smoked fish. The African fishermen occupy some 30 camps along the lake, and a cash economy (where none previously existed) is becoming established; the injection of money into the area is of importance in development. Fish are collected and marketed by the concessionaire and independent traders.

Total production from the south bank increased until 1964 when it reached 2700 metric tons. Thereafter, there has been a decline to a level of between 1500 and 1800 metric tons per annum. The percentage by weight of the landings are as follows for 1969: cichlids, 62%; *Labeo* and *Distichodus*, 8%; *Hydrocynus*, 14%; and *Clarias*, 16%. The composition has not greatly altered except that, in the cichlid group, *Haplochromis codringtoni* and *T. rendalli* now form a significant part of the catch.

A comprehensive system of collection of statistical data has been set up. Landings by species, numbers and weights, effort, and other figures are submitted by the concessionaire for each statistical area in the concession, and enumerators obtain detailed information from fishermen in camps in other areas. These statistics have facilitated a study of catches in relation to effort and intensity and have been of value in indicating trends. In terms of fishable water to a depth of 20 meters, production per hectare increases from mid lake to 30–50 kg/ha in the Sanyati basin.

Training of fishermen was an important activity in the early stages. At present, schemes are under consideration or are being applied to provide for more permanent settlement, schools, community development advisors, and so on.

HEALTH ASPECTS

The problem of bilharziasis immediately comes to mind in any discussion of tropical waters. Before 1964 the constantly rising water level would have inhibited the establishment of a gasteropod population. The Blair Research Laboratory in Salisbury reported a noticeable increase in snail numbers from 1964, and, by 1967, heavy infestation of persons exposing themselves by swimming in inshore waters near Kariba township was reported. *Biomphalaria pfeifferi* and *Bulinus globosus*, the intermediate hosts, are confined to depths of <5 meters. The most stable populations occur in bays and inlets, and, where human contact takes place, transmission is serious. Snails have been transported from infected localities on *Salvinia* plants, and thus control is somewhat difficult. A rigid system of control along the lakeshore is necessary. Where frequent contact occurs, as is true in the case of water sportsmen, spraying of the shoreline with molluscicide is carried out. The Ministry of Health is tackling the problem of hygienic education.

OTHER RESEARCH

The impact of Lake Kariba on surrounding ecosystems has been investigated by wildlife workers and others not concerned with the aquatic system. *Jarman* [1969, also unpublished data, 1965], for example, carried out research on the effects of the lake on animal populations in the research reserve in the Chete area. Hippopotamus, waterbuck, and bushbuck initially suffered a loss of habitat. The dense growth of vegetation along the margin after the 1964 rains was used by elephant, impala, buffalo, and others.

The drowning of the Zambezi Valley vegetation and some of its specialized habitats and the emergence of new regimes have had considerable impact on bird populations (B. G. Donnelly, personal communication, 1971). Human activities resulting in the creation of bare ground and grassland in the form of roads, airstrips, and so on have opened the woodlands of the eastern section of the lake environs and allowed seasonal access by birds more characteristic of open environments.

DOWNSTREAM EFFECTS

The trapping of silt by Lake Kariba has resulted in an impoverishment of the alluvial floodplain in the Mana Pools area some 80–100 km below the dam wall. The ecological dynamism of the river has been reduced as a result of the stabilization in flow [*Atwell,* 1970]. Suggestions have been made for alleviating the damage with due regard to the primary requirements for which the impoundment was created.

ANIMAL RESCUE

During the period when the lake waters were rising, >6000 animals were moved from the area. In the course of the operation a quantity of information on behavior and other data were accumulated [*Child,* 1968; *Junor,* 1960*a, b*]. The operation generated a great deal of public interest throughout the world and was of great value to the cause of wildlife conservation.

RESETTLEMENT

The initial steps in explaining to the people and seeking their cooperation were made in 1955 when the chiefs chose their new areas in unsettled land. Preparations were made in these areas; roads were built, boreholes were sunk, and dams and weirs were built. The plan provided for taxpayers to be exempted for 2 years, for free grain ration for 2 years, and for vitaminized food concentrates and powdered milk to compensate for the lack of supplies in the initial period. Until the new settlements were established, medical attention, stock inoculation, and clearing of tsetse flies from the one area where they occurred were also catered to.

Customary observances being adhered to, people were moved in tribal and family groups in 1956. By 1957 the major moves had been successfully accomplished. In all, 22,000 people were involved.

In the new areas, >1600 km of roads and 20 dams and weirs were constructed, and 233 boreholes were sunk. A hospital, stores, and administration station was established at Binga, and schools and hospitals were set up elsewhere [*Cockroft,* 1967]. Improved agricultural methods and the fishing industry have had a considerable impact on the way of life of the people. The major cost of resettlement in the initial phase (£1 million) was borne by the Hydroelectric Board.

MULTIPURPOSE USE OF THE LAKE

In addition to its primary purpose, Kariba provides the opportunity for multipurpose management toward a host of other uses. The impact on tourism is considerable, and hotels, boat liveries, and safari cruises are concentrated at Kariba township and several other localities. Before the advent of the lake, much of the surrounding land was wildlife or hunting area and was little developed. The setting aside of national parks, wildlife areas, and reserves along the lakeshore and inland has been accomplished. The fishery itself is managed as an economically important recreational and sport fishery as well as a food-producing industry.

Although transport on the lake is of importance only to the villages and centers around it, there are a considerable number of vessels operating. A navigational and safety control system using three radio stations along the lake and ships' radios is in operation.

CONCLUSION

The amount of research effort stimulated by Lake Kariba has been considerable and far ranging. Much of it has had practical aims in view but has been of fundamental importance. Natural processes appear to be telescoped within a short period in the evolution of man-made lakes, and it is important to understand these changes thoroughly before greatly interfering with the system. As the study of man-made lakes progresses, a firmer understanding of the basic principles will be obtained; this understanding will allow for wiser interference than perhaps has previously been the case.

Acknowledgments. The author is indebted to numerous colleagues for information on a wide variety of subjects. Much use has been made of unpublished reports of the Lake Kariba Fisheries Research Institute staff.

REFERENCES

Allison, G. F., The hydrological management of Kariba, *Rhodesian Sci. News, 4,* 49–50, 1970.

Archer, C. B., Ten years of Kariba earthquakes, *Rhodesian Sci. News, 3,* 132–133, 1969.

Attwell, R. I. G., Some effects of Lake Kariba on the ecology of a flood plain of the mid-Zambesi Valley of Rhodesia, *Biol. Conserv., 2,* 189–195, 1970.

Begg, G. W., Observations on water quality and nature of affluent rivers of Lake Kariba with reference to their biological significance, *Limnol. Soc. S. Afr. Newslett., 13,* suppl., 26–33, 1969.

Begg, G. W., Limnological observations on Lake Kariba during 1967, *Limnol. Oceanogr., 15,* 776–788, 1970*a*.

Begg, G. W., Observations on the water quality of the affluent rivers of Lake Kariba with special reference to the importance of *Salvinia* mats on anadromesis, *Rhodesian Sci. News, 4,* 61–62, 1970*b*.

Boughey, A. S., The explosive development of a floating weed vegetation on Lake Kariba, *Adansonia, 3,* 49–61, 1963.

Bowmaker, A. P., Aspects of the physical hydrology of the Mwenda River mouth, Lake Kariba, *Limnol. Soc. S. Afr. Newslett., 13,* suppl., 9–15, 1969*a*.

Bowmaker, A. P., Fish population fluctuations associated with anadromesis at the Mwenda River mouth, Lake Kariba, *Limnol. Soc. S. Afr. Newslett., 13,* suppl., 45–49, 1969*b*.

Bowmaker, A. P., A prospect of Kariba, *Optima, 20,* 68–74, 1970.

Bowmaker, A. P., Potamodromesis in the Mwenda River, Lake Kariba, in *Man-Made Lakes: Their Problems and Environmental Effects. Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Caulton, M. S., A quantitative analysis of the mode of replacement of inorganic phosphates and nitrates in waters of Lake Kariba during December 1969–January 1970, *Limnol. Soc. S. Afr. Newslett., 15,* 52–57, 1970.

Child, G., *Behavior of Large Mammals during the Formation of Lake Kariba,* 123 pp., Trustees National Museum, Salisbury, Southern Rhodesia, 1968.

Crockroft, I. G., Kariba, *Nada, Rhodesian Min. Intern. Aff. Annu., 9,* 25–28, 1967.

Coke, M., Some observations on fish population dynamics in Lake Kariba, *Limnol. Soc. S. Afr. Newslett., 13,* suppl., 35–38, 1969.

Donnelly, B. G., A preliminary survey of Tilapia nurseries in Lake Kariba during 1967/68, *Hydrobiologia, 34,* 195–206, 1969*a*.

Donnelly, B. G., The growth of *Tilapia mossambica* and *Tilapia melanopleura* in Lake Kariba, *Limnol. Soc. S. Afr. Newslett., 13,* suppl., 44, 1969*b*.

Fish, G. R., A limnological study of four lakes near Rotorua, New Zealand, *N. Z. J. Mar. Freshwater Res., 4,* 165–194, 1970.

Harding, D., Lake Kariba, The hydrology and development of fisheries, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 7–20, Academic, London, 1966.

Jackson, P. B. N., Ecological effects of flooding by the Kariba Dam upon middle Zambezi fishes, *Proc. Fed. Sci. Congr. 1st,* 277–284, 1960*a*.

Jackson, P. B. N., The desirability or otherwise of introducing fishes to waters foreign to them, *Publ. 63,* Sci. Counc. for Afr. S. of the Sahara, Louvain, Belgium, 1960*b*.

Jackson, P. B. N., Ichthyology, The fish of the middle Zambezi, in *Kariba Studies,* Manchester University Press, Manchester, England, 1961.

Jarman, P. J., The effect of the creation of Lake Kariba upon the terrestrial ecology of the middle Zambesi Valley with particular reference to the large mammals, *Nuffield Lake Kariba Research Station Report, 1962–1968,* pp. 26–30, University College of Rhodesia, Salisbury, 1969.

Junor, F. J. R., Observations on the relative proportions of impala, bushbuck, duiker, grysbok, warthog, bushpig, antbear in the animal populations at Kariba during rescue operations, *Proc. Fed. Sci. Congr. 1st,* 285–286, 1960*a*.

Junor, F. J. R., Preliminary observations on the behaviour of various non-aquatic mammals under man-made flood conditions as noted at Kariba Dec. 1968–July 1959, *Proc. Fed. Sci. Congr. 1st,* 319–325, 1960*b*.

McLachlan, A. J., A study of the bottom fauna of Lake Kariba, *Nuffield Lake Kariba Research Station Report, 1962–1968,* pp. 13–14, University College of Rhodesia, Salisbury, 1969*a*.

McLachlan, A. J., Some effects of water level fluctuations on the benthic fauna of two Central Africa lakes, *Limnol. Soc. S. Afr. Newslett., 13,* suppl., 15–19, 1969*b*.

McLachlan, A. J., The effect of aquatic macrophytes on the variety and abundance of benthic fauna in a newly created lake in the tropics, *Arch. Hydrobiol., 66,* 212–231, 1969*c*.

McLachlan, S. M., Some physical and chemical characteristics of the mud and water of Lake Kariba with special reference to the habitat provided for benthos, *Nuffield Lake Kariba Research Station Report, 1962–1968,* pp. 11–12, University College of Rhodesia, Salisbury, 1969.

Mitchell, D. S., Supply of plant nutrient chemicals in Lake Kariba, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Mongr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973*a*.

Mitchell, D. S., Aquatic weeds in man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973*b*.

Sleigh, R. W., How Kariba dented the earth, *Rhodesian Sci. News, 3,* 129–131, 1969.

Thomasson, K., Notes on algal vegetation of Lake Kariba, *Nova Acta Regiae Soc. Sci. Upsal., Ser. 4, 19,* 1–34, 1965.

Lake Kariba: The UNDP Program and North Shore

LEONARD S. JOERIS

UNDP/FAO Central Fisheries Research Institute, Chilanga, Zambia

Lake Kariba, one of the largest man-made lakes in the world and the first in Africa to be assisted in its economic development by the United Nations Development Program (UNDP) and the Food and Agriculture Organization (FAO), has had an extremely interesting history both from scientific and from political aspects. The money needed to construct the dam was provided largely through a loan from the World Bank to the government of the Federation of Rhodesia and Nyasaland and the government of Great Britain, the three territories of the federation being at that time colonies of Great Britain.

Almost from the moment that the loan from the World Bank was signed, the project started to move into an international sphere (not by plan, but by necessity) to meet the rapidly changing political situation emerging in central and southern Africa. Because of political events subsequent to the breakup of the federation in December 1963, a basis for coordination of any type of lake-wide research or development had disappeared. Kariba had for all practical purposes become two separate lakes with little or no exchange of ideas or interests other than those concerning the Central African Power Corporation, which had been established to take over the functions of the Federal Power Board as a legal international organization to develop power and to safeguard the interests of the World Bank.

Kariba has provided much experience that can be used by the planners and developers of the more recently established man-made lakes. Certainly the most important lesson to be learned is the need for a strong lake or overall river authority, coordinating committee, or similar organization responsible for the planning and developing of all aspects of the area. This responsibility would include power production, fisheries, agriculture, tourism, resettlement, community development, public health, and numerous related interests.

MANAGEMENT AND RESEARCH

In the case of Kariba we have an excellent example of what can happen when all aspects except power production are left to a variety of committees and discussion groups with no legal authority or status and with limited technical guidance. To have predicted what was going to happen and to plan a program of development for Lake Kariba in a logical way would have been impossible. If, however, the Federal Power Board, to whom the original loan was made, had been given broader powers than those strictly concerned with the construction of the dam and the operation of the power facilities, Kariba would be in a far better position today.

The Lake Kariba Coordinating Committee was formed and functioned until late 1963. One of its major contributions was a request in 1961 to the UNDP for assistance in the establishment of a Lake Kariba Fisheries Research Institute. The request was granted; by January 1964, all negotiations had been completed, and the institute, which was located on the Southern Rhodesian side of the lake, was a functioning organization even though by that time the federation had ceased to exist.

When Southern Rhodesia declared independence in November 1965, the Southern Rhodesian government took over the institute's support entirely and has continued to develop and expand the original program on the Southern Rhodesian side. At this time the Central Fisheries Research Institute was established in Zambia by the UNDP and the Republic of Zambia to continue work on Lake Kariba and to expand operations to all Zambian fisheries.

I will attempt to restrict my presentation to the work carried on by the institute from its inception in January 1964 to December 1965 for the whole lake and to the work carried out on the Zambian, or north, side of the lake by the UNDP-supported Central Fisheries

Research Institute from 1966 to the present time.

One of the few lake-wide studies completed during the life of the institute as an international organization is the limnological study of the lake conducted by *Coche* [1971*a*]. Another valuable accomplishment begun during this period and completed later in Zambia is a multidisciplinary bibliography on Lake Kariba [*Coche*, 1971*b*].

The Lake Kariba Coordinating Committee was responsible for the introduction of an experimental fishing program designed to ascertain, if possible, the condition of the fish stocks as they developed so that they could be properly managed. This program, consisting of fishing fleets of topset and bottomset gill nets ranging in mesh size from about 38 to 178 mm, was carried out at 3-month intervals throughout the lake and produced large volumes of catch data from the beginning of the lake until 1968, at which time the program on the north bank was discontinued because it was failing to produce the data needed to manage the fishery.

To replace this study, a series of chemical fishing operations and extensive echo-sounding surveys have been conducted through the Zambian half of the lake in selected bays ranging in size from 0.2 ha to 2 ha. This study is now producing what is felt to be reliable estimates of total ichthyomass and potential harvestable fish stocks far above what is now being used. Dr. Eugene Balon, FAO fishery biologist, has, in cooperation with associates in Czechoslovakia, numerous manuscripts under preparation.

The number of species known to be present in the lake has increased from about 30 at the time of construction of the dam to 40 at the present time. Of these species, only two have been introduced; the remainder have moved downriver from above Victoria Falls and have in most cases become well established. A suspicion that no species originally inhabiting the Zambezi River would be able to occupy the vast offshore areas was confirmed by 1965, and efforts to introduce *Limnothrissa miodon* from Lake Tanganyika were made during 1967 and 1968. These efforts were successful, and this species now inhabits all open water areas. However, *Alestes lateralis*, originally extremely scarce in the middle Zambezi area, has been able to expand rapidly and now occupies much of the open water, whereas *Alestes imberi*, previously very abundant in shallow areas only, has all but disappeared. This change occurred between 1963 and 1968 and is documented by *Balon* [1971].

Soon after the dam was closed, a large eel population was observed in the lake. Because of the extreme height of the dam it was assumed that this population would surely be eliminated, since no practical means could be organized for transferring the elvers returning from the Indian Ocean to the lake. An occasional large individual, assumed to be a member of a year class that moved upriver before the closing of the dam, has been caught in the lower part of the lake. The assumption that the population would be eliminated was subjected to serious doubt, however, when chemical fishing operations conducted in streams leading into the upper reaches of Kariba provided a number of relatively small immature eels in 1970, 11 years after the closure of the dam. Recent studies have now demonstrated that a large eel population with representatives from age groups of 2–10 years is present on the Zambian side of the lake and must be assumed to be present throughout the lake. How they are overcoming the barrier created by the dam is under serious study.

RESETTLEMENT

Although the construction of the dam was carried out as a federal government project, resettlement and the development of the fishery were left to the territorial governments who organized and carried out their own programs. Approximately 30,000 people were resettled on the north bank. The major difference in the programs was that Southern Rhodesia assumed full responsibility for the people to be resettled and provided full support for them until they were moved and self-sufficient in their new areas whereas Northern Rhodesia (Zambia) left much more to the individual after providing him with a small cash settlement and providing large sums of money to the Gwembe Valley Authority to be used for the development of the fishery, tourism, agriculture, and supporting industry. On the Zambian side a successful fishery training school was established to train local fishermen in basic fishing operations and in the handling of new fishing gear and the use of new processing methods.

The changes that have occurred politically and economically in the area have drastically changed the needs of the local people and have overshadowed all the problems caused by their removal from the river valley and resettlement on higher ground. The changes have virtually eliminated any problems that could be directly attributed to movement and resettlement.

FISHERY MARKETING AND PROCESSING

During the early life of Kariba the bulk of the gill net fishery took place in the cleared areas located near new villages or fishing camps. However, with experience and encouragement the bulk of fishing now takes place in the tree-covered areas where the preferred species appear to congregate (Figure 1).

During the time when the lake was under construction, the governments of Southern Rhodesia and Zambia established their individual policies for the industrial development of the fishery. The Southern Rhodesian government granted concessions to two large refrigeration companies to fish. They also collected and marketed fish from the south shore of the lake. Concessionaires constructed two freezing plants on the lake, one with a −30°C air blast freezer with a daily capacity of 9 metric tons, a block ice plant with a daily capacity of 1.8 metric tons, and a staff of 200 local workers. By 1965 this plant was operating at an average daily level of 4.5 metric tons and an annual production of 1275 metric tons of frozen fish. A second plant capable of producing 1.8 metric tons per day was established well up the lake, but this plant never started operation because of a shortage of fish in the area. The concessionaires subsequently merged. Both of these concessionaires had their own fishing crews of local people using gill nets and small boats or dugout canoes, as well as larger boats that collected fish from their own crews and from individual fishermen in the area.

A third independent organization with permission to buy fish from local fishermen (but prohibited from conducting its own fishing operations) started work in January 1965. Although located in a remote area at the base of the escarpment where the only communication was by boat, this plant provided a ready market for fishermen, who rapidly established a village nearby. The plant had a daily capacity of 3.6 metric tons of fresh fish. The fish were brined, smoked, and dried and distributed throughout the agricultural areas of Southern Rhodesia. During the approximately 10 months that it operated before being forced out of business by the larger competitors, this plant produced approximately 450 metric tons of fish with a 12-man labor force and a total plant investment of under $5000, whereas the larger plant employing a work force of 200 in a plant that was at least 15 times more expensive produced approximately 1275 metric tons.

Fig. 1. Fishing scene, north shore of Lake Kariba.

The fishery on the north bank was to be developed by local fishermen with the aid of the government who established a few small market facilities, including a building with running water, tables, and washing tanks for the fishermen and traders. In addition, the Department of Fisheries stationed fish guards with scales to provide a weighing service for fishermen and traders, to collect production statistics data, and to assist fishermen and traders in extension and development.

One large commercial block ice plant with a daily capacity of 7.4 metric tons was constructed approximately 160 km up the lake to supply ice for the fishing trade. However, this plant was forced to close in 1966 for lack of business. The idea of factories to develop the fishery not only on the Zambian side of Kariba but throughout Zambia's numerous remote fishing areas was enthusiastically accepted, but as yet none of the six factories built has been developed. Of the fish caught in Kariba in Zambian waters and reaching the commercial market in 1965, approximately 50% was sold fresh, the remainder being sold as dried fish produced entirely by local fishermen.

Following the closure of the ice plant in 1966 the production continued to decline to 820 metric tons in 1967 but since then has climbed to 1550 metric tons per year in 1970 in Zambia. The bulk is marketed as dried fish. With this trend from fresh to dried fish a new fish-drying technique has been developed by the Central Fisheries Research Institute and introduced through the Fisheries Division Training School on Lake Kariba. Previously salted fish were unacceptable on the Zambian market, and all dried fish were hot smoked and sun dried and had an expected storage life of about 1 or 2 months before being completely destroyed by dermestid beetles. The new technique includes brining the fish to a point where they contain 7–10% salt concentration and then warm smoking and sun drying them. The finished product retains 40–45% of its original weight, whereas fish prepared by traditional methods retain only about 25%. The storage life is 1–2 years. This product was not available in the markets prior to 1968 but now makes up as much as 75% of the dried fish offered for sale in Zambia [*Watanabe and Cabrita,* 1971; *Watanabe and Dzekedzeke,* 1971].

FISHING GEAR

The extension work that was originally planned to train the fishermen and to continue their education deteriorated, and by late 1966 all contact with local fishermen for extension and training purposes had practically stopped. In addition, rapid expansion took place in the Zambian economy soon after independence that provided large numbers of jobs in government and industry and attracted many of the better fishermen away from fishing. Other successful fishermen who had accumulated adequate savings moved into the industrial areas to establish small businesses or real estate interests for the rapidly growing urban populations.

The gill net has been practically the only gear used commercially in the lake since it was formed. Efforts to introduce other types of gear have proved unsuccessful because of the vast numbers of trees left standing in the lake, the secondary growth that came up during the almost 2 years from the time of clearing to filling, and the extremely rough bottom conditions throughout the lake.

Y. Znamensky, FAO fishing gear technologist, has made some substantial improvements in the gill net fishery by reducing the hanging coefficient of the gill nets from 0.5 to 0.4. This reduction has produced a one to twofold increase in the unit of effort catch of the nets. All fishermen are now being encouraged to use the improved nets, and these nets have been responsible for much of the increased production in 1969–1970.

With the successful introduction of the Lake Tanganyika sardine, *L. miodon,* a newly developed fishing method from Lake Tanganyika has been introduced to Kariba to harvest the sardines and predator species associated with them. The new chiromila net, similar to a small purse seine, is proving quite successful for the open water sardine fishery now developing. Long lines have produced good catches of eels and large catfish, but the market for these has not yet been developed.

In light of the early predictions on the potential production expected from Kariba and the early efforts to reach this potential, the poor production from Kariba can only be a serious disappointment to all involved. On the basis of Dr. Balon's recent work, our best estimate at this time is that <10% of the available fish crop in

Kariba is being harvested. The maximum potential production of 27,300 metric tons estimated from Kariba at the time of its construction can now be considered very conservative.

CONCLUSION

I am pleased to say that the Lake Kariba Fisheries Research Institute located at Kariba, Southern Rhodesia, and the Central Fisheries Research Institute located at Chilanga, Zambia, have produced valuable research and development information that has led to recent investments in the related fishing industries of fish processing, fiber glass boat building, and net making of better than $5,000,000 by the Republic of Zambia and private industries. Large sums are also being made available to local fishermen in the form of loans for purchase of nets and boats by fishermen participating in training courses in modern fishing, processing, and marketing courses.

REFERENCES

Balon, E. K., Replacement of *Alestes imberi,* Peters, 1852, by *Alestes lateralis,* Boulenger, 1900, in Lake Kariba, with ecological notes, *Fish. Res. Bull. Zambia, 5,* 119–162, 1971.

Coche, A. G., Description of physico-chemical aspects of Lake Kariba, an impoundment, in Zambia-Rhodesia, *Fish. Res. Bull. Zambia, 5,* 200–267, 1971*a.*

Coche, A. G., Lake Kariba basin: A multi-disciplinary bibliography, 1954–1968, *Fish. Res. Bull. Zambia, 5,* 11–87, 1971*b.*

Watanabe, K., and F. J. Cabrita, Directions for the preparation of salted and dry-smoked fish, *Fish. Res. Bull. Zambia, 5,* 225–238, 1971.

Watanabe, K., and O. Dzekedzeke, Taste preference of Zambians for various types of dried and smoked fish, *Fish. Res. Bull. Zambia, 5,* 199–205, 1971.

Results of Fish Population Size Assessments in Lake Kariba Coves (Zambia), A Decade after Their Creation

EUGENE K. BALON[1]

UNDP/FAO Central Fisheries Research Institute, Chilanga, Zambia

Lake Kariba, the second largest man-made lake after Lake Volta, has a fairly rich history of fishery investigations. At the time of my arrival (1967) the decline in fish catches was most alarming, and from this decline emerged the priority of fish stock assessment. But an intensive search through available data showed that none of the data were suitable for any further processing from the stock size assessment point of view. The research data, mostly from gill net catches, could not be related to area; fish catches and landing statistics were found to be so erroneous that any single value given was completely unrealistic. There was no doubt that only a new quantitative sampling scheme could be of some help.

Full details on the morphometry of Lake Kariba are given by *Coche* [1968], and new area values used for the present work were kindly supplied by him from unpublished data. The dendritic shoreline of the lake [*van der Lingen,* this volume, Figure 1], with numerous bays and coves, made fish sampling by chemical means eminently suitable, even though it was realized at the start that because of the size of the lake the samples could not be numerous enough to represent acceptable statistical limits, especially with the time and manpower at our disposal. However, no other more satisfactory method was available.

Preliminary data from samples taken in early 1968 proved our working theory: since the whole fish population was of riverine origin, its distribution was limited to shallow inshore waters. This theory was also confirmed by gill net catches [*Coke,* 1968]. However, we needed to define the limits of this distribution to obtain the mean area inhabited by fish as a basis for further calculations. With the help of a large-scale echo-sounding survey the topographic, vertical, diel, and seasonal distributions of fish were studied. The mean area of Lake Kariba inhabited by fish in 1968 and 1970 corresponded to 25% of the depth area of 0–20 meters at normal water level (i.e., 33,422 ha, which represents 6.2% of the total lake surface).

We found practically no fish in the open water and deepwater areas except for small schools of *Alestes lateralis* that started to appear more and more offshore as a result of their enormous population density in inshore areas and their tendency to colonize the uninhabited lake areas [*Balon,* 1971*a*]. The second exception was the eel (*Anguilla nebulosa labiata*), which contradicted the predictions of *Jubb* [1964] by moving regularly over the dam wall to form a fairly abundant population in the medium deep water of the lake. For example, eels were caught on every third hook of long lines (Y. Znamensky, personal communication, 1970), and small juvenile eels were common in samples from the Kalomo River at the Siengwazi Falls (1969). Furthermore, the introduction of the Lake Tanganyika clupeid (*Limnothrissa miodon*) in the last years before the start of our investigations [*Bell-Cross and Bell-Cross,* 1971] recently proved to be successful, and the first abundant schools of this species were observed in open waters in late 1969. Therefore our data are valid only for the original natural fish stock of the lake. The evaluation of the new open water fish stock and its interrelationship with the original stock should be done in further studies.

This paper is restricted to descriptive data only and is a preliminary list of the values obtained. How well these data represent each lake basin or

---

[1] Now at Department of Zoology, University of Guelph, Guelph, Ontario, Canada.

TABLE 1. Location and Description of Sampling Experiments, Lake Kariba Coves

Experiment	Basin	Locality	Date	Area, ha	Maximum Depth, meters	Topography	Sampling Methods
A	4	cove near Siavonga shore	March 20 to 23, 1968	0.818	16	deep rocky cove with sand beach end; submerged trees, small groups of drifted *Salvinia*, and few bunches of *Ceratophyllum demersum* and *Chara*; clean rocks and sand on bottom	rotenone in 0.114-ppm concentration; area blocked by small mesh net on surface only
B	4	inshore waters of island N102 near Siavonga	March 21 to 22, 1968	0.476	21	high steep rocky shore and few submerged trees and bushes; rock, gravel, and sandy bottom with little mud and detritus; little *Potamogeton pusillus*	electric discharge in a 20-m^2 area with four 226-gram plastic explosives and one 150-meter cord
C	3	Chikanka Island cove	June 21 to 25, 1968	1.210	5	long narrow cove with rocky and muddy shores; *Salvinia* mats cover a quarter of the area at the inland end; bottom of soft mud and gravel; groups of *Phragmites*, *Lagarosiphon*, *Nymphaea*, and *Cyperus*	toxaphene in 7-ppm concentration; area completely blocked with double small mesh nets
D	2	cove of island N20 southwest of Sinazongwe	Dec. 11 to 14, 1968	1.147	16	valley cove of *Euphorbia* hills; rock and sand on shores, very little *Salvinia*, lots of submerged vegetation in shallow part (*Ceratophyllum*, *Lagarosiphon*, *Potamogeton sweinfurthii*), submerged trees and bushes; soft mud bottom	toxaphene in 7-ppm concentration; area completely blocked with double small mesh nets
E	3	Chete Island cove	March 20 to 25, 1969	5.273	4	shallow cove with swampy and grassy shores; quarter of the area covered by *Salvinia*; lots of submerged *Ceratophyllum demersum* and *Potamogeton pusillus*	toxaphene in 7-ppm concentration; area completely blocked with double small mesh nets
E_2	3	intermittent stream estuary at end of Chete Island cove	May 25, 1969	0.021	0.5	shallow swampy part of cove with numerous submerged bushes; bottom of deep mud and sand; submerged *Panicum*, *Ludwigia*, and *Typha*	toxaphene in completely blocked area

TABLE 1. (continued)

Experiment	Basin	Locality	Date	Area, ha	Maximum Depth, meters	Topography	Sampling Methods
F	3	cove 1 in Chipepo Bay	May 26 to 31, 1969	0.191	4.5	small cove at Kota Kota Hills Valley with steep rocky and forest shores; completely covered by *Salvinia* mat and full of *Ceratophyllum*, *Phragmites*, and *Vossia*; bottom of soft mud	toxaphene; area completely blocked by double net; *Salvinia* and some other plants were removed before treatment
G	3	cove 2 in Chipepo Bay	May 28 to 31, 1969	0.083	5.4	similar to the description given above for experiment F	toxaphene; area completely blocked by double net; *Salvinia* and other plants were not removed before treatment

the whole lake is not discussed. A precise critical evaluation is under preparation.

SAMPLING TECHNIQUE AND TREATMENT OF DATA

The sampling procedures and data processing are detailed elsewhere [*Balon,* 1972]. A summary only is given here. On the average, such sampling should represent the whole fish population. Fifteen localities from the Zambian territory were sampled. Seven were treated without blocking nets and were used to supplement the data from echo surveys of the fish distribution. They were not included in the quantitative estimates because of the strong evidence that chemical samples obtained without blocking nets are not representative [*Swingle,* 1950; *Lambou and Stern,* 1958]. These samples were, however, used to complete the list of Lake Kariba fish species from which three species were missing in representative blocked-off samples. Two other incompletely blocked samples are listed to show the difference with properly blocked samples. The latter are the only ones used for further calculations, especially as far as means are concerned (Table 1).

The blocking nets (8-mm mesh for the 1-meter top strip and 25-mm mesh for the remainder of the net) were set at different hours of the day to avoid blocking the highest evening or the lowest morning concentration (discovered from echo-sounding records related to diel changes in fish distribution). Cove A was sampled at 0530 hours; B, 1240 hours; C, 1200 hours; D, 1800 hours; E, 1900 hours; E_2, 0945 hours; F, 1830 hours; and G, 1300 hours.

Because the supply of 5% emulsifiable rotenone was adequate for only one experiment, 75% emulsifiable toxaphene was later used. The concentrated solution was distributed by boat through a 5-mm hole made in the original 25-liter container and was mixed by the propeller of the outboard engine. The water volume within the blocked area was roughly estimated to calculate the necessary amount of toxicant. The lethal dose [*Anwand,* 1968; *Balon,* 1968] was highly overestimated because it was essential to kill all the fish at once and to get the residual fish on the bottom that surfaced not later than the third or fourth day. Under the prevailing water temperature of >20°C the fish that appeared later were so rotten that it was difficult to handle them. Fast killing was also essential to limit the bias due to predation by birds, mammals, and occasionally crocodiles and monitor lizards. Even so, some *Clarias* died only on the third day. The overdosing had a limited effect out of the cove area. As the total area treated involved only about 15 ha (0.03% of the lake area inhabited by fish and <0.002% of the total lake area), the use of toxaphene was justified. One month later the treated area had a higher abundance and standing crop of fish than it had prior to treatment (compare locations E and E_2 in Table 3).

Fish were collected in the deepest part by dip nets from boats and along the shore by hand. As far as was possible, all fish, including the smallest juveniles, were collected. On some of the larger fish, measurements were made on the spot, but the majority of the fish were preserved in 4–10% formalin for later study in the laboratory.

Before the sampling ended and the blocking was lifted the entire cove was measured by using a plane table and soundings. A detailed bathymetric map was made. The area, length of shoreline, maximum and average depth, and volume of water were then estimated. Finally, the cove was checked by a diver for residual fish that were estimated from counts taken on transects along the bottom.

Every specimen was taxonomically determined. Its standard length was recorded. Weight and total length were also taken from the first few hundred fish of every species. Conversion diagrams and tables for total length and weight incorporating corrections for fresh, rotten, and preserved fish weight differences were calculated. These diagrams and tables simplified the processing of later experiments based on standard length measurements only. All weight data mentioned in this paper, therefore, are derived values. The length was measured with a precision of 1 mm, and the weight was measured with a precision of 0.1 gram (small fish) or 1 gram (large fish). The results hereafter are based on a total number of 106,088 fish.

FISH STOCK ABUNDANCE

One advantage of this sampling procedure is seen in the diversity of species found. Eight new species for Lake Kariba, five of which were economically preferred species, were sampled for the first time: *Tilapia andersonii, Sargochromis giardi, Haplochromis carlottae, Serranochromis robustus jallae, Serranochromis macrocephalus, Barbus unitaeniatus, Barbus poechii,* and *Labeo lunatus.* In contrast with our list of 39 species (Table 2), *Jackson* [1961] listed 28 species from the middle Zambezi River prior to the creation of Lake Kariba, *Harding* [1964] listed 31, and both authors recorded six other species occurring in the plateau tributaries (recently recorded by us as well); *Bell-Cross* [1965, 1966] listed 29 species for Lake Kariba and the middle Zambezi region. From the frequency of occurrence in our samples, not all listed species are equally distributed; the percentage of abundance reflects this unequal distribution even better. At least 10 species are relatively rare, six species are economically preferred, and four are accompanying species.

Such division of the species into three groups must be further discussed. In principle, it follows the division based on the relative growth [*Balon,* 1964]. The growth of all species having not yet been evaluated, only an approximate and subjective division is used here, and this division is also based on the fisherman's attitudes toward certain species. The eel, for example, appears in the secondary species group, although according to its species average size value it should clearly belong to the first group. The same can be said of *Alestes lateralis* and *Limnothrissa miodon,* which on the basis of size should belong to the last group except for the local preference. The groups reflect better the secondary view of such a division: economically preferred species are selected for commercial use primarily and without hesitation, secondary species form a not fully or not at all exploited reserve for commercial use, and accompanying species are nonexploited. From this point of view, *Harding*'s [1964] nine species of commercial importance are extended to 17 species, and his secondary group is extended to 25 species even if a few of them are not landed very often and are thus recorded in the statistics under other species headings.

In general, the most abundant fish was *Alestes lateralis,* which had a mean occurrence of 58.78% in all samples recorded. It is followed by *Tilapia mortimeri,* which had a 10% occurrence, and *Cyphomyrus discorhynchus,* which had an 8% occurrence (Table 2). On the basis of total number sampled the most abundant group is formed of secondary species (67.78%), owing to the extremely high abundance of *Alestes lateralis.* The extremely high abundance of economically preferred species in locality E_2 was due to *Tilapia* juveniles, because the cove treated was a typical nursery for them [*Donnelly,* 1969]. Some of the

TABLE 2. Recent (1968 to 1970) List of Lake Kariba Fish Species in Economic Order According to the Average Size, Abundance, Topographic Frequency of Occurrence, and Mean Percentage of Total Number of Specimens

Order Number	Species	Frequency of Occurrence	Mean Percentage of Total Number
	Economically Preferred		
1	*Tilapia mortimeri* Trewavas, 1966	8	10.00
2	*Tilapia rendalli* (Boulenger, 1896)	8	3.62
3	*Hydrocynus vittatus* Castelnau, 1861	8	2.48
4	*Clarias gariepinus* (Burchell, 1822)	6	2.00
5	*Sargochromis codringtoni* (Boulenger, 1908)	6	1.10
6	*Heterobranchus longifilis* Val., 1840	6	0.09
7	*Mormyrops deliciosus* (Leach, 1818)	5	0.47
8	*Labeo altivelis* Peters, 1852	5	0.18
9	*Mormyrus longirostris* Peters, 1852	4	0.05
10	*Distichodus schenga* Peters, 1852	3	0.28
11	*Labeo congoro* Peters, 1852	3	0.02
12	*Tilapia andersonii* (Castelnau, 1861)	2	0.85
13	*Sargochromis giardi* (Pellegrin, 1904)	2	0.16
14	*Haplochromis carlottae* (Boulenger, 1905)	1	0.10
15	*Serranochromis robustus jallae* (Boulenger, 1896)	1	0.04
16	*Serranochromis macrocephalus* (Boulenger, 1899)	1	0.04
17	*Distichodus mossambicus* Peters, 1852	1	0.03
Total			21.51
	Secondary		
18	*Alestes lateralis* (Boulenger, 1900)	8	58.78
19	*Cyphomyrus discorhynchus* (Peters, 1852)	6	7.94
20	*Eutropius depressirostris* (Peters, 1852)	5	0.74
21	*Gnathonemus macrolepidotus* (Peters, 1852)	5	0.12
22	*Malapterurus electricus* (Gmelin, 1789)	5	0.07
23	*Schilbe mystus* (Linnaeus, 1762)	3	0.13
24	*Anguilla nebulosa labiata* Peters, 1852	...	...
25	*Limnothrissa miodon* (Boulenger, 1906)	...	...
Total			67.78
	Accompanying		
26	*Haplochromis darlingi* (Boulenger, 1911)	8	5.20
27	*Barbus fasciolatus* Günther, 1868	5	4.64
28	*Barbus unitaeniatus* Günther, 1866	8	1.80
29	*Hemihaplochromis philander* (Weber, 1897)	7	1.28
30	*Synodontis zambezensis* Peters, 1852	6	1.02
31	*Micralestes acutidens* (Peters, 1852)	6	0.41
32	*Synodontis nebulosus* Peters, 1852	5	0.33
33	*Brachyalestes imberi imberi* (Peters, 1852)	5	0.28
34	*Aplocheilichthys johnstonii* (Günther, 1893)	5	0.04
35	*Labeo cylindricus* Peters, 1852	3	0.01
36	*Barbus lineomaculatus* Boulenger, 1903	2	0.02
37	*Barbus poechii* Steindachner, 1911	2	0.02
38	*Labeo lunatus* Jubb, 1963	1	0.02
39	*Barbus paludinosus* Peters, 1852	...	...
Total			15.07

high abundance of secondary species is due to spawning concentrations of *Alestes lateralis.*

The average relative abundance of fish in Lake Kariba was 36,623 specimens per hectare (Table 3), of which there were 5849 economically preferred species, 24,823 secondary species, and 5950 accompanying species; the calculations are in specimens per hectare. If we extrapolate these data to the total area inhabited by fish in Lake Kariba, the total number of fish would be 1224 million; of this number, 195 million would belong to the economically preferred group, 830 million to the secondary group, and 199 million to the accompanying group of species. In Table 4, data are also given for the different basins of the lake. As most of the sampled coves were in basin 3, the

TABLE 3. Relative Abundance of Lake Kariba Fish after Block-Off Net Sampling in Coves

Experiment	Number of Species	Economically Preferred Species, Number per Hectare	Secondary Species,[§] Number per Hectare	Accompanying Species, Number per Hectare	Total
A[*]	14	170	130	839	1,139
B[†]	9	92	645[#]	662	1,399
C	29	1,276	1,760	386	3,422
D	29	1,609	29,192	1,417	32,218
E	27	1,044	6,116	918	8,078
E_2	9	26,285	11,238[#]	8,524	46,047
F	23	2,612	63,900	17,025	83,537
G	25	2,371	36,735	7,432	46,538
Range		1,044 to 26,285	1,760 to 63,900	386 to 17,025	3,422 to 83,537
Mean		5,849	24,823	5,950	36,623

[*] In this experiment the cove was blocked by the net only in the surface water layers, and these values are excluded from the mean.

[†] This experiment only includes the part of the stock sensitive to explosion, and these values are excluded from the mean.

[§] Abundant stocks of *Limnothrissa miodon* and *Anguilla nebulosa labiata* of open and deep water are not included.

[#] *Alestes lateralis* only.

estimated data should be within acceptable limits for this basin.

STANDING CROP

For evaluating protein reserves, standing crop data are more important than values of abundance. The relative importance of the species in this respect also differs substantially from the one based on abundance. The highest mean standing crop was shown by *Tilapia mortimeri* (97 kg/ha), followed closely by *Cyphomyrus dischorhynchus* (96 kg/ha) and *Mormyrops deliciosus* (92 kg/ha). Then appears the second bream, *Tilapia rendalli* (56 kg/ha), and the barbel, *Clarias gariepinus* (52 kg/ha), followed by the completely unexploited electric catfish, *Malapterurus electricus* (48 kg/ha). Then, in order, those species with the highest to lowest standing crops are: the tiger fish, *Hydrocynus vittatus* (31 kg/ha); *Alestes lateralis* (29 kg/ha); *Synodontis zambezensis* (19 kg/ha); *Mormyrus longirostris* (18 kg/ha); *Heterobranchus longifilis* (14 kg/ha); *Sargochromis codringtoni* (13 kg/ha); *Eutropius depressirostris* (9 kg/ha); *Labeo altivelis* (6 kg/ha); *Haplochromis darlingi* (5 kg/ha); and all other species with <3–1 kg/ha.

For the area of Lake Kariba inhabited by fish the standing crop is estimated at 17,814 metric tons, of which 64% is economically preferred species, 30% is secondary species, and 6% is accompanying species (Table 5).

DISCUSSION AND NOTES ON PRODUCTION

At best the above-mentioned values give only an overall picture of the size of the Lake Kariba fish population. It must be remembered that the values hold only for the years under study and are biased by sampling errors. Calculated biomass values will be much higher. On the other hand, the many data on standing crop and production obtained so far lead to the conclusion that their final values for certain regions are more or less stable even if species saturation in relation to habitat capacity is far from being attained, as seems to be the case for Lake Kariba.

As far as the species occurrence is concerned, the samples studied provide nearly a full list of the species present. Only eels were missing. However, two additional species were discovered later in a different sample procedure. Eels, as has already been said, inhabit the deeper offshore areas of the lake and therefore could not be recorded from cove samples. Deeper coves seem to be inhabited by more species than the shallow ones without relation to cove size, and the coves up the lake carry more species than those nearer to the dam wall. But the latter statement needs more material to be verified. Juveniles were par-

TABLE 4. Grand Total Abundance of Fish Population in Inhabited Shoreline Area of Lake Kariba in Thousands of Specimens

	Fish-Inhabited Area		Economically Preferred Species	Secondary Species	Accompanying Species	Total
	ha	% of Total Area				
Basin 1	218	2.4	1,275	5,411	1,297	7,983
Basin 2	4,062	6.0	23,759	100,831	24,169	148,759
Basin 3	11,995	5.9	70,159	297,752	71,370	439,281
Basin 4	17,146	6.7	100,287	425,615	102,019	627,921
Total	33,422	6.2	195,485	829,634	198,861	1,223,980

ticularly abundant in nursery ground coves like E_2, F, and G. There was also an increase in the abundance of harvestable fish in bigger coves that did not always correspond to an increase in the standing crop. These findings confirm the results obtained for the Douglas Reservoir (Perry branch) where the relative standing crop of coves of different sizes did not differ from the total standing crop of the whole branch. But if we examine the size classes of all fish, 'the weights of harvestable fish were under-estimated by cove samples and those of young fish are over-estimated, showing that the apparent lack of bias for total fish may represent simply a balance of two opposing biases' [*Hayne et al.*, 1968]. Thus, in our case, there is an overestimation of juveniles and an underestimation of harvestable fish, since we did not sample the outside ranges of the inshore population distribution. The tiger fish stock analysis seems to prove this situation [*Balon,* 1971*b*].

No difference in stock size was found between bush-cleared areas and uncleared areas, although samples are again too few to allow more than preliminary conclusions. But such conclusions seem to be fairly well supported by *McLachlan*'s [1968, 1970] investigations showing that submerged trees were the poorest (60 mg/m^2 mean faunal weight) of the substrates, epilimnetic mud bottom (206 mg/m^2 mean faunal weight) and aquatic vegetation (1064 mg/m^2 mean faunal weight) being richer in food organisms. To increase the value of tree substrata because of the considerable surface area available may prove wrong, because, from the point of view of fish food availability, these substrata still have the poorest grazing concentration. More fish probably will be attracted by high food concentrations [*Lellák,* 1957] as well as food preference [*Ivlev,* 1961]. There is more evidence supporting higher concentrations of fish in coves with a higher density of aquatic vegetation (especially coves F and G; see Table 3). These higher concentrations of fish might be due to the shelter offered [*Swingle and Smith,* 1942; *Holčik,* 1970*a*] as well as the higher mass of food organisms [*McLachlan,* 1969].

As far as I know, there is no information about standing crop from any tropical or subtropical reservoir; our data may be compared only with dry season pools of the Sokoto River, where *Holden* [1963], using the capture-mark-recapture

TABLE 5. Grand Total Standing Crop of Fish Population in Inhabited Shoreline Area of Lake Kariba

	Fish-Inhabited Area		Economically Preferred Species, metric tons	Secondary Species, metric tons	Accompanying Species, metric tons	Total
	ha	% of Total Area				
Basin 1	218	2.4	75	35	7	117
Basin 2	4,062	6.0	1,393	646	126	2,165
Basin 3	11,995	5.9	4,114	1,907	372	6,393
Basin 4	17,146	6.7	5,881	2,726	531	9,138
Total	33,422	6.2	11,464	5,314	1,036	17,814

method, found 626–1017 kg/ha in sandy bottom pools, 196–270 kg/ha in muddy bottom pools, and 585–1440 kg/ha in mixed bottom pools. In two freshwater pools of Cuba, *Holčik* [1970*a*] recently found by toxaphene sampling 321 and 326 kg/ha. This finding brings the warm zone standing crop more or less into the Lake Kariba range of 276–1225 kg/ha. The up-to-date standing crop values listed for the temperate zone always stay in the lower half of this range, but the differences are not as high as one might expect. *Jenkins* [1968] collected data from 127 United States reservoirs whose standing crop values ranged from 15 to 605 kg/ha (mean of 208 kg/ha). In part of the Douglas Reservoir the mean standing crop was 163 kg/ha, which is very close to the values (75–171 kg/ha) estimated by the capture-mark-recapture method for the European Kličava Reservoir by *Holčik* [1970*b*]. Higher standing crop values are known in temperate zones from river backwaters and oxbows: for North America, *Carlander* [1955] gives a value of 570 kg/ha, and, for the European Elbe River backwaters, *Oliva* [1955, 1960] gives a value of 558 kg/ha. In Danube River oxbows, *Balon* [1963, 1966*a*, 1966*b*] found 259 kg/ha and 497 kg/ha for a larger river arm [*Balon*, 1967]. Similar values are known for ponds: *Jenkins* [1958] found 382 kg/ha in 42 Oklahoma ponds, and *Turner* [1960] found 431 kg/ha in 22 Kentucky ponds.

Much more serious differences occur between tropical and temperate zones in the fish production values. However, we must keep in mind that the values given are obtained by different methods, which may cause many of the differences listed. For the temperate area, *Chapman* [1967] collected values for 20 North American and European lakes, reservoirs, ponds, streams, and rivers; he stated the net production to be 1.4–181 kg/ha/yr. From this range are excluded the extremely high fish production estimates for the Horokiwi stream (547 kg/ha/yr) by *Allen* [1951] and for the River Thames (426 kg/ha/yr) by *Mann* [1965]. Chapman, however, already listed possible sources of error, especially those in Allen's estimation. For the Kličava Reservoir, *Holčik* [1970*b*] gave fish production estimates ranging from 27.5 to 39.9 kg/ha/yr. His data were obtained by a method similar to ours. He also gave, as far as I know, the only fish production estimates for a warmwater region (220 and 277 kg/ha/yr) for two Cuban freshwater pools.

Lake Kariba production estimates have up to now been obtained for only a few species, but, because the differences in percentage of available production and yield are not principally significant in these few species values, we have allowed ourselves the preliminary estimates given in Table 6. The production of economically preferred species only reached as high as 686 kg/ha/yr. This value gives an available yield of 219 kg/ha/yr and 7319 metric tons per year. As there are no similar yield data available for other localities, let us try to use the few known harvest (catch) data. For 121 United States reservoirs, *Jenkins* [1968] gives a mean sport fish harvest of 25 kg/ha and a mean commercial harvest of 11 kg/ha for 46 reservoirs. In Lake Kariba the most rough estimates for the years under study are 56 kg/ha for the total lake area or 90 kg/ha for the fish-inhabited area. But in equatorial Lake George the annual harvest is 1850 kg/ha, of which 80% is *Tilapia nilotica* [*Dunn*, 1970]. These values seem to prove that production is usually much higher in tropical regions than in temperate regions and that our estimates for Lake Kariba might be reasonable.

Already *Holčik* [1970*a*] has tried to explain the highest production of tropical waters by the different age composition of population. We are inclined to add that the shortness of the average life-span of tropical fish might lead to a similarly high production as those known from short-living clupeiforms [e.g., *Boerema et al.*, 1965; *Johnson*, 1970] or freshwater bleak stocks in temperate regions [*Entz*, 1952] where the metabolic turnover is speeded up mainly by the early age of sexual maturity and the high fecundity. In the case of the tropics the high species diversity is most probably better able to use the food availability and the food production and thus may also assist toward relatively high fish production. *Ruivo and Ben-Tuvia* [1967] stated in regard to marine fish: 'It is characteristic of the tropical and subtropical fisheries that they are mostly based on species with a short life cycle, but often a very fast growth rate.' This characteristic also seems to be true for freshwater populations. In Lake Kariba, apart from the unharvested part of the maximum sustainable yield of economically preferred species as stated, we have many unexploited reserves, e.g., *Cyphomyrus discorhynchus*, eels, clupeids, and so on. The final available yield will therefore be much higher than that given in this paper. For correct fishery management, however, the single-

TABLE 6. Scheme of Preliminary Fish Production and Yield Calculations from Tiger Fish of Chikanka Island Experiment

Age Group	Number of Fish n per Hectare	Sample Curve Intercepted Number of Fish $\hat{n}$ per Hectare	Mean Weight of One Specimen $\hat{w}$, grams	Mean Weight Increments of One Specimen h, grams	Total Increments of Age Groups per Year $h\hat{n}$ per Hectare, kg
0	186	116	140	140	16.2
1	29	55	590	450	24.7
2	21	27	1050	460	12.4
3	11	12	1530	480	5.3
4	1	6	2000	470	2.8
5	...	2	2400	400	0.8
6	2	2	3000	600	1.2

Relative annual production of tiger fish (total $h\hat{n}$ per hectare), 63.9 kg/ha/yr; relative annual production of tiger fish in percent of ichthyomass (533 kg), 12%; relative annual production of tiger fish in percent of its mean standing crop (30.8 kg), 207.5%; maximum annual sustainable yield (after harvestable size 1.3 kg and 38-cm length) of tiger fish, 23.2 kg/ha/yr; annual yield of tiger fish in percent of its mean standing crop, 75.3%; annual production of economically preferred species (preliminary at a rate of 200% of ichthyomass of 343 kg/ha), 686 kg/ha/yr; annual yield of economically preferred species (preliminary at a rate of 75% of ichthyomass), 219 kg/ha/yr; and annual yield of economically preferred species per 33,422 ha of fish-inhabited lake area, 7319 metric tons per year.

species maximum sustainable yield will be more important, since overexploitation can be more easily achieved for some species (e.g., tiger fish) than for others. The future catch limits should therefore be species specific. A detailed final report is being prepared on this subject.

Acknowledgments. Thanks are due and hereby rendered to L. S. Joeris, Project Manager, whose constant help and encouragement have considerably eased the task of fulfilling this work; Dr. A. G. Coche for his invaluable assistance in supplying information and literature and for his patient reviews of the draft; G. Bell-Cross, who kindly identified and checked problematic fish species; L. C. Makayi, my assistant, for his invaluable technical help; and all African hands that helped in the field and in the laboratory. I am also in great debt to A. B. E. Mabaye for reviewing the manuscript.

REFERENCES

Allen, K. R., The Horowkiwi stream: A study of a trout population, *Fish. Bull. N. Z., 10,* 1-238, 1951.

Anwand, K., Möglichkeiten der Beseitigung underwünschter Fischbestände in Seen durch Melipax-Spritzmittel (Toxaphen), *Z. Fisch., 16*(1/2), 103-118, 1968.

Balon, E. K., Einige Fragen über das Vorkommen und Biomasse der Fische in Inundationsseen und im Hauptstrom der Donau in der Zeit des Niedrigen Wasserstandes, *Zool. Anz., 171*(11/12), 415-423, 1963.

Balon, E. K., On relative indexes for comparison of the growth of fishes, *Vestn. Cesk. Spolecnosti Zool., 28*(4), 369-379, 1964.

Balon, E. K., Bemerkungen über die Fischgemeinschaften und über die Ichthyomasse eines Inundationsarmes der Donau, *Verh. Int. Ver. Limnol., 16,* 1108-1115, 1966*a*.

Balon, E. K., The ichthyomass and abundance of the fish in the Danubian backwater near Bratislava with a description of toxaphene poisoning (in Slovak), *Biologia Bratislava, 21*(14), 295-307, 1966*b*.

Balon, E. K., Evolution of the Danube fish fauna, its recent state and an attempt for the prediction of further changes after the hydro-electric power buildings (in Slovak), *Biol. Prace SAV, 13*(1), 5-121, 1967.

Balon, E. K., Die Anwendung der Pisciziden für die Bestimmung von Fischabundation und Ichthyomasse in den Inundationsgewässern der Donau, *Z. Fisch., 16*(3/4), 169-195, 1968.

Balon, E. K., Replacement of *Alestes imberi* Peters, 1852, by *Alestes lateralis* Boulenger, 1900, in Lake Kariba, with ecological notes, *Fish. Res. Bull. Zambia, 5,* 119-162, 1971*a*.

Balon, E. K., Age and growth of *Hydrocynus vittatus* Castelnau, 1861, in Lake Kariba Sinazongwe area, *Fish. Res. Bull. Zambia, 5,* 89-118, 1971*b*.

Balon, E. K., Possible stock size assessment and available production survey as developed on Lake Kariba, *Afr. J. Trop. Hydrobiol. Fish., 2,* 45-73, 1972.

Bell-Cross, G., Additions and amendments to the check list of the fishes of Zambia, *Puku, 3,* 29-43, 1965.

Bell-Cross, G., Additions and amendments to the check list of the fishes of Zambia, 2, *Fish. Res. Bull. Zambia, 4,* 99-101, 1966.

Bell-Cross, G., and B. Bell-Cross, Introduction of clupeid and shrimp from Lake Tanganyika into Lake Kariba, *Fish. Res. Bull. Zambia, 5,* 207-214, 1971.

Boerema, L. K., G. Saetersdal, I. Tsukayama, J. E. Valdivia, and B. Alegre, Report on the effects of fishing on the Peruvian stock of anchovy, *Fish. Tech. Pap. 55,* pp. 1-44, Food and Agr. Organ., Rome, 1965.

Carlander, K. D., The standing crop of fish in lakes, *J. Fish. Res. Bd. Can., 12,* 543–570, 1955.

Chapman, D. W., Production in fish populations, in *The Biological Basis of Freshwater Fish Production,* edited by S. D. Gerking, pp. 3–29, Blackwell, Oxford, England, 1967.

Coche, A. G., Description of physico-chemical aspects of Lake Kariba, an impoundment, in Zambia-Rhodesia, *Fish. Res. Bull. Zambia, 5,* spec. issue, 200–267, 1968.

Coke, M., Depth distribution of fish on a bush-cleared area of Lake Kariba, central Africa, *Trans. Amer. Fish. Soc., 97*(4), 460–465, 1968.

Donnelly, B. G., A preliminary survey of tilapia nurseries on Lake Kariba during 1967/68, *Hydrobiologia, 34*(2), 195–206, 1969.

Dunn, I. G., Fish, in *Progress Report of the African Freshwater Biological Team on Lake George, Uganda,* International Biological Program, London, 1970.

Entz, B., Distribution of winter shoals of fishes in 1950–1951 year in the small Tihany Bay (Kis-Öböl, Lake Balaton), with a special evaluation of commercial use of bleak (in Russian), *Acta Biol. Budapest, 3*(4), 543–572, 1952.

Harding, D., Hydrology and fisheries in Lake Kariba, *Verh. Int. Ver. Limnol., 15,* 139–149, 1964.

Hayne, D. W., G. E. Hall, and H. M. Nichols, An evaluation of cove sampling of fish populations in Douglas Reservoir, Tennessee, in *Reservoir Fishery Resources Symposium,* edited by C. E. Lane, pp. 244–297, American Fisheries Society, Washington, D C., 1968.

Holčik, J., Standing crop, abundance, production, and some ecological aspects of fish populations in some inland waters of Cuba, *Vestn. Cesk. Spolecnosti Zool., 33*(3), 184–201, 1970*a*.

Holčik, J., The Kličava Reservoir (An ichthyological study), *Biol. Prace SAV, 15*(3), 5–94, 1970*b*.

Holden, M. J., The populations of fish in dry season pools of the River Sokoto, *Colon. Offic. Fish. Publ., 19.* 1–58, 1963.

Ivlev, V. S., *Experimental Ecology of the Feeding of Fishes,* 302 pp., Yale University Press, New Haven, Conn., 1961.

Jackson, P. B. N., Ichthyology, The fish of the middle Zambesi, in *Kariba Studies,* pp. 1–36, Manchester University Press, Manchester, England, 1961.

Jenkins, R. M., The standing crop of fish in Oklahoma ponds, *Proc. Okla. Acad. Sci., 28,* 157–172, 1958.

Jenkins, R. M., The influence of some environmental factors on standing crop and harvest of fishes in U.S. reservoirs, in *Reservoir Fishery Resources Symposium,* edited by C. E. Lane, pp. 298–321, American Fisheries Society, Washington, D. C., 1968.

Johnson, P. O., The wash sprat fishery, *Fish. Invest. London, Ser. 2, 26*(4), 1–77, 1970.

Jubb, R. A., The eels of South African rivers and observations on their ecology, Ecological studies in southern Africa, *Monogr. Biol., 14,* 186–205, 1964.

Lambou, V. W., and H. Stern, An evaluation of some of the factors affecting the validity of rotenone sampling data, paper presented at 11th Annual Conference, *Southeast Ass. of Game and Fish Comm.,* Mobile, Ala., Oct. 20–23, 1958.

Lellák, J., Der Einfluss der Fresstätigkeit des Fischbestandes auf die Bodenfauna der Teiche, *Z. Fisch., 6,* 622–633, 1957.

Mann, K. H., Energy transformations by a population of fish in the River Thames, *J. Anim. Ecol., 34,* 253–275, 1965.

McLachlan, A. J., A study of the bottom fauna of Lake Kariba, Ph.D. thesis, Univ. of London, London, 1968.

McLachlan, A. J., The effect of aquatic macrophytes on the variety and abundance of benthic fauna in a newly created lake in the tropics, *Arch. Hydrobiol., 66,* 212–231, 1969.

McLachlan, A. J., Submerged trees as a substrate for benthic fauna in the recently created Lake Kariba (central Africa), *J. Appl. Ecol., 7*(2), 253–266, 1970.

Oliva, O., The composition of fish populations in three natural ponds in the Elbe River region (in Czech), *Univ. Carolina Biol., 1*(1), 61–74, 1955.

Oliva, O., Further contribution to the knowledge of fish populations composition in Elbe River backwaters (in Czech), *Vestn. Cesk. Spolecnosti Zool., 24*(1), 42–49, 1960.

Ruivo, M., and A. Ben-Tuvia, Trend in world high seas fisheries and potential exploitation of living resources of the sea, *Stud. Trop. Oceanogr., 5,* 437–451, 1967.

Swingle, H. S., Relationships and dynamics in balanced and unbalanced fish populations, *Ala. Agr. Exp. Sta. Bull., 274,* 1–73, 1950.

Swingle, H. S., and E. V. Smith, The management of ponds with stunted fish populations, *Trans. Amer. Fish. Soc., 71,* 102–105, 1942.

Turner, W. R., Standing crops of fishes in Kentucky farm ponds, *Trans. Amer. Fish. Soc., 89,* 333–337, 1960.

van der Lingen, M. I., Lake Kariba: Early history and south shore, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Potamodromesis in the Mwenda River, Lake Kariba

A. P. Bowmaker

Division of Biological Sciences, University of Rhodesia
Salisbury, Southern Rhodesia

The term 'potamodromous' as used in this paper was proposed and defined by *Meyers* [1949] to describe fish that are truly migratory and whose migrations occur only within freshwater. Compared with the considerable quantity of data that has been accumulated on the migratorial behavior of the fish of the northern temperate zone, little information is available on the migratorial behavior of tropical fish, particularly those in Africa. In east Africa, *Whitehead* [1959] has studied fish migration in the rivers of northeastern Lake Victoria. *Fryer and Whitehead* [1959] reported in greater detail on the breeding biology of one of the more important potamodromous species of this lake, *Labeo victorianus* Boulenger, which was the subject of further studies by *Cadwalladr* [1965*a, b*]. *Van Someren* [1962] used an inclined grid trap on a small river in Kenya principally to sample catadromous species, but he gained incidental information on potamodromous species. Subsequently, *Welcomme* [1969] clarified certain aspects of the biology of smaller fish in a stream-swamp system that flows into Lake Victoria and gave evidence of complex migrational movements.

In southern tropical Africa, work on migration of freshwater fish has been even more restricted. *Mortimer and Bell-Cross*'s [1960] data revealed a complicated bidirectional movement of fish in a ladder situated in the spillway of a small dam in Zambia. *Badenhuizen* [1965] gave preliminary results on the potamodromous behavior of fish in the Lufubu River at the southern end of Lake Tanganyika, which is an important weir fishery. *Pott* [1969] has studied the biology of fish in the Pongolo River of South Africa in an attempt to assess the effects of the proposed J. G. Strijdom Dam on the fish life and gained valuable information on fish movements.

Apart from knowing the species that are potamodromous [*Lowe,* 1952; *Jackson,* 1961; *Jubb,* 1967], this lack of knowledge has to be accommodated by generalization. Generally speaking, potamodromous species are thought to congregate at river mouths prior to the onset of the rains and, when a suitable flow is realized, to move upstream varying unspecified distances to varying substrates. Present knowledge has hardly progressed beyond the statement made by *Fryer and Whitehead* [1959] more than 10 years ago:

> The most we can say is that this species (*Labeo victorianus*) exhibits a positive response to the influx of flood water, which leads mature individuals to sites . . . where spawning activities can be successfully carried out.

The 'triggering' mechanism for upstream migration, it is generally believed, cannot be attributed to any single factor but results from the combination of many physical and chemical factors associated with flooding. However, *Lake* [1967], working in Australia, believes that a single substance, 'petrichor,' may provide the final stimulus for spawning. This oil is released from dry ground when it is dampened and is a complex mixture of organic compounds containing acidic, basic, and neutral fractions.

The pressing need to gain detailed knowledge of the variations in behavior and requirements of different African potamodromous species is particularly important for a man-made lake where essentially lotic species are forced into a lentic environment and breeding still occurs to a large extent in the rivers. This behavior offers an ideal opportunity for human manipulation, but is one that should be thoroughly understood prior to interference.

MWENDA RIVER

The Mwenda River (27°15′E, 17°10′S) is one of the smaller rivers flowing into Lake Kariba and is perhaps typical of most of the drowned Zambezi tributaries. The catchment, which extends over an area of 270 km², is relatively local, since it is below the edge of the Zambezi escarpment. The river flows some 42 km from its source to the lake through broken country typical of the area. The mean elevation gradient is approximately 1:125, but the riverbed is stepped and characterized by frequent small waterfalls and some long boulder-strewn rapids interspersed with broad flat stretches of mud, sand, and gravel or mixtures of these.

At the beginning of the rains, normally in December, the river starts flowing, and its main characteristic thereafter is one of intermittent, violent flash floods that can cause a rise of up to 3 meters in 30 min when the flow is approximately 57 m³/sec. These floods are followed by an equally abrupt decrease of lesser magnitude. Then there is a gradual decrease to a trickle of 0.1–0.3 m³/sec within a week to 10 days, and the flow may actually cease. For most of the rainy season therefore the river is characterized by long postflood periods when small, slowly decreasing quantities of water flow downstream. A high silt load is carried, and the water is turbid. The Mwenda River stops flowing in April or May at the end of the rains and quickly dries up into a series of pools several hundred meters apart, which largely persist until the onset of the following rains. The water temperature in the area ranges between 18° and 31°C and the rainfall between 350 and 780 mm annually.

FISH MIGRATION

This paper considers the first two phases of a three-phase study on the breeding migration of fish of the Mwenda River. Details of results achieved in the first two phases are available [*Bowmaker,* 1969*b*]. The first phase was incorporated with a general hydrobiological survey of the mouth of the Mwenda River that took place between January 1967 and February 1968. This part of the survey involved a comprehensive quarterly program of sampling using gill nets of varying mesh size set simultaneously on the surface and bottom, trammel nets set across the flowing river, seining and poisoning of dry season pools, and electric fishing and trapping.

Gill netting was carried out at varying distances from the mouth of the Mwenda River at five stations. Results from these nettings showed a definite seasonal congregation of fish at Parrot Bend, a point where the Mwenda Bay narrows abruptly, some 1.5 km from the entry point of the river. The congregation occurred prior to the onset of the rains in October and November and was followed by a marked paucity of fish the following February. At the same time, migrating fish were taken in the river. As there was some indication of variation in behavior between species, the situation seemed ideal for further study.

The second phase between June 1968 and April 1969 involved fortnightly netting at Parrot Bend. The results from this phase of the work were more revealing than those from the first phase but were largely inadequate for definite conclusions, principally owing to the inaccuracy of gill and trammel nets as sampling methods and the damage caused to these by crocodiles. The third phase of this investigation should result in a far greater degree of accuracy. This phase will involve the use of a two-way fish trap incorporated in a flume-type flow-gaging weir and constant recording of physical and chemical characteristics of the river. Narcotics and biotelemetric tracking devices developed locally are also to be used.

The species that have been found to migrate upstream for breeding purposes are *Mormyrus longirostris* Peters, *Hydrocynus vittatus* Castelnau, *Alestes imberi* Peters, *Labeo cylindricus* Peters, *Labeo lunatus* Jubb, *Labeo congoro* Peters, *Labeo altivelis* Peters, and *Clarias gariepinus* (Burchell). Species that were found to migrate upstream essentially for feeding purposes but whose juveniles were found in small numbers in the pools are *Heterobranchus longifilis* C&V, *Synodontis zambezensis* Peters, and *Tilapia mossambica* Peters. *Cyphomyrus discorhynchus* (Peters) also moved upstream in small numbers, but no juveniles were found. Two species were found only in the river and pools and not in the lake. These were *Chiloglanis neumanni* Boulenger and *Micralestes acutidens* (Peters). *Alestes lateralis* Boulenger was found in the pools but was not caught during migration. The main population of this species was, however, found throughout the year in weed beds along the lake margins.

Four of the truly potamodromous species, *Mormyrus longirostris, Hydrocynus vittatus, Labeo altivelis,* and *Clarias gariepinus,* constituted 74% of the population by weight as reflected by the gill nets at Parrot Bend. With the reservations imposed by the methods used the behavior of these four species was, briefly, as it is described below.

Hydrocynus vittatus. This species gradually accumulated at the netting station in September 1967, 3 months before moving upstream during heavy floods in early December. There was a subsequent constant migration of prebreeding fish into the river mouth area throughout the breeding season, and the accumulation of *Hydrocvnus* occurred even if the river ceased to flow. Migrational runs occurred in waves of fish as if shoals had been formed and were moving together. There was some indication of diurnal activity, and heavy runs took place on overcast days if the river was flowing sufficiently; but these two conditions were normally concurrent. Spent female fish were taken moving downstream in January at the same time as prebreeding fish moved upstream. Male fish were sexually precocious and were exuding milt while migrating in the company of prebreeding females. There seemed to be a variation between individuals regarding their length of stay in the river, which was probably dependent on the distance upstream they migrated. Spawning females were taken at the first point in the river on the one hand and on the other hand must have traveled considerable distance upstream, since year 0 juveniles were present in some quantity in the highest dry season pool sampled, some 4 km from the lake. A behavioral adaptation of the larvae that would seem to specifically allow for passive downstream transport and that will be discussed below indicates that spawning must take place considerably farther than 4 km from the lake. Migration occurred only after flow had reached a level that was higher than the level that seemed necessary for other species.

Mormyrus longirostris. Unlike the *Hydrocynus* population, the *Mormyrus* population started at a high level at Parrot Bend and gradually fell off before the river started to flow. This decline would indicate a gradual movement from Parrot Bend toward the river mouth. All migrating fish were adult, and both females and males stayed in the prebreeding condition during migration. Movement upstream seemed to occur sporadically throughout the rains, particularly during the lower postflood periods. This sort of movement is perhaps understandable in view of the weak swimming ability of this species. As *Mormyrus* is found in deep water and is probably capable of electroorientation [*Lissman*, 1963], it is anticipated that the third phase of this study will show predominantly nocturnal movement. There was, nevertheless, considerable movement during the day. Large numbers of juveniles were found in rocky pools; very few were found in pools free of cover. The indications were that *Mormyrus* tended to spend a longer period in the river than the other species.

Labeo altivelis. The population of *Labeo altivelis* increased greatly at Parrot Bend 6 weeks before the first floods, and the numbers decreased just as rapidly following the initial flood. Use was thus made of the initial flooding, but both upstream and downstream migrations occurred throughout the rainy period when flow permitted. A seeming preference for lower flow periods was shown, and *Labeo* was frequently running at the same time as *Mormyrus*. Both species were found in association with *Hydrocynus* at higher flow rates, but *Labeo* seemed more capable of migrating during these higher flows than *Mormyrus*. The indications were that spent fish returned downstream as soon as the flow allowed. On the basis of the breeding readiness of the fish that accumulated at the river mouth and the numbers that undertook an upstream migration, *Labeo* appeared to be strongly potamodromous, and the males exuded milt during migration. *Labeo* appeared to be more transitory at the river mouth than the other species; once at the river mouth, this species moved upstream at the first opportunity. Similarly, *Labeo* did not anticipate the floods for as long a period as *Hydrocynus*, *Clarias*, and *Mormyrus*. Quite frequently, migrating fish of this species could be seen moving upstream, since the very tip of the high dorsal fin just protruded above the surface. As the water depth in the observed cases was sufficiently great not to impose surface movement in the species, it is considered that this behavior could be of orientational value in turbid water and would explain a function of selective value for the inordinately deep dorsal fin of this species.

Clarias gariepinus. The *Clarias* migration was found to be entirely different from that of the other species. Some 6 weeks before the first floods, an extraordinarily dense concentration of *Clarias* was observed to be lying quiescently on the bottom underneath the *Salvinia* mat in 1–2 meters of water at the very highest point of back flooding of the river by the lake. These fish migrated upstream immediately when the very first floodwaters reached them and were observed leaping upstream with some abandon. Many were damaged on the leading edge of the mouth from collisions with rocks in the first rapid, and crocodiles took toll of considerable numbers. The nature of the flood was such that this first and probably last wave of the migration could only have traveled 200 meters upstream before meeting an impassable barrier, but male fish, which had been lying quiescently in prebreeding condition only hours previously, were exuding milt within 12 hours. The only female fish caught in the rocky pool below the barrier was found to be spawning. Data collected in other years also indicate that this species moves upstream at the first opportunity only, as they were never found to be migrating upstream in the lower reaches of the river after the very first floods. Downstream movement must, on the basis of the data available, also occur on the first opportunity following spawning.

VARIATIONS IN BREEDING BEHAVIOR

The reasons for upstream migration vary, and in the Mwenda River they are associated with either breeding or feeding. The timing and duration of the upstream migration for breeding purposes also seemed to vary from a single massive early run by *Clarias* to the more fragmentary migrations of *Hydrocynus, Labeo,* and *Mormyrus,* which were apparently varyingly dependent on the flow volume.

There were also differences in prebreeding behavior. *Clarias, Mormyrus,* and *Hydrocynus* seemed to 'anticipate' flooding by several months in that they accumulated at the river mouth some time before the rains started. Whereas this was the only time that breeding *Clarias* accumulated, *Hydrocynus* and *Mormyrus* seemed to migrate from the lake to the river mouth continuously throughout the rains, particularly during the first few months of the season. On the other hand, *Labeo* appeared to concentrate at the river mouth only after the rains had commenced and before the river started to flow and spent a considerably shorter period in the area. The breeding sequence of individual *Labeo* would therefore seem to have been more rapid in that they moved upstream at the earliest opportunity.

Present data cannot answer the question regarding the length of stay in the river. There were indications, however, when consideration is given to the variation in gonad state between the different species during upstream migration and the accumulation of postbreeding fish after flooding, that here also there was variation. *Mormyrus* would appear to have bred some time after moving upstream, whereas *Clarias, Hydrocynus,* and *Labeo* bred more quickly once the river had been entered. Spawning females of all three of these latter species were taken at the first possible point available in the river, though the frequency at which these females were found suggests alternative main breeding areas farther from the lake.

A further point to consider is the variation in substrate chosen by the different species. *Jackson* [1961] considered that breeding of most species present in the middle Zambezi River prior to formation of the lake took place in shallow flooded vegetation and that this behavior was of considerable significance in the role that it played in predator evasion. *Clarias gariepinus* has been observed to spawn in newly flooded grassland on the Rhodesian plateau [*Holl,* 1968], essentially similar to the substrate used by *C. mossambicus* of Lake Victoria [*Greenwood,* 1955]. *Lowe* [1952] reports that the *Labeo mesops* of Lake Nyasa spawns on this substrate. The well-documented spawning run of *Labeo altivelis* up the Luapula River [*Matagne,* 1950] suggests the possibility of two types of spawning substrate, namely, flooded swamp vegetation or soft muds in association with slowly flowing water.

Bowmaker [1969*a*] observed nonanadromous breeding in the *Alestes macropthalmus* of Lake Bangweulu. This species is reported elsewhere as being anadromous but could well fall into *Corbett*'s [1961] stage 3 (namely, a species that feeds and breeds in both lakes and rivers), for breeding occurred on a wave-washed sandy shoreline. Thus probably more than one of the Mwenda species does not have to spawn on exactly the same sort of substrate, and *Greenwood*'s [1965] suggestion may be correct, i.e., that a ruling factor in the choice of spawning sites for some species is the necessity for a cleansing action by rolling of the ova either in turbulent or in flowing water. This postulate is lent support by the nature of the Mwenda River, since nowhere on this river is there the type of back flooding of vegetation mentioned by *Jackson* [1961] as being so necessary for successful breeding. Substrates offered by the river are either rock, sand, or mud, and vegetation is offered only by the occasional trailing branches of the bush *Combretum obovatum* F. Hoffm. Back flooding of grassland along the river margins occurs only occasionally and in a very limited area when the lake level rises to excessive heights.

A further problem arises from the 'anticipatory' accumulation of fish at the river mouth. The recognition of rivers and in some cases particular rivers by fish has long been considered to result from perception of the particular odors of the rivers, and *Hasler* [1954] showed that odor perception in fish can be extremely acute. The fact that fish may perceive the mouth of a river that ceased to flow some 7 months previously suggests either that orientation is not necessarily based only on odor perception or that the sense of smell in the fish involved is remarkably well developed.

Are the species mentioned in this paper necessarily exclusively potamodromous? This is a factor of importance in forming management policy and a question that cannot be answered with any certainty. The only data remotely pertaining to this question arise from the atrophication of ripe ovaries of *Hydrocynus*, which has been found to occur with some frequency in the Mwenda area between January and May [*Bowmaker*, 1973]. This atrophication may result from too long a wait prior to the sufficient flooding of the river but could also result from disease or some breakdown in the ethological breeding sequence. On the other hand, the observed presence of large shoals of adult *Clarias gariepinus* in Lake Kariba some distance away from the river mouth at the time that the single breeding run of *Clarias* occurred suggests that this species also breeds elsewhere, probably on the flooded shoreline.

Although a wealth of evidence suggests that potamodromesis is innate and therefore obligatory, exceptions do occur, probably because essentially lotic species either evolve into or have a predisposition for lentic breeding, provided the essential conditions are fulfilled [*Corbett*, 1961]. In Lake Victoria, for example, two nonendemics (*Mormyrus kannume* and *Bagrus docmac*) are apparently not obligately potamodromous [*Whitehead*, 1959]. It would therefore be unwise at this stage to apply a general rule regarding the obligation of the potamodromous species of Lake Kariba to breed in the rivers.

The complexity and variability of behavior between species indicated by this preliminary study suggest ancient behavioral mechanisms in lotic stock that may not necessarily be advantageous under the lentic conditions imposed by damming. It would seem that, in the case of Kariba, some of the potamodromous species form a more important part of the lentic fish population (*Clarias* and *Mormyrus*) than they did under lotic conditions, others remain more or less the same (*Hydrocynus*), and yet others (*Labeo altivelis* and *L. congoro*) are showing a changing pattern of distribution and importance [*Begg*, 1969] depending on the character of the basins that make up Kariba, as described by *Coche* [1968].

Two further facts, relating to the return of juveniles to the lake, need discussion. The first involves the behavior of *Hydrocynus* larvae, which is remarkably similar to the behavior of larvae of *Labeo victorianus* [*Fryer and Whitehead*, 1959]. Larvae react to touching the bottom by swimming rapidly upward to the surface. Once the surface is reached, the larvae become quiescent, and, since they are slightly more dense than water, they sink slowly to the bottom. When they touch the bottom, the cycle is repeated. That two species with widely differing ancestry should both share this larval behavior and be potamodromous suggests a possible link between the behavior of adult and larvae. The larval behavior encourages rapid downstream movement away from the breeding ground and thus facilitates an early reintroduction into the lake or large river that the breeding river joins. The rapidity of the downstream movement of larvae is dependent on the flow regime, and its actual occurrence in the Mwenda River is supported by the very small numbers of juvenile fish remaining in the pools, which bear little relationship to the large numbers of breeding adults.

It has been suggested that in Lake Kariba the presence of *Salvinia auriculata* mats at river mouths may hinder the movement of adult fish upstream and the return of juveniles downstream because of a barrier of deoxygenated water underneath the mat [*Begg*, 1969]. It has been shown, however, that in the Mwenda River the flow levels required to initiate migration of adults are such that they break through this barrier as an oxygenated density current [*Bowmaker*, 1969*c*]. Though some of the larvae and young fish must enter the lake at low flow levels and could be killed, the majority would probably do so during flooding and would thus be swept through the *Salvinia* before coming to quiet waters; this situation may not be the case in the long gorges where some of the larger rivers enter the lake. The main danger is considered to be the creation of an underflow on the drowned riverbed that may actually penetrate the lake thermocline and carry larvae to the deoxygenated hypolimnion. In rivers of the size of the Mwenda, this underflow could only occur during exceptional floods, but all larvae in the river at such a time would almost undoubtedly be carried by this type of flow.

REFERENCES

Badenhuizen, T. R., Lufubu River research notes, *Fish. Res. Bull. Zambia 1963–1964*, 1965.

Begg, G. W., Observations on the water quality and nature of the affluent rivers of Lake Kariba with reference to their biological significance, *Limnol. Soc. S. Afr. Newslett. 13*, suppl., 26–33, 1969.

Bowmaker, A. P., Contribution to knowledge of the biology of *Alestes macrophthalmus* Gunther (Pisces: Characidae), *Hydrobiologia, 33*, 302, 1969*a*.

Bowmaker, A. P., Fish population fluctuations associated with anadromesis at the Mwenda River mouth, Lake Kariba, *Limnol. Soc. S. Afr. Newslett. 13*, suppl., 45–49, 1969*b*.

Bowmaker, A. P., Aspects of the physical hydrology of the Mwenda River mouth, Lake Kariba, *Limnol. Soc. S. Afr. Newslett. 13*, suppl., 9–15, 1969*c*.

Bowmaker, A. P., A study of the hydrobiology of the Mwenda River mouth, Lake Kariba, Ph.D. thesis, Univ. of the Witwatersrand, Johannesburg, South Africa, 1973.

Cadwalladr, D. A., Studies on the breeding biology and ecology of *Labeo victorianus* Boulenger (Pisces: Cyprinidae) of Lake Victoria, *Rev. Zool. Bot. Afr., 72*, 109, 1965*a*.

Cadwalladr, D. A., The decline in the *Labeo victorianus* Blgr (Pisces: Cyprinidae) fishery of Lake Victoria and an associated deterioration in some indigenous fishing methods in the Nzoia River, Kenya, *East Afr. Agr. Forest. J., 30*, 249, 1965*b*.

Coche, A. G., Description of the physico-chemical aspects of Lake Kariba, an impoundment, in Zambia-Rhodesia, *Fish. Res. Bull. Zambia, 5*, 200–267, 1968.

Corbett, P. S., The food of non-cichlid fishes in the Lake Victoria basin, with remarks on their evolution and adaptation to lacustrine conditions, *Proc. Zool. Soc. London, 136*, 1, 1961.

Fryer, G., and P. J. P. Whitehead, The breeding habits, embryology and larval development of *Labeo victorianus* Boulenger, *Rev. Zool. Bot. Afr., 59*, 33, 1959.

Greenwood, P. H., Reproduction in the cat-fish *Clarias mossambicus* Peters, *Nature London, 176*, 516, 1955.

Greenwood, P. H., Predation and its effects on migration and speciation in African fishes: A comment, by G. Fryer, *Proc. Zool. Soc. London, 144*, 301, 1965.

Hasler, A. D., Odour perception and orientation in fishes, *J. Fish. Res. Bd. Can., 11*, 107, 1954.

Holl, E. A., Notes on the spawning behaviour of the barbel *Clarias gariepinus* Burchell in Rhodesia, *Zool. Afr., 3*, 185, 1968.

Jackson, P. B. N., *The Fishes of Northern Rhodesia*, Government Printer, Lusaka, Zambia, 1961.

Jubb, R. A., *Freshwater Fishes of Southern Africa*, Balkema, Capetown, South Africa, 1967.

Lake, S. J., Rearing experiments with five species of Australian freshwater fishes, *Aust. J. Mar. Freshwater Res., 18*, 137, 1967.

Lissman, H. W., Electric location by fishes, *Sci. Amer., 208*, 50, 1963.

Lowe, R.H., Report on the *Tilapia* and other fish and fisheries of Lake Nyasa (1945-47), *Colon. Office Publ. 1*, London, 1952.

Matagne, F. L., Premières notes au sujet de la migration des Pumbu (*Labeo* sp.) bief de Luapula-Mwero, *Bull. Agr. Congo Belge, 41*, 39, 1950.

Mortimer, M. A. E., and G. Bell-Cross, Observations in the movements of fish in a fish ladder in Northern Rhodesia, *Joint Fish. Res. Organ. Annu. Rep., 9*, 67, 1960.

Myers, G. S., Usage of anadromous, catadromous and allied terms for migratory fishes, *Copeia, 2*, 89, 1949.

Pott, R. M., The fish life of the Pongolo River before the closure of the J. G. Strijdom Dam, M. Sc. thesis, Univ. of the Witwatersrand, Johannesburg, South Africa, 1969.

van Someren, V. D., The migration of fish in a small Kenya river, *Rev. Zool. Bot. Afr., 66*, 375, 1962.

Welcomme, R. L., The biology and ecology of the fishes of a small tropical stream, *J. Zool. London, 158*, 485, 1969.

Whitehead, P. J. P., The anadromous fishes of Lake Victoria, *Rev. Zool. Bot. Afr., 59*, 329, 1959.

Supply of Plant Nutrient Chemicals in Lake Kariba

DAVID S. MITCHELL

Department of Botany, Division of Biological Sciences, University of Rhodesia
Salisbury, Southern Rhodesia

Lake Kariba, one of the largest man-made lakes in the world, is situated in south central Africa on the boundary between Zambia and Southern Rhodesia. Aside from chemicals present in the initial lake waters the supply of plant nutrients is dependent on the pattern of inflows and outflows and their chemical content. The drainage basin of Lake Kariba covers an area of 823,200 km^2, but, in a normal season, only 6% of the precipitation falling on this area will enter the lake. Rainfall on the lake itself was calculated to supply an average annual total of 3.11 km^3 during the period July 1961 to June 1970. Mean annual inflow from the Zambezi River during the same period was estimated to total 52.10 km^3, compared to 5.36 km^3 for all the other rivers. The replacement time for Lake Kariba, calculated as the ratio of volume at a lake level of 485 meters above mean sea level to average inflow from all sources, estimated over the above period was 2.64 years.

Water is lost from the lake through sluice gate spillage, turbine discharge, evaporation from the lake surface, and transpiration from plants growing near the perimeter. So far, because construction work below the wall has not been completed, it has not been possible to maintain a regular pattern of spillage through the sluice gates, and a meaningful average cannot be calculated. Turbine discharge, which averaged 16.78 km^3 between July 1961 and June 1970, has steadily increased and will further increase when the north bank power station becomes operational. Mean loss of water by evaporation from the lake surface during the above period was estimated to be 8.76 km^3. Transpiration losses have not been calculated.

The chemistry of Lake Kariba during its early years was studied by *Coche* [1968], *Harding* [1964, 1965, 1966], and *Mitchell* [1970]. In this period the lake waters became more dilute because the outflows were chemically richer than the main inflow. The eutrophic status of the lake during filling was indicated in several ways. In many areas there were almost continuous blooms of blue green algae dominated by *Anacystis cyanea* (*Microcystis aeruginosa*), and the hypolimnion was completely deoxygenated. In the first year the surface lake water was characterized by a conductivity of 100 $\mu\Omega^{-1}$ at 20°C [*Harding*, 1966]. These conditions have gradually changed, and the lake has progressively become mesotrophic. Algal blooms are now rare and of very short duration, deoxygenation of the hypolimnion is limited to certain drowned river valleys and gradually increases to the whole hypolimnion shortly before overturn, and the conductivity of the surface water has dropped to about 70 $\mu\Omega^{-1}$ (G. W. Begg, personal communication, 1970). The direction of this trend is clear, and it has been widely predicted that the lake will become oligotrophic. Interpretation of these trends is obviously significant for those concerned about the productivity of the lake at any trophic level and should be taken into account in estimates of fisheries' productivity. However, the situation is complex, and the ultimate productivity of the lake will depend on the balance between nutrients entering and leaving the lake's ecosystem; this balance, in turn, will be controlled by the degree to which nutrients entering the lake are used and recycled in biological processes away from the lake outlets. Some of the factors that affect this situation are discussed in this paper.

NUTRIENT CONTENT OF THE LAKE

The flooding of the middle Zambezi Valley by the waters of Lake Kariba drowned a large biomass of plants and animals living in the area. The decay of this immense quantity of organic matter must have released a considerable amount of plant nutrient ions into the rising waters of the lake. In addition, nutrients would have been immediately available from the ash resulting from bush clearing operations in which all the woody plants in an area of 970 km^2 were cleared to ground level, swept into long rows, and burnt. However, the high rate of organic production induced by the prevailing tropical conditions resulted in the rapid absorption of nutrients into the lake biomass so that the nutrient content of the water did not appear to be high at any time.

Climatic conditions were especially favorable for plant growth, and it seems likely that, as nutrients became available, they were taken up into the primary trophic levels of the ecosystem. However, because of the changing lake levels, only free-floating plants were able to take full advantage of this favorable situation. *Salvinia molesta* D. S. Mitchell was particularly successful and underwent an explosive population growth during these formative years of the lake. In 1962 the plant occupied about 1000 km^2 of the lake surface, and it is estimated to have weighed 8512 $\times$ 10^3 metric tons at that time. On the basis of averages of analyses of *Salvinia* from a number of localities on Lake Kariba, it can be calculated that this quantity of weed would have contained 7924.67 metric tons of nitrogen, 417.09 metric tons of phosphorus, 16445.18 metric tons of potassium, 6435.07 metric tons of calcium, and 2800.45 metric tons of magnesium. Since the prevailing winds on Lake Kariba blow away from the outlets in the dam wall and *Salvinia* is mainly dispersed on the lake by wind, this vast quantity of plant material has been an important trap for plant nutrients that might otherwise have been lost to the lake ecosystem.

Nutrients contained in *Salvinia* are released when plants decay after the death of older parts and after whole plants are killed either by being pounded by waves against exposed shores, or by flood action in river inlets, or by desiccation on the lakeshore after a fall in water level. Potassium is released at an early stage in the decay process, whereas the other nutrients are released much more slowly, some apparently being retained within a refactory portion of the plant material that does not decay [*Mitchell,* 1970]. Notwithstanding the differential rate of release, most of these nutrients would be readily available only for further *Salvinia* growth, since most decay takes place within the confines of existing weed mats. Only catastrophic events that destroy substantial portions of these mats are likely to break this cycle.

The most important continuous source of supply of chemical nutrients into Lake Kariba is the influent rivers. Unfortunately, it has not been possible to monitor the flow or chemical content of all these rivers, but from the information available it is apparent that initial flows at the beginning of the rainy season, which would contain mainly runoff water, are chemically rich. Dilution of these flows takes place during high flood levels and is particularly noticeable in the Zambezi where the conductivity of the water drops from 70 to 35 $\mu\Omega^{-1}$. At the end of the rainy season the rivers mainly contain percolation water, and the concentration of chemicals again increases as the rivers begin to dry up. Selected analyses of river waters and lake water in 1964 are given in Table 1.

By contrast with the other rivers the Zambezi continues to flow throughout the year and is peculiar in that the main floods enter the lake well after the main rains have finished. This delay is caused by the passage of the river through the Barotse and Chobe swamp areas, which are extensively flooded. A large portion of the chemical content and silt load of the river is respectively absorbed or deposited in these areas, and the river is consequently low in these values in comparison with most other African rivers. Since the Zambezi contributes by far the greatest proportion of the water entering the lake, this factor is very important for the potential productivity of the lake, and the gradual dilution of the chemical content of the lake is directly attributable to this factor.

Wherever it has been possible to undertake water sampling over a series of depth profiles in river mouths, it has been apparent that river waters entering the lake initially mix with the lake water and then, when the drowned river valley becomes deep enough to contain the river flow, these waters plunge beneath the surface and flow as a density current; normally these waters follow the course of the submerged riverbed. The density current may also flow in the region of the thermocline between the epilimnion and hypolimnion [*Mitchell,* 1970]. The temperature of the inflowing river water appears to be the main factor controlling the depth at which the density current will flow, though silt load and chemical content must also affect the density of the water and therefore its depth.

TABLE 1. Selected Chemical Analyses of Water Collected from Various Localities on Lake Kariba during 1964

Locality	Date	Depth	PO_4^{3-}, mg/l	$NO_3^- \cdot N$, mg/l	$NO_2^- \cdot N$, mg/l	Na^+, mg/l	K^+, mg/l	Ca^{2+}, mg/l	Mg^{2+}, mg/l
Sampakaruma open lake	2/18/64	surface	Nil	Trace	Nil	2.92	1.30	13.0	0.4
		hypolimnion	0.040	0.082	Nil	2.68	1.08	8.2	2.5
		bottom	0.054	0.039	0.017	6.0	0.92	6.8	4.6
Sampakaruma open lake	8/17/64	surface	0.010	0.034	Nil	3.24	1.22	9.0	2.7
		hypolimnion	0.020	0.083	Nil	3.34	1.22	9.0	3.2
		bottom	0.018	0.083	Nil	3.34	1.22	9.7	2.3
Sanyati basin open lake	12/22/64	surface	0.014	0.027	Nil	3.16	1.08	12.1	0.3
		hypolimnion	0.023	0.116	Nil	3.36	1.08	12.1	1.1
		bottom	0.023	0.166	Trace	3.46	1.08	12.9	Nil
Above the Sinamwenda-Zambezi confluence	5/23/64	surface	0.020	0.039	Nil	3.44	1.02	2.3	9.7
		hypolimnion	0.016	0.042	Nil	3.44	1.02	2.7	9.7
		bottom	0.121	0.014	0.0004	2.42	0.40	1.7	6.7
Sinamwenda 'Estuary'	1/14/64	surface	0.010	0.006	0.0008	3.20	1.50	5.1	12.4
		bottom	0.039	0.253	0.0048	7.96	1.92	4.5	14.2
Sinamwenda 'Estuary'	6/7/64	surface	0.022	0.046	Nil	3.65	1.12	2.3	9.0
		bottom	0.016	0.048	Nil	3.44	1.12	2.3	10.4
Zambezi River	1/7/64	surface	0.060	0.016	0.0016	4.68	1.96	1.9	12.8
	5/12/64	surface	0.019	0.032	0.0012	1.40	Trace	0.9	5.2
Gwai River	1/8/64	surface	0.031	0.092	0.004	23.0	3.70	6.4	20.4
Sebungwe River	1/8/64	surface	0.017	0.009	Trace	4.04	1.46	2.9	10.8
Chezya River	1/4/64	surface	0.022	0.010	Nil	4.8	1.60	4.5	11.5
Sanyati River	1/64	surface	0.009	0.007	0.003	7.2	2.08	18.9	10.4
	8/20/64	surface	0.016	0.071	0.0053	3.76	1.54	9.7	2.7
Lufua River	1/28/64	surface	0.140	0.082	0.005	11.0	4.32	15.8	46.0

Two consequences of this phenomenon have important effects on the chemical limnology of the lake. In the first place, it is clear that the chemicals contained in the rivers, which, with the exception of the Zambezi, are generally richer in this respect than the lake water, are not available to plants in the photic zone once the water has begun to flow as a density current. This unavailability is particularly so in the case of a river density current that follows the bottom profile. However, these chemicals would be circulated through the whole lake during the winter overturn, though, for the most part, this overturn would only affect the open waters of the lake. The second important consequence is that the turbulence caused by the density currents contributes to eddy diffusion in the lake, particularly in inshore areas. It is believed that this turbulence makes a significant contribution to the mixing of the lake waters because of the apparently limited extent of seiche movements, which appear to be rapidly damped by frictional resistance [*Mitchell*, 1970].

POSSIBLE LIMITATION OF PLANT GROWTH BY NUTRIENTS

Because of the presence of climatic conditions that are generally favorable for plant growth in the lake throughout the year, it is probable that primary production would eventually tend to be limited by the availability of one or more nutrient ions.

Lake enrichment experiments have shown that nitrate is the plant nutrient most likely to limit the growth of *Salvinia* in Lake Kariba [*Mitchell*, 1970]. Furthermore, the lake catchment is dominated by savanna grassland, and soils in these areas are poor in available nitrogen, little if any nitrate-nitrogen being found, particularly when the dominant grasses are species of Andropogonae [*Nye and Greenland*, 1960; *Henzel*, 1962; *Martin*, 1962; *Boughey et al.*, 1964]. Thus it is probable that the potential nitrogen recruitment to the lake ecosystem through its inflows may be low in comparison with other plant nutrients. Further support for the possibility that nitrogen rather than another plant nutrient may be limiting plant growth is obtained from the generally exceptionally low concentrations of its ions in the surface waters of Lake Kariba (see Table 1).

In Lake Kariba the situation is affected by the presence of *Salvinia*. Plants exhibiting nitrogen deficiency symptoms [*Mitchell*, 1970] have been found in open waters of the lake, though they are not present in weed mats where sufficient nitrogen is released from the decay of dead plant material in the mat. However, if a significant proportion of the nitrogen is retained within a refactory part of the dead plants and is not released by decay, then the plant will also contribute to the shortage in the supply of this nutrient. However, more work is required to verify the presence and possible extent of this phenomenon.

NUTRIENTS IN INSHORE WATERS

A. J. McLachlan [1968, 1970] and *S. M. McLachlan* [1970] have shown that inshore waters are affected by fluctuations in lake level and become very productive when the lake level is rising. At these times, considerable quantities of nutrients are released from animal droppings and vegetation on shores that are submerged by the rising lake.

The influence of the inshore waters on productivity is obviously considerable. In the situation where increases in nutrient levels in surface waters of the lake are manifested as plant growth rather than as detectable rises in the concentrations of dissolved chemicals, differences in the fertility of areas are indicated by differences in primary and secondary biological production, and up to now coastal waters appear to have been significantly more productive than pelagic. Although there are clearly other factors such as light penetration and wind dispersal that influence the distribution of plants and animals, a consequence of their higher concentration in coastal regions is that nutrients, released by fluctuations in lake level and by water mixing due to wind action and the activity of density currents, are taken up and circulated through the ecosystem away from the lake outlets. Thus productivity is likely to be maintained in these areas and may even be increased as nutrients are continuously supplied to them. However, the presence of *Salvinia,* which occurs on the shoreline of Lake Kariba wherever there is sufficient protection from wave action and sufficient means of anchorage for weed mats, is likely to affect this development, as the plant is an important competitor for and reservoir of plant nutrients that become available in these areas. Also, there is evidence that at one time the establishment and development of populations of other aquatic plants was being inhibited by the widespread presence of *Salvinia* [*Mitchell,* 1969; *Magadza,* 1970]. However, recently, there has been a marked increase in both submerged and emergent shoreline plant populations and apparently little inhibition of this growth by *Salvinia.*

CONCLUSIONS

Harding [1966] has stated that the future productivity of Lake Kariba will depend largely on the affluent rivers and that the lake's apparent decline in productivity will continue until the lake water takes on the chemical characteristics of the combined inflows. This view gains some support from a comparison of the conductivities of the outlet from the lake and the main inflow, the Zambezi. When the latter is in flood and the bulk of water for any 1 year is entering the lake, its conductivity is $<40\ \mu\Omega^{-1}$, and it is low in dissolved salts. In contrast, the conductivity of the outflow, which at times may consist mainly of hypolimnotic water, is about $80\ \mu\Omega^{-1}$, and this outflow is chemically richer. However, this view must be tempered by the behavior of the flora and fauna of the inshore waters of the lake, and it is contended that the lake's biomass may be maintained at a higher level than that which is capable of being supported by the chemical content of the inflows alone because of the cycling of nutrients along the shoreline away from the lake outlets. The accuracy of this contention is dependent on the process of maturation in the lake, and it is still too early to predict the outcome of this process.

REFERENCES

Boughey, A. S., J. Meiklejohn, P. E. Munro, R. M. Strang, and M. J. Swift, Antibiotic reactions between African savanna species, *Nature London, 203,* 1302–1303, 1964.

Coche, A. G., Description of physico-chemical aspects of Lake Kariba, an impoundment, in Zambia-Rhodesia, *Fish. Res. Bull. Zambia, 5,* 200–267, 1968.

Harding, D., Hydrology and fisheries in Lake Kariba, *Verh. Int. Ver. Limnol., 15,* 139–149, 1964.

Harding, D., Research on Lake Kariba 1962/63, *Fish. Res. Bull. Zambia, 1,* 38–55, 1965.

Harding, D., Lake Kariba, The hydrology and development of fisheries, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 7–20, Academic, London, 1966.

Henzell, E. F., The use of nitrogen fertilizers on pastures in the subtropics and tropics, A Review of Nitrogen in the Tropics, *Bull. 46,* pp. 161-172, Commonwealth Agr. Bur., Farnham Royal, Buckinghamshire, England, 1962.

Magadza, C. H. D., A preliminary survey of the vegetation of the shore of Lake Kariba, *Kirkia, 7,* 253–267, 1970.

Martin, A. E., Nitrogen transformation in soil, excluding denitrification, A Review of Nitrogen in the Tropics, *Bull. 46,* pp. 72–82, Commonwealth Agr. Bur., Farnham Royal, Buckinghamshire, England, 1962.

McLachlan, A. J., A study of the bottom fauna of Lake Kariba, Ph.D. thesis, Univ. of London, London, 1968.

McLachlan, A. J., Some effects of annual fluctuations in water level on the larval chironomid communities of Lake Kariba, *J. Anim. Ecol., 39,* 79–90, 1970.

McLachlan, S. M., The influence of lake level fluctuations and the thermocline on water chemistry in two gradually shelving areas in Lake Kariba, central Africa, *Arch. Hydrobiol.*, *66*(4), 499-510, 1970.

Mitchell, D. S., The ecology of vascular hydrophytes on Lake Kariba, *Hydrobiologia*, *34*, 448–464, 1969.

Mitchell, D. S., Autecological studies of Salvinia auriculata Aubl., Ph.D. thesis, Univ. of London, London, 1970.

Nye, P. H., and D. J. Greenland, The soil under shifting cultivation, *Bull. 51*, Commonwealth Agr. Bur., Farnham Royal, Buckinghamshire, England, 1960.

Great Man-Made Lake of Bhakra, India

K. L. RAO
Ministry of Irrigation and Power, New Delhi, India

B. R. PALTA
Beas Project, Talwara Township, India

BHAKRA LAKE

Bhakra Lake is created by a straight gravity concrete dam 225.5 meters (740 feet) high built across the Sutlej River about 350 kilometers (217 miles) northwest of Delhi. There are two powerhouses symmetrically located at the foot of the dam. The installed capacity of the two powerhouses is 1050 Mw. The dam with the left powerhouse was completed in 1963, but partial storage in the lake was started in 1958 to provide early irrigation. The right powerhouse was completed in 1967. Figure 1 depicts a view of the completed Bhakra Dam and power plants.

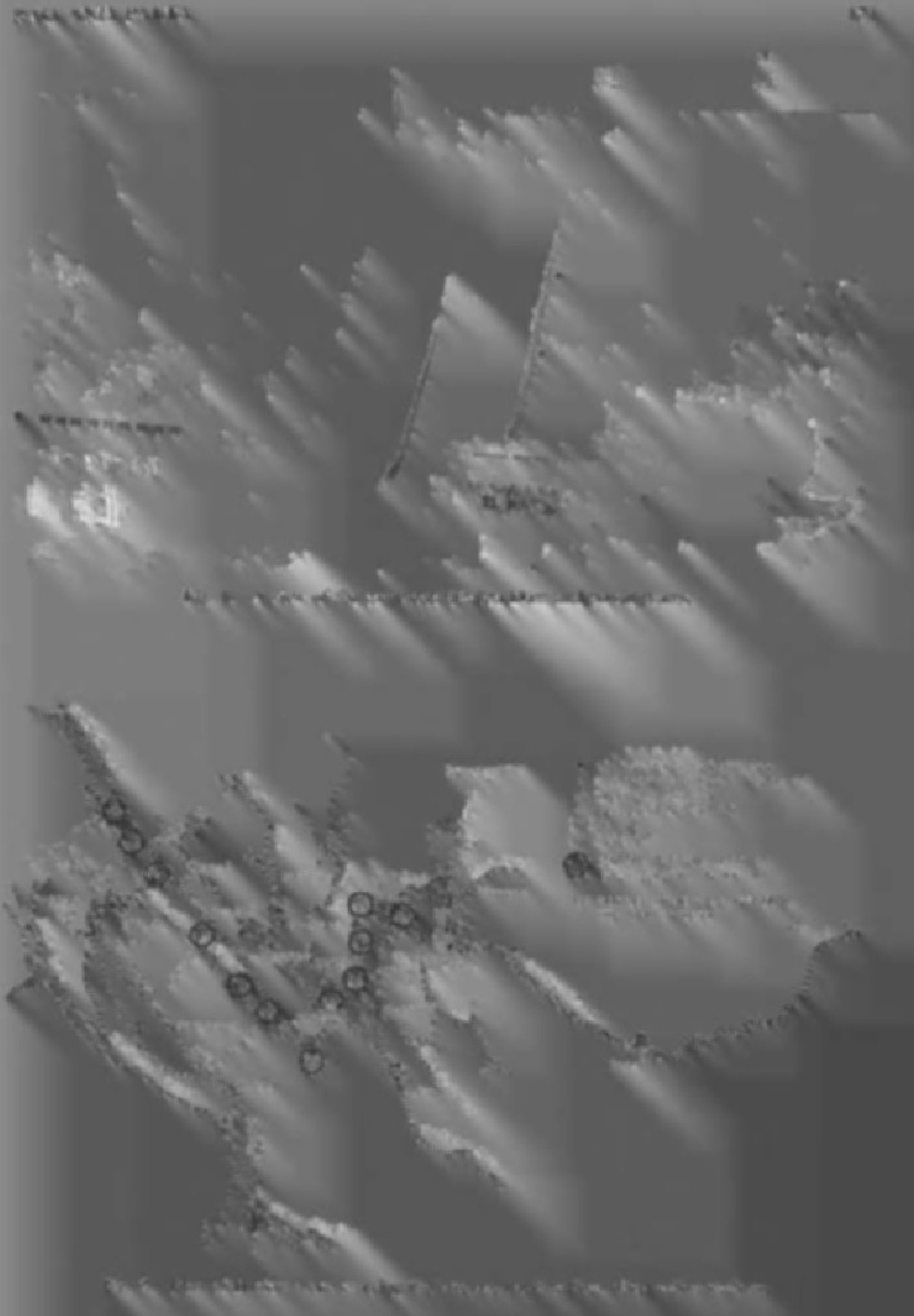
The Bhakra project has changed the entire economy of the area it serves. It has brought about agricultural revolution in the area by providing irrigation to about 1.46 million ha (3.6 million acres) of land. Rural electricity and tube well irrigation have raised the living standards of the farming community. There has been significant industrial development also.

Bhakra Lake spreads over an area of 168 km^2 (65 mi^2) at the maximum storage level and extends for a length of 97 km (60 miles) upstream. The lake has a maximum depth of 155 meters (510 feet). The maximum lake elevation has been kept at 515.1 meters (1690 feet) above mean sea level, whereas the minimum elevation of permissible drawdown has been fixed at 445.6 meters (1462 feet) for power generation. In between these two limits the lake provides a live storage capacity of 7438 million m^3 (6.03 million acre-feet) for controlled irrigation and power generation. The lake also provides facilities for navigation, fish culture, and recreation.

A number of seasonal rain-fed streams, locally known as khads, join the Sutlej in this area, the important ones being the Ali, Gambrola, Gambhar, Sir, and Lunkhar (Figure 2). These khads carry nominal discharge during the dry season of October–June but have appreciable discharge during the monsoons of July–September. With the rise of water level in the lake the water extends in all these and other khads and thereby forms a number of arms. The average gradient of the river in the lake area is about 1.89 m/km (10 ft/mi).

CATCHMENT

The Sutlej River has its origin near the Mansrovar Lake in Tibet at elevation of about 4572 meters (15,000 feet) above mean sea level. The glaciers of the famous Kailash Parbat flow into the river. The river has cut a channel about 914 meters (3000 feet) deep through the Tibetan plateau. The banks are almost vertical as there is no rainfall in that area. The river enters India near Shapkila about 322 km (200 miles) upstream of the dam. The principal tributary of the Sutlej is Spiti, which drains a large area behind the great Himalayan range. Its confluence with the Sutlej is at Nimgia (near Pooh). The total catchment area of the Sutlej above the site of Bhakra Dam is 56,876 km^2 (21,960 mi^2), about 36,260 km^2 (14,000 mi^2) of which lies in Tibet. In the upper part of the catchment beyond the Himalayan range, there is hardly any vegetation, and the area is mostly snow bound all year round. About 11% of the catchment area of the Sutlej River is covered with glaciers. The mean elevation of glacier area above mean sea level is 6096 meters (20,000 feet). This figure of 11% does not include the areas where seasonal snowfall occurs. The lower catchment has mean annual rainfall of about 114 cm (45 inches). The mean annual runoff of the river



is about 16,775 million m^3 (13.6 million acre-feet).

PROBLEMS AND ENVIRONMENTAL EFFECTS OF BHAKRA LAKE

The primary objects of providing irrigation, hydroelectric power, and flood control have been fully realized with the creation of the Bhakra Lake. A number of secondary problems (such as growth of aquatic weeds in unlined irrigation channels taking off from the Sutlej River, resettlement of population, timber transportation, and damage to migratory fish especially downstream of the dam) cropped up after the construction of the dam and the lake. The artificial formation of this dystrophic lake with a heterogeneous bottom has changed the topography, ecology, and climatic condition and resulted in a drastic change in the fauna and flora of the lake and the extinction of some fish and plants existing earlier. Studies on these problems and other topics relating to Bhakra Lake have been carried out and are discussed in this paper.

PRECIPITATION

It is typical of the northwestern Himalayan catchments to receive heavy rainfall during the summer monsoon season, generally extending from late June to late September. The Sutlej catchment receives the moisture-bearing winds from both the Arabian Sea and the Bay of Bengal. The monsoon season as such is generally marked by high river flows and floods in the Sutlej.

Winter precipitation also occurs in small measures, owing to cyclonic winds that pick up moisture from the Arabian Sea on their way to the Himalayan regions. This winter precipitation is usually confined to the months of December–February and results in winter freshets.

A large number of rain gages have been installed in the catchment area. The formation of Bhakra Lake has not affected the rainfall pattern or intensity in the area. There is no regular record of snowfall precipitation in the upper catchment as no snow gages have been installed there. Moreover, most of the catchment area under permanent snow lies in Tibet.

RIVER FLOWS

The Sutlej River runoff basically consists of two components, one derived from the melting of the snow and the other from the rainfall in the catchment. The discharge derived from the melting of snow makes the river perennial, its contribution being maximal during summer months. Inflow in the Sutlej River at Bhakra due to snowmelt varies from 3022 million m^3 (2.45 million acre-feet) to 6414 million m^3 (5.2 million acre-feet).

The high base flow during the monsoons (i.e., from late June to the end of September) is occasionally punctuated by sharply peaked high flood flows of short duration. Figure 3 illustrates the flood hydrographs at Bhakra showing maximum floods in living memory and recorded floods. Now Bhakra absorbs the floods, and the releases downstream of the dam are regulated to meet the irrigation and power requirements, the inflow and the available lake storage being kept in view.

Bhakra Lake generally starts filling by the end of May when there is heavy inflow due to melting snow in the Himalayas. The inflow is further augmented by rainfall during the monsoons from late June to the end of September. Depletion of the lake starts in October. Inflow and outflow hydrographs at Bhakra Dam and corresponding lake levels for the period 1958–1969 are shown in Figure 4.

EVAPORATION

When the project planning report was being prepared, no data were available regarding losses due to evaporation. The losses observed at Lake Mead in the United States were assumed to be applicable in the case of Bhakra Lake, as the climatic conditions at the two places are about the same. The evaporation losses were assumed to be 123 million m^3 (0.1 million acre-feet), i.e., 1.219 meters (4 feet) of water at the mean area of the lake.

Standard evaporimeters from the United States have been installed along the periphery of the lake; locations are shown in Figure 2. Lake evaporation data based on these observations are given in Table 1 and indicate that the actual evaporation losses are more than those assumed.

METEOROLOGICAL OBSERVATIONS

Air temperature. Maximum and minimum daily air temperatures have been recorded at Bhakra Dam for the years 1946–1952 for the preconstruction period and since 1963 for the postconstruction period. Monthly averages of the maximum and minimum daily air temperatures

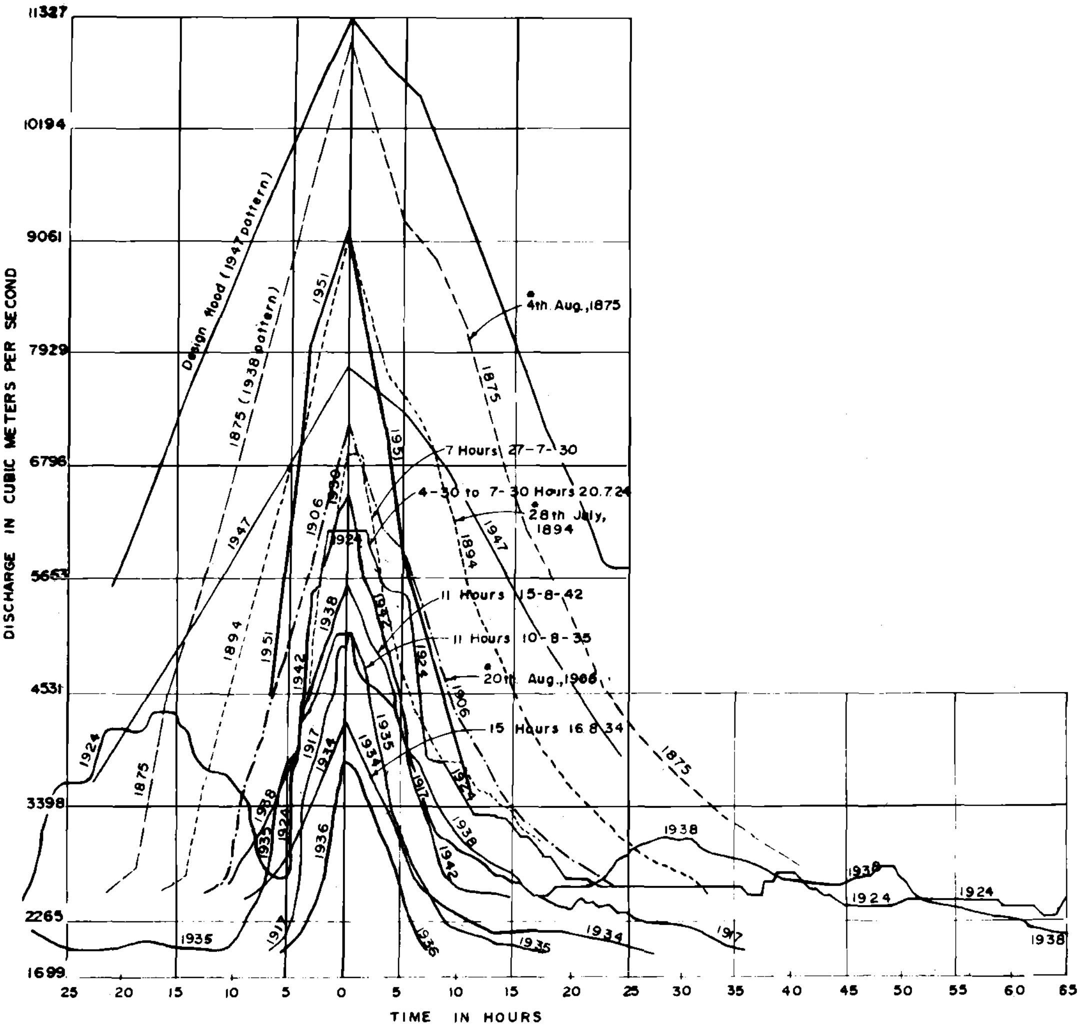


Fig. 3. Flood hydrographs at Bhakra showing maximum flood in living memory and recorded floods. The hydrographs for the years 1875, 1894, and 1906 have been constructed by proportional extrapolation from the 1938 hydrograph, which is plotted from actual observations. The dates marked with an asterisk have been worked from the rainfall record.

as observed at Olinda (near Bhakra Dam) are given in Tables 2 and 3. The observations show that the maximum temperatures have become lower in summer months and the minimum temperatures have become higher throughout the year since the formation of Bhakra Lake. The observations also indicate that the variation between minimum and maximum temperatures has been reduced.

Water temperature. For design purposes the mean monthly water temperature was assumed to vary from a minimum of 11.1°C in December and January during the low flow season to a maximum of 20.6°C in August and September toward the end of flood season. The data of mean monthly water temperatures for the years 1946–1952 as observed at Olinda downstream of the damsite also support these assumptions. However, the observations made during the post-construction period (1963–1969) show that the mean monthly river water temperatures at Olinda vary from 17.2° to 21.1°C. Data for all these years are given in Table 4. Observations for measurement of water temperature at different

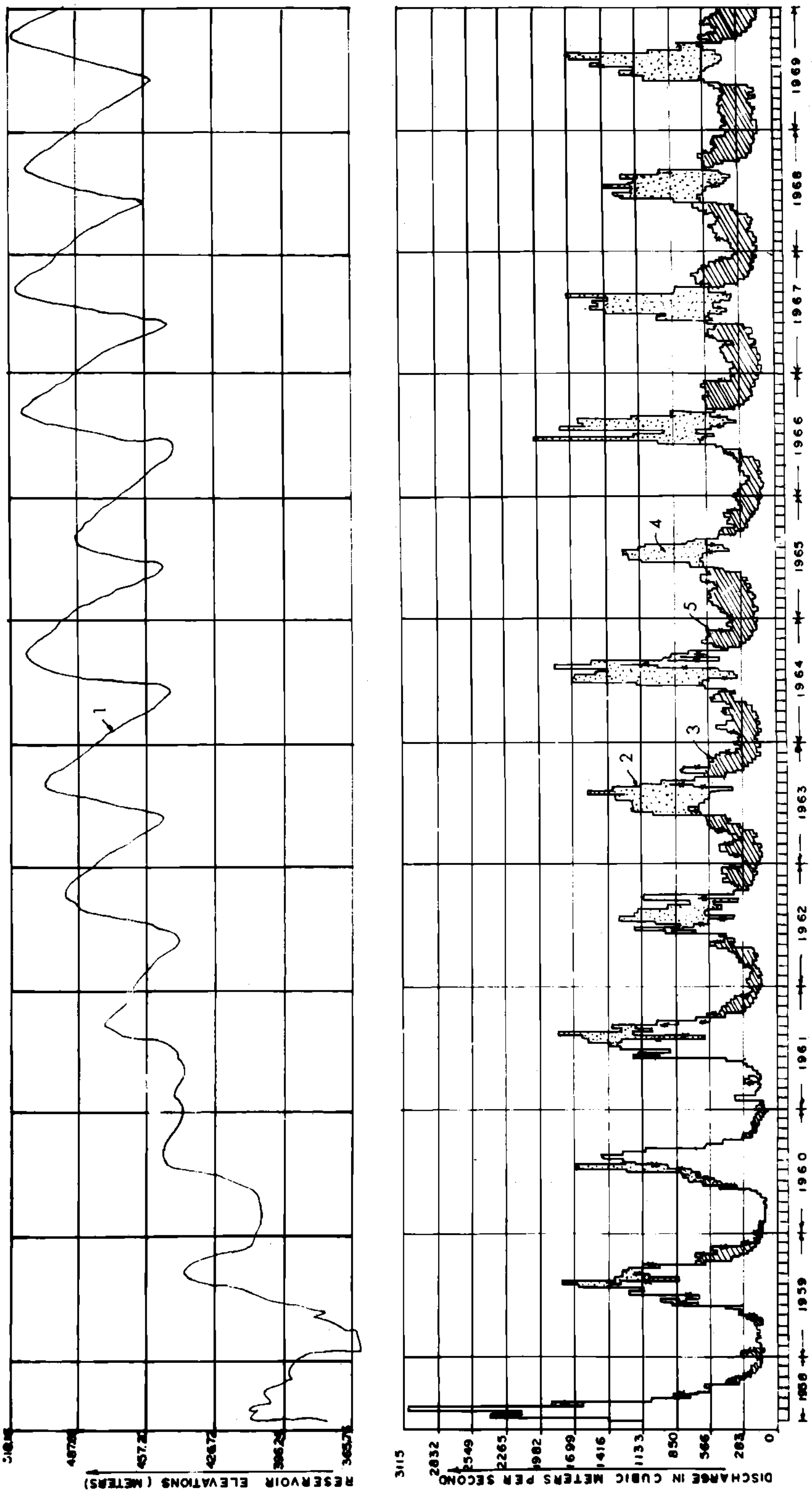


Fig. 4. Bhakra Lake elevation, inflow, and outflow hydrograph. The following numbers define the graph: 1, reservoir elevation; 2, inflow hydrograph (10-day average); 3, outflow hydrograph; 4, filling (dotted area); 5, depletion (shaded area).

TABLE 1. Evaporation Data

	Assumed Evaporation, cm	Actual Observed Evaporation, cm					
		1964 to 1965	1965 to 1966	1966 to 1967	1967 to 1968	1968 to 1969	1969 to 1970
April	17.7	22.9	15.9	21.8	16.5	16.8	21.4
May	20.5	31.8	29.4	27.2	26.0	26.0	25.1
June	15.4	26.4	29.5	20.9	26.0	22.8	28.1
July	9.7	12.2	16.8	14.8	11.4	10.5	15.9
August	8.4	14.7	12.5	12.7	8.8	9.4	12.0
September	7.7	11.9	12.2	10.4	10.1	13.2	11.0
October	6.1	13.0	13.0	10.9	11.0	11.1	10.7
November	5.2	8.7	8.6	7.7	6.6	8.7	7.8
December	5.5	4.5	6.7	5.5	3.6	5.5	9.0
January	6.5	5.4	6.3	5.0	3.3	5.3	3.1
February	7.3	6.4	7.8	7.4	4.9	6.7	6.3
March	11.9	14.3	15.2	10.2	10.2	13.7	10.8
Total*	1.219	1.722	1.739	1.545	1.384	1.497	1.612
Total†	125.8	172.3	146.5	147.9	142.8	162.9	167.3

*Total evaporation at the mean area of the lake in meters.
†Total evaporation for the whole lake in million cubic meters.

depths in the lake have not been carried out as yet, but temperatures are being observed throughout the body of the dam.

Humidity. The observations of relative humidity at Bhakra were started in March 1963, and the monthly average humidity observed for the period from 1963 to 1969 is given in Table 5. The observations show that since the formation of the lake the relative humidity of the area surrounding the lake has increased and climate has become more humid at Bhakra.

GEOLOGIC FEATURES

The Bhakra Lake has been impounded on Recent and sub-Recent gravels and rocks of the Siwaliks, Dagshai, Sabathu, and Shali formations. The Siwaliks consist of boulder, conglomerate, sandrock, sandstone, and clay shale and occupy a major portion of the lake from Nangal to Bilaspur. The Dagshais and Sabathus are comprised of sandstones, clay shales, and limestones and occur between Bilaspur and Dehar along the Sutlej River. Maroon shales, pink quartzites, and dolomites of the Shalis occur in the sector east of Dehar.

No major landslides of any potential danger have been observed in the lake area. Creation of the lake has led to a rise in the subsoil water and a corresponding reduction in the shear strength of the material forming the lake slopes. Moreover,

TABLE 2. Monthly Averages of the Maximum Daily Air Temperatures Observed at Olinda from 1946 to 1952 and from 1963 to 1969 in Degrees Celsius

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1946	22.2	23.7	28.9	35.9	40.9	40.0	36.1	34.3	40.5	31.6	27.0	20.5
1947	19.6	24.2	30.4	38.6	42.1	44.0	37.6	34.8	32.1	31.9	27.9	21.6
1948	21.4	21.7	26.0	36.5	43.3	42.8	36.6	33.1	31.4	34.6	26.1	21.1
1949	22.0	22.2	27.9	37.2	40.8	40.8	34.5	33.8	34.8	31.6	25.1	21.1
1950	25.3	28.2	34.8	37.1	40.9	41.3	35.8	31.9	31.2	31.4	27.0	21.2
1951	19.3	22.7	27.7	31.1	38.5	40.7	36.3	33.2	32.2	33.8	32.7	22.1
1952	25.3	23.8	26.7	36.7	39.8	39.1	33.4	33.5	33.5	32.5	26.9	21.3
Average	22.2	23.8	28.9	36.2	40.9	41.2	35.8	33.5	33.7	32.5	27.5	21.3
1963	21.8	25.6	26.9	31.9	37.4	38.6	35.1	32.8	29.9	29.0	25.1	21.2
1964	17.3	21.6	29.5	33.1	35.9	39.3	31.9	30.2	30.1	31.4	25.8	21.2
1965	22.5	22.5	25.5	31.0	39.1	33.8	32.0	33.6	33.6	31.4	28.2	23.2
1966	22.3	24.6	28.4	33.8	35.6	37.3	34.4	33.3	32.7	30.7	26.0	21.3
1967	19.4	25.5	25.8	31.9	37.2	31.9	33.7	32.3	31.4	30.6	25.4	21.3
1968	18.5	20.4	27.4	33.7	37.2	37.7	33.1	32.8	35.2	30.4	27.5	22.2
1969	20.8	22.3	31.3	33.1	35.0	40.0	34.0	32.9	33.2	32.7	29.6	24.3
Average	20.4	23.2	27.8	32.6	36.8	36.9	33.4	32.6	32.3	30.9	26.8	22.1

TABLE 3. Monthly Averages of the Minimum Daily Air Temperatures Observed at Olinda from 1946 to 1952 and from 1963 to 1969 in Degrees Celsius

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1946	6.6	8.1	12.0	16.0	20.8	25.1	25.1	24.3	21.1	17.5	9.1	7.0
1947	5.8	7.2	12.0	15.4	22.2	26.0	25.7	25.1	23.2	18.0	9.0	6.7
1948	6.8	6.3	11.4	16.3	18.8	23.8	25.5	24.4	24.7	17.5	7.2	6.5
1949	6.6	7.9	11.4	17.1	23.0	24.8	25.1	24.3	22.3	15.0	6.3	4.1
1950	9.2	8.4	14.1	16.0	20.8	24.5	24.7	23.1	21.0	13.1	6.2	3.0
1951	5.3	6.4	10.8	14.5	19.5	23.1	24.1	23.9	22.0	17.7	9.3	6.0
1952	5.9	8.9	11.9	16.8	20.5	24.0	23.5	24.1	22.3	16.5	7.9	7.1
Average	6.6	7.6	11.9	16.0	20.8	24.5	24.8	24.2	22.4	16.5	7.9	5.8
1963	11.0	15.6	17.8	23.1	25.8	27.1	26.0	25.4	24.6	23.0	16.2	11.0
1964	8.3	12.0	18.0	23.0	24.6	27.3	24.3	24.4	22.7	20.4	15.8	11.4
1965	11.0	12.0	16.2	20.1	24.3	28.1	24.4	24.0	23.3	21.8	17.9	11.8
1966	11.3	14.4	17.0	22.7	24.3	26.9	24.7	24.0	23.3	20.6	15.9	11.0
1967	9.9	14.1	15.8	20.2	24.9	26.7	24.9	23.5	23.0	19.6	15.3	12.0
1968	9.1	10.0	15.7	21.5	24.2	25.1	24.2	24.1	23.4	18.3	15.9	11.5
1969	10.0	11.9	17.4	21.8	23.5	26.7	24.4	24.2	23.1	20.3	15.9	10.8
Average	10.1	12.9	16.8	21.8	24.5	26.8	24.7	24.2	23.3	20.6	16.1	11.4

because of fluctuations of the water level in the lake during operation, certain slump and creep types of slides have taken place. These slides may further affect, though to a minor extent, the process of sliding in the adversely jointed and sheared zones and may also initiate slides in other structurally weak and topographically critical zones.

Besides these geologic weaknesses in the rock formations, other human activities in the area might also lead to the development of slides. At present, a road along the lake rim is under construction. The cutting of the hillslopes for road construction may result in disturbing the stable slopes in critical reaches. Accordingly, studies to observe and investigate the development of landslides along the lake rim above the minimum lake level and to work out the measures to stabilize them are in progress.

SEISMIC OBSERVATIONS

The Bhakra Dam is situated in a highly seismic

TABLE 4. Mean Monthly Water Temperatures from 1946 to 1952 and from 1963 to 1969 in Degrees Celsius

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1946	10.9	12.2	16.9	18.8	18.8	19.9	20.5	21.1	21.3	20.8	15.4	10.5
1947	10.0	11.9	17.2	19.1	18.7	18.1	19.9	21.0	21.0	20.4	15.6	15.2
1948	10.9	13.0	16.1	17.6	18.3	17.8	18.2	18.8	17.5	18.1	13.1	11.3
1949	10.7	12.4	21.1	19.1	17.2	17.7	18.5	20.4	20.6	17.6	12.5	11.1
1950	12.3	12.0	13.8	18.6	20.2	19.0	19.0	20.1	20.3	20.5	12.6	10.1
1951	11.1	11.6	17.7	19.8	19.7	19.8	20.0	20.5	21.1	19.7	14.8	11.0
1952	10.4	12.6	15.5	18.8	18.7	18.4	20.4	20.4	20.4	19.0	13.9	11.5
Average	10.9	12.2	16.9	18.8	18.8	18.7	19.5	20.3	20.3	19.4	14.0	11.5
1963	...	...	...	17.9	20.8	20.4	19.2	19.8	19.1	19.8	19.8	19.3
1964	18.6	18.6	19.0	18.2	19.6	21.0	19.3	18.4	18.4	17.9	16.8	16.9
1965	17.0	17.4	17.5	17.2	18.6	21.8	20.7	20.3	20.2	19.9	19.7	18.5
1966	16.8	16.4	16.5	17.5	19.3	22.4	20.8	19.5	19.2	19.2	19.1	18.5
1967	17.4	18.2	17.5	17.8	18.6	20.8	19.8	19.1	18.7	18.4	17.7	17.0
1968	19.6	16.5	17.7	18.2	18.2	19.7	20.2	20.4	20.3	18.1	19.1	17.9
1969	16.9	17.0	17.5	17.5	18.2	21.3	20.0	19.7	19.1	19.0	18.8	18.4
Average	17.7	17.3	17.6	17.8	19.0	21.1	20.0	19.6	19.3	18.9	18.7	18.1

TABLE 5. Monthly Averages of Humidity in Percent at 0800 Hours at Bhakra from 1963 to 1969

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1963	...	...	...	62.7	64.2	72.6	85.3	89.9	82.4	72.7	76.5	81.2
1964	79.7	81.7	74.4	70.2	68.2	75.6	89.0	90.3	89.8	87.0	84.6	82.6
Average	79.7	81.7	74.4	66.5	66.2	74.1	87.2	90.1	86.1	79.9	80.6	81.9
1965	71.7	82.5	81.3	79.6	77.9	74.6	87.3	88.1	86.2	87.6	88.5	86.2
1966	85.2	86.3	85.3	74.3	66.4	74.6	89.6	89.1	89.5	87.7	89.1	84.4
1967	84.6	87.2	86.5	78.3	72.4	77.2	89.6	89.8	89.0	88.0	84.5	87.4
1968	85.7	84.6	83.7	80.7	77.3	83.6	88.3	89.5	85.9	87.2	85.5	85.0
1969	86.6	86.9	86.5	80.2	76.0	72.7	85.4	88.9	89.1	87.5	88.1	86.5
Total Average	83.9	84.9	83.0	75.1	71.8	75.8	87.8	89.4	87.4	85.4	85.3	84.8

zone. The Indian Meteorological Department set up a seismological observatory in the tunnel at an elevation of 414.5 meters (1360 feet) on the right abutment. The observatory started functioning in January 1965 and is equipped with the following instruments: three units of a high magnification seismograph (Hagiwara Electro-Magnetu), two units of a Wood Anderson seismograph, and one accelerograph. In addition, a number of observatories have been set up in the area where important projects are under construction.

Data recorded by this observatory together with those recorded by the nearby observatories were used in locating the epicenters of earthquakes with origin in the neighborhood of Bhakra Dam. The epicenters of such earthquakes are shown in Figure 5. It has been observed that no epicenter is located within 50 km of Bhakra and that the alignment of epicenters is parallel to the Himalayan boundary fault zone. None of these tremors were strong enough to be felt at Bhakra. Hence the ground acceleration due to them could be put at <0.5% of gravity. None of the earthquakes recorded since 1965 has actuated the accelerograph in operation in the seismological observatory. Thus the acceleration reaching Bhakra due to any earthquake during this period was below 0.01 *g*. After data are obtained for a few more years, it will be possible to map out the zone of weakness, if any, within 150 km (93 miles) of Bhakra Dam.

SEDIMENTATION STUDIES

The direct and indirect benefits of a man-made lake depend on its storage capacity and its life. Silt inflow into the lake, although a natural phenomenon, affects both its storage capacity and its life. Sedimentation studies have therefore been carried out to observe the present rate of sedimentation in relation to the assumptions made when the project was being planned. These assumptions and observations are discussed briefly in this paper.

Most of the catchment area of the Sutlej River above Bhakra of 56,876 km^2 (21,960 mi^2) contributes silt through snowmelt except for 6475–7770 km^2 (2500–3000 mi^2) situated in the lower hills. This area has a heavy annual rainfall of about 114 cm (45 inches) and contributes heavily to the flood discharges and siltation due to floods.

Project assumptions. The sedimentation studies in the project report assumed that no check dam would be provided upstream of the Bhakra Lake either on the main river or on any of the main tributaries to arrest movement of the sediment. The following behavior of the silt deposits was assumed:

1. A suspended silt load of 35,053,725 metric tons (34,500,000 tons) per annum was assumed on the basis of actual silt observations in past years. The bed load carried by the river could not be assessed and was taken as 15% of the suspended silt load. To determine the volume occupied by the deposits, an estimate of the probable density of the deposits was made. The available data indicated a large variation in the densities observed at various places, and upper and lower average values of 1.04 g/cm^3 (65 lb/ft^3) and 1.44 g/cm^3 (90 lb/ft^3), respectively, were assumed for the preliminary studies. The rate of loss of storage capacity was determined for these extreme values.

Based on the observed silt data the following

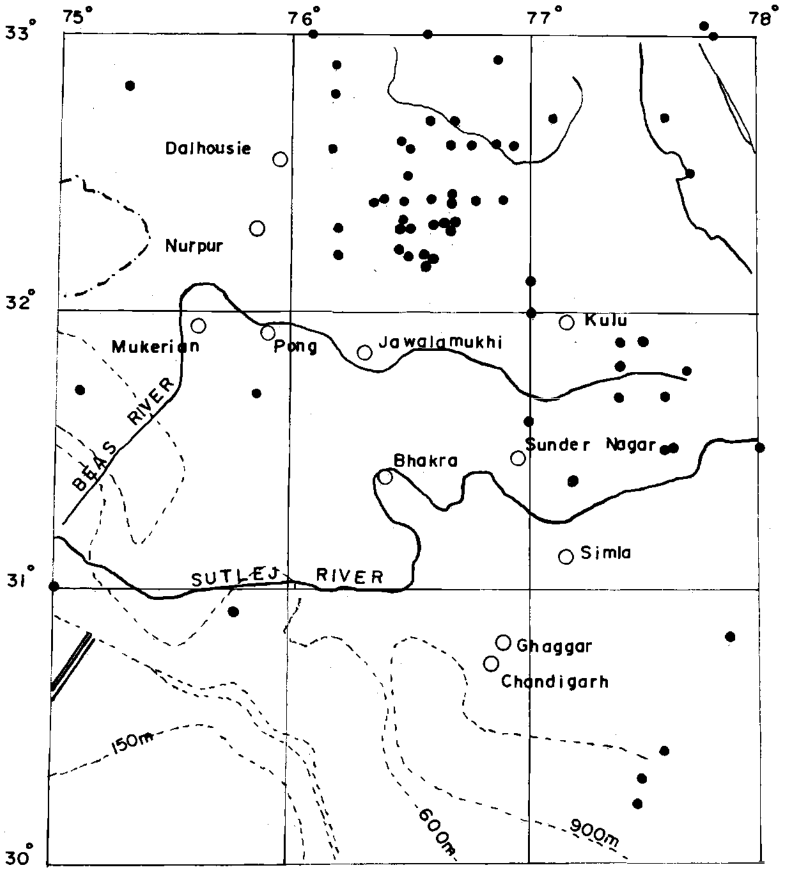


Fig. 5. Location plan of seismological observatories (open circles) and epicenters of earthquakes (closed circles).

classification of silt was assumed in these studies: coarse silt (+0.2 mm), 33%; medium silt (0.2–0.02 mm), 57%; and fine silt including clay (−0.02 mm), 10%.

2. Out of the total silt load the entire fine silt load including clay and about 5% of the remaining silt load were assumed to pass downstream over the spillway in floods and through the openings in the body of the dam as density currents.

Silt observations. To study the actual silt deposits and to compare them with the assumptions in the project report, capacity surveys were started in the year 1959–1960 and have been carried out every year. These surveys consist of observing soundings along predetermined cross sections that are 609 meters (2000 feet) apart by means of an echo sounder and then superimposing the yearly results on the previous data to calculate the quantity of silt deposited at each cross section and thus in the whole lake. The results of these observations are tabulated in Table 6. A profile of the silt deposited along the river portion of Bhakra Lake is shown in Figure 6.

Figure 2 shows the depths of the silt deposited in Bhakra Lake. Notice that, in the reach from 24,079 to 36,271 meters above the dam (reduced distance), there has been a very heavy silt deposit. In the reach from 24,079 to 25,298 meters above the dam, where the stream opens out into a vast expanse, a hump of silt has been formed and is functioning as a natural barrier. When the river starts rising, most of the silt is entrapped upstream of the barrier. The hump levels are dictated by the lowest level in a particular year and the intensity of the floods. Most of this silt is deposited upstream of the barrier in the live storage zone. Part of this silt is carried to the

TABLE 6. Sedimentation Data

	Silt Deposited, 10^6 m^3	Inflow, 10^6 m^3	Silt Deposited per Million Cubic Meters of Inflow, m^3
1959 to 1962 (4 years)	135.9	64,498.7	2220
1963 to 1964 (2 years)	92.6	33,032.6	2805
1965	24.2	12,162.1	1990
1966	51.7	15,036.12	3440
1967	32.5	15,011.5	2160
1968	16.4	14,555.1	1130
1969	44.7	15,813.2	2830

The silt yield per annum per square kilometer of catchment area during the period of 1959 to 1969 works out to be 1665 m^3. For every 1 million m^3 of inflow the silt yield works out to be 2385 m^3.

dead storage in the reach extending from 0 to 25,298 meters above the dam during the depletion period. Thus the silt is exposed in most of the reach upstream of 25,298 meters and gives the lake a look of sandy dunes.

The silt deposition has also been worked out as a percentage of the total capacity between various elevations (Figure 7). It has been noticed that maximum storage has been lost between an elevation of 426.7 and 457.2 meters (1400 and 1500 feet). This loss is due to the fact that deposition of silt starts at the minimum storage of the lake level; during the initial filling, this storage level was at an elevation of 396.2 meters (1300 feet), whereas after the initial filling the lake was depleted to an elevation of 445.6 meters (1462 feet) every year.

The average silt deposit per year during 1959–1969 is 36.86 million m^3 (29,880 acre-feet). The average silt deposit per year during 1965–1969 (5-year average) is nearly 33.9 million m^3 (27,485 acre-feet) as against an average of 39.32 million m^3 (31,877 acre-feet) per annum during 1959–1964. It may also be stated that 4 years out of 5 of the 1965–1969 cycle are years of mean flow. Thus the indications are that the rate of siltation has decreased. However, it is too early to say anything definitely.

Sixty-five percent of the silt deposit lies in the dead storage zone, and 35% lies in the live storage zone. Of the total silt deposited (404.58 million m^3, or 328,000 acre-feet), 47% is deposited in the reach above 25,298 meters from Bhakra Dam, i.e., in a portion where the lake is narrow. In this reach, about 70% of the silt is exposed during the months of April, May, and June, and this exposure has made it possible to observe the actual densities in this reach by boring. The densities are about 1441.7 kg/m^3 (90 lbs/ft^3). A density of >1361.6 kg/m^3 (>85 lbs/ft^3) is achieved in about 3 years after deposit. The rest of the silt (53%) mostly lies below the dead storage level and downstream of the reach 25,298 meters above the dam. The silt in this region is naturally finer and of less density. Further, it is disturbed when the water is drawn through turbines and river outlets, particularly in the months of May, June, and July when the water level in the lake is low. The density in the reach extending from 0 to 25,298 meters above the dam is expected to be well below 1441.7 kg/m^3 (90 lbs/ft^3), and the average density of the whole mass has been taken as 1241.5 kg/m^3 (77.5 lbs/ft^3). This average would consolidate to 1441.7 kg/m^3 (90 lbs/ft^3) in due course.

Silt in the water entering into and flowing out of the lake is also being measured by silt sampling. The observations reveal that 99.3% of the silt is trapped in the lake.

It was also assumed in the project that 14.5% of the silt would flow out through river outlets and penstocks. This silt outflow does not happen today, as the main silt deposit (silt hump) is 25.8–27.4 km (16–17 miles) from the dam. It will actually happen when the main silt deposit gets nearer the dam, and the rate of silt deposit in the lake will be further reduced.

AQUATIC WEED GROWTH IN IRRIGATION CHANNELS

In the canals of the pre-Bhakra days the water carried silt and was turbid, and this turbidity did not allow aquatic weeds to grow in the channels. Since the creation of Bhakra Lake the water released downstream is almost clear. This water has affected the irrigation channels extending from the Sutlej River on the downstream side, where an abnormal growth of aquatic weeds has been observed in the unlined channels; the result has been a drastic reduction of the water-carrying capacities of the channels. Before Bhakra these channels had been running for decades without any trouble. Aquatic weeds commonly found in the channels fed from the Bhakra Lake are both the submerged and the emergent types.

By the year 1963 (i.e., 5 years after storage in Bhakra Lake had started), all the Bhakra channels were affected by aquatic weed growth. The manifestation of aquatic weed growth in the earthern channels of the Bhakra canal system at

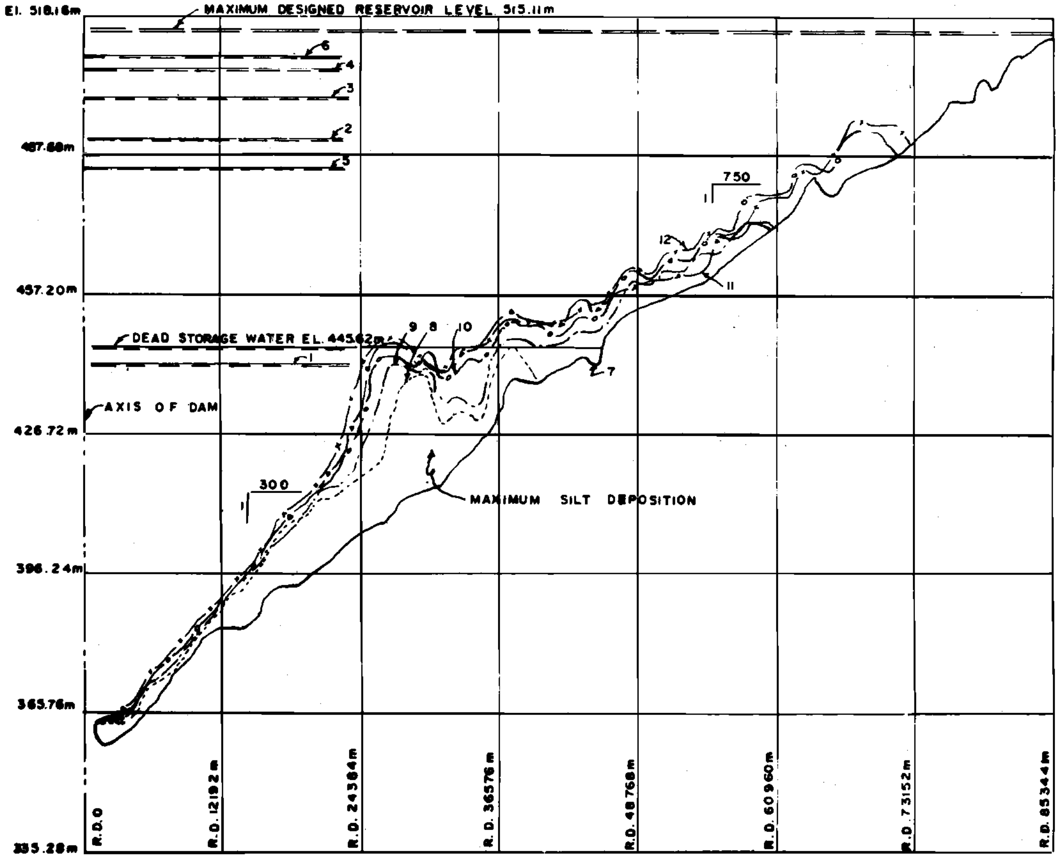


Fig. 6. Profile of yearly silt deposit in the main channel of Bhakra Lake. Numbers 1–7 show the maximum reservoir elevation for the following years: 1, 1959; 2, 1962; 3, 1963; 4, 1964; 5, 1965; and 6, 1966. The number 7 indicates the original bed. Numbers 8–12 show the silted bed for the following years: 8, 1962; 9, 1963; 10, 1964; 11, 1965; and 12, 1966. The reduced distance (R.D.) is given in meters upstream of the dam axis.

that time was a formidable problem, and the trouble steadily increased. It became an established practice to close a channel for 7 days once every 2 months and to employ hundreds of laborers to cut any weeds accessible in the knee-deep and snake-infested stagnant waters. Mechanical methods of aquatic weed removal were also adopted at a number of places. However, both manual and mechanical methods proved very expensive. The frequent closure of channels, in addition to normal rotational closures, made the equitable distribution of water impracticable. Because of the toxic effect of herbicides on irrigated crops, animals, and human beings, chemical controls have not been used.

A comprehensive statistical study of the aquatic weed problem was made in 1968 in about 2897 km (1800 miles) of Bhakra channels. The study revealed the following:

1. A channel was less prone to weed growth if the depth of water was >1.5 meters (5 feet) and if the channel was not subjected to frequent rotational closures.
2. A channel was not prone to weed growth if its bed was drained dry within 48 hours of the closure from the head and was allowed to dry for about 5 days thereafter.
3. Whereas the rotational closures contributed a great deal toward the weed growth, these very rotational closures could be helpful in the eradication of weed growth if only the bed could be drained dry within 48 hours of the closure from the head.

These conclusions were put into practice, and

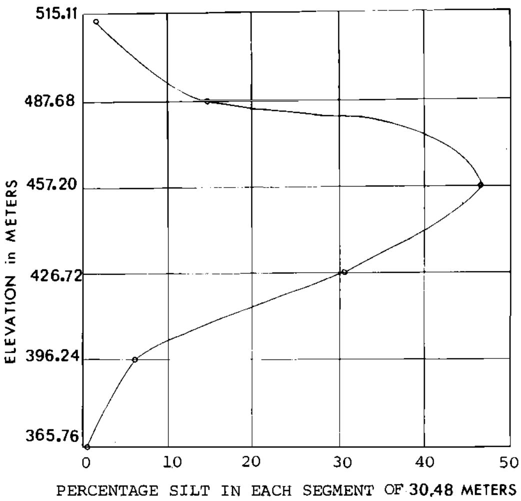


Fig. 7. Curve showing the percentage silt deposit at various elevations of Bhakra Lake.

all-out efforts were made to drain the beds. Drainage pipes were fixed in falls and regulators. Suitably graded cunnets were excavated in the bed, and the crests of the outlets were lowered wherever feasible. Where drainage pipes could not be fixed, victolic pipe siphons with suitable controls were introduced to drain the beds. 'Drain the bed dry' operations were extended to >2736 km (>1700 miles) of channel by the end of 1968, and the results were very encouraging. This method of weed eradication has proved very successful, and the channels can now be run with their normal supplies without any trouble.

CANALIZATION OF THE SUTLEJ RIVER

Since the creation of the Bhakra Lake, there has been a controlled escapage into the Sutlej River. The inflow caused by freshets in the catchment areas of various tributaries and torrents joining the river downstream of the dam are not appreciable. Thus there is practically no flood problem along the river.

A scheme of canalizing the Sutlej River first from the Ropar headworks to Phillaur Bridge and then up to its confluence with the Beas River was prepared. On the basis of model experiments the width of the river downstream of the Ropar headworks has been kept at 914–1219 meters (3000–4000 feet) as compared to 3–5 km (2–3 miles) earlier. The left embankment was completed before the 1963 flood season, and construction of the right embankment began after the monsoons of 1963; canalization of the Sutlej River was completed by 1965.

A number of spurs were constructed across the course of the river, and it was observed that the major diversions at 90, 104, 127, and 134 km worked satisfactorily and that the river had taken a new course. The spurs along the right and left embankments have been very useful in keeping the floodwaters away from the embankments, and the result has been silt deposit and thick growth of high grass upstream and downstream of the spur.

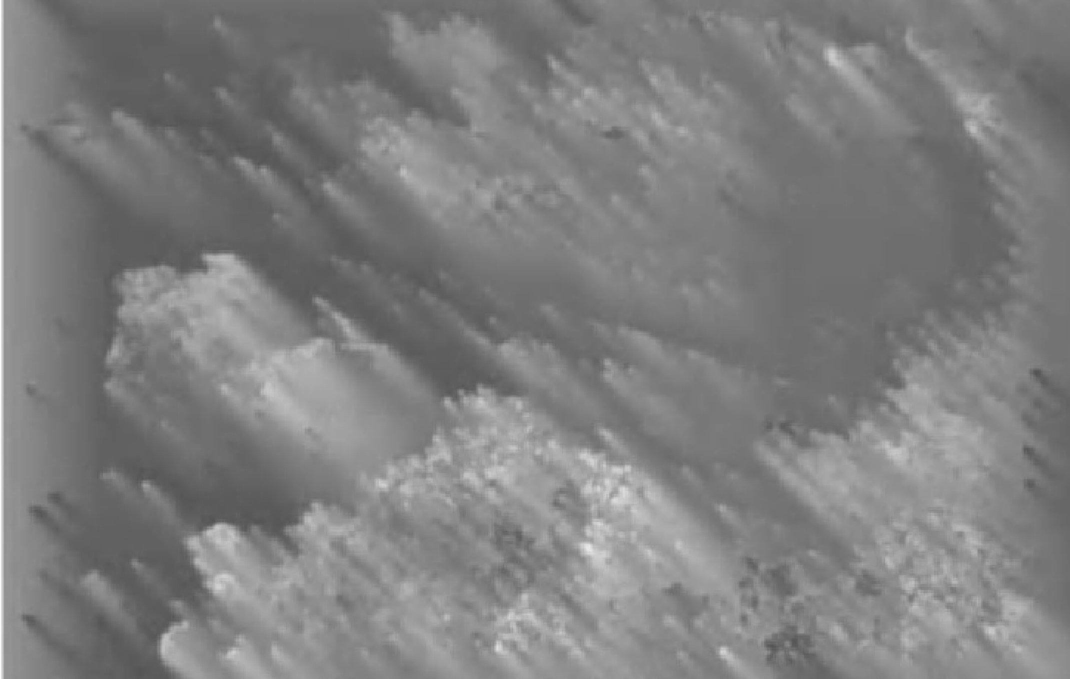
With the narrowing and deepening of the river channel and consequent lowering of water levels, it has been possible to reclaim about 80,937 ha (0.2 million acres) of land that previously formed the riverbed stretching over several miles. This reclamation also relieves water logging in the lands bordering the drained swamps. Mosquitoes have been eradicated, and thus the health of the people has been improved.

RESETTLEMENT AND FORESHORE CULTIVATION

Bhakra Lake affected 371 villages having a population of 36,000. An area of 17,898 ha (44,153 acres) of land was submerged in the lake. Out of this area, 9656 ha (23,863 acres) were privately owned. The number of land-owning families affected was 7206. Sixty-two villages were completely submerged, and the remaining villages were affected in varying degrees. The historic town of Bilaspur, which had a population of 5000, was completely submerged.

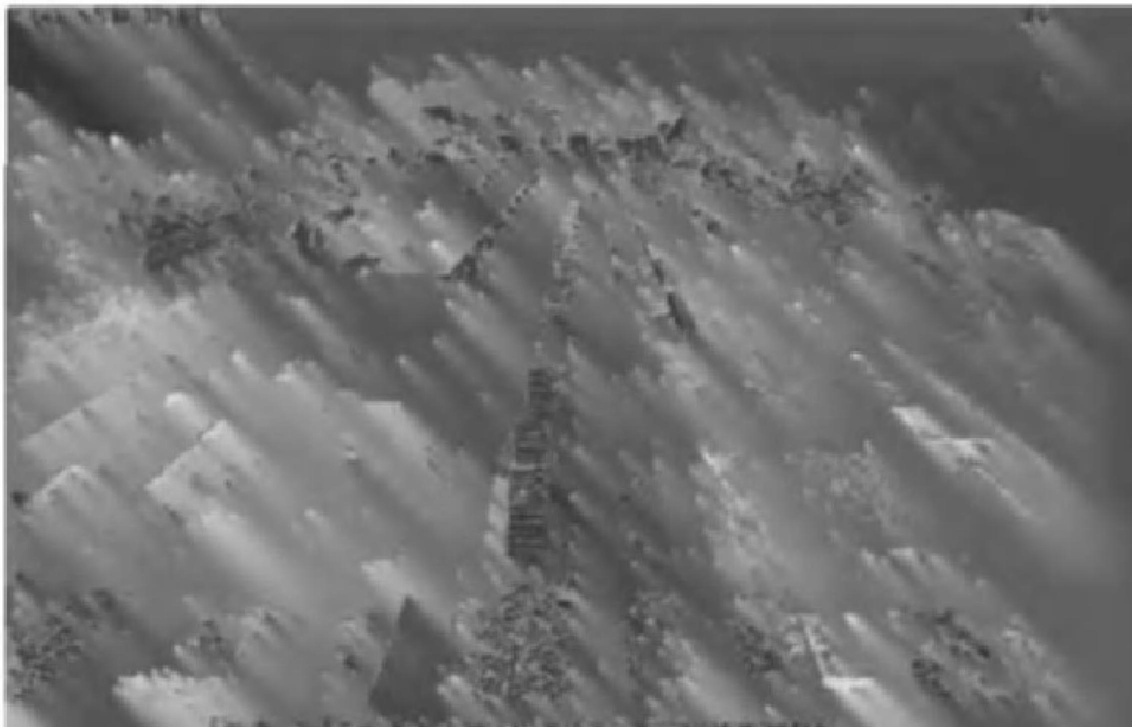
The land in the lake area was acquired after giving full compensation for the acquisition of land, houses, trees, water mills, and other submerged property. Since a large number of persons were involved, the question of resettlement of displaced persons was considered by the management at quite an early stage. Lands in the area to be irrigated by the Bhakra canals were acquired in large blocks, and displaced persons were settled there. For the resettlement of persons living in the town of Bilaspur a new planned township at a higher elevation was constructed, and a much more prosperous and populous township has developed.

As the means of transport and communications were dislocated with the storage of water in the Bhakra Lake, new ferry services were established and new roads were provided. Two major bridges were also constructed across the lake for proper communication (Figure 8).



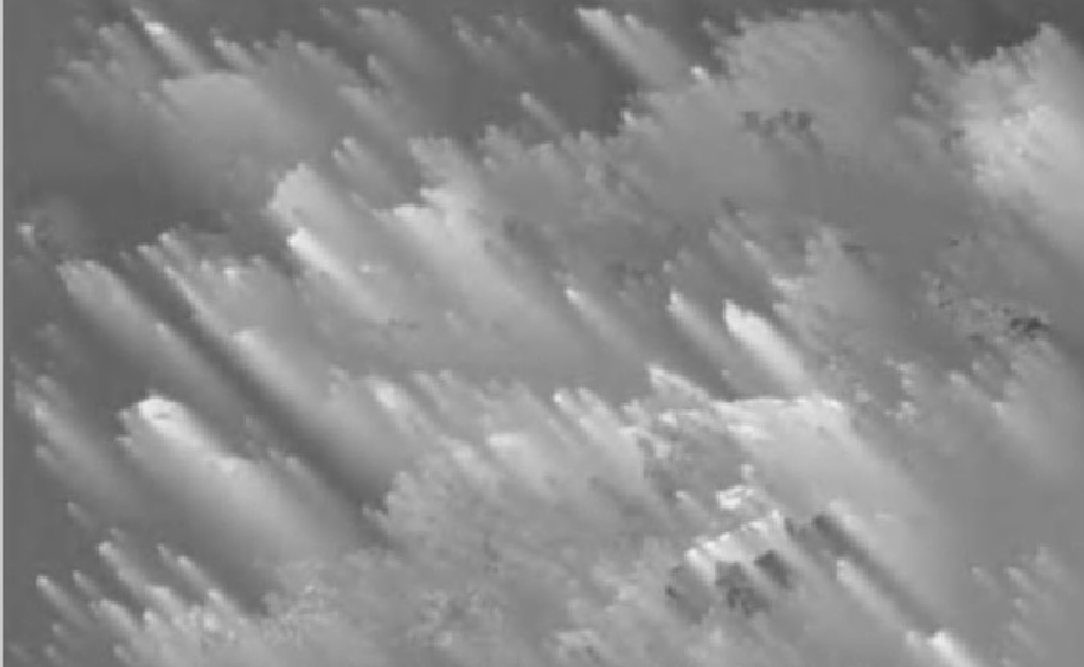
[illegible]

[illegible]



[illegible]

[illegible]



[illegible]

putitora breeds in May and September. *Mystus seenghala* breeds in May and lays eggs in nests. *Cyprinus* varieties lay eggs in April.

Under the changed circumstances of formation of a deep and unevenly bottomed lake the old and primitive fishing gear that were in operation in the river became obsolete, and it was necessary to evolve and recommend an effective gear. Thus experimental and exploratory fishing was done. It has been concluded that the gill net having a stretched mesh size of 45–55 mm is the most effective gear. It has also been observed that the best fishing grounds are the shallow areas of the khads or their tail ends where fish accumulation is high.

In 1963, Bhakra Lake was not even producing 10 metric tons of fish annually. At present, at the most conservative estimate, it is producing 400 metric tons of fish annually, and the production is likely to go up to 1000 metric tons annually in the next few years.

MANAGEMENT FOR MULTIPLE USE

Bhakra Lake operation was planned primarily to provide irrigation to fertile lands in the desert areas of the Punjab, Haryana, and Rajasthan states. Power was just a byproduct, and only one powerhouse was completed at first. The releases were governed by the irrigation requirements of crops and varied from season to season. However, a great demand for power soon developed, and the second powerhouse was constructed by 1967. The irrigation releases have been modified to generate more power. The dead storage level to which the lake may be depleted has been raised from an elevation of 438.9 meters (1440 feet) to an elevation of 445.6 meters (1462 feet) to increase the firm power generation of the Bhakra units.

Demand for irrigation is heavy during the months of October and November when winter crops are sown, February and March when winter crops mature, and May and June when summer crops are sown.

A management board composed of a chairman and two full-time members, one for irrigation and one for power, has been constituted. The storage available at the end of the monsoon season is distributed between the two facilities, and releases are made accordingly. However, another project, called Beas-Sutlej link, is now under construction; this link will transfer about 4564 million m^3 (3.7 million acre-feet) of water from the Beas River to Bhakra Lake.

Acknowledgments. The authors are grateful to the Bhakra Management Board, the Fisheries Department of Himachal Pradesh, and the Meteorological Department of the Government of India for the facilities given by them to undertake the detailed studies on Bhakra Lake.

Lake Brokopondo

P. LEENTVAAR
State Institute for Nature Management
Leersum, Netherlands

Lake Brokopondo in Surinam (Dutch Guiana) was constructed to produce electricity used for the melting of aluminium out of alumina. Before the dam was built, the technical and economic aspects were considered in several reports. These studies finally resulted in the establishment of a joint venture of the Surinam government and the Surinam Aluminum Company (Suralco); an agreement was signed in 1958 for a period of 75 years.

The scientific, medical, and sociologic aspects were investigated by the Foundation for Scientific Research in Surinam and the Netherlands Antilles; these investigations drew attention to the ecological consequences of the project. As a result, some preliminary studies were made by *Schulz* [1954], *van Thiel* [1962], and *Westermann* [1956]. Details of the preimpoundment period were compiled extensively in a publication by *Westermann* [1971]. He also devotes a chapter to the research program for the lake that started in 1963 and deals with its financing, organization, and progress. This paper outlines the results of work done by the Brokopondo team as far as has been published or condensed in the progress reports from the biological Brokopondo research project.

TECHNICAL DATA

The catchment area of the Suriname River above the dam is 12.550 km^2, the average yearly outflow discharge for 1966–1970 is 270 m^3/sec, the average yearly discharge of the power station is 510 m^3/sec (full use), and surface area of the lake is approximately 1500 km^2. The shoreline is approximately 2000 km.

Maximum water level near the dam is +45.5 meters NSP (new Surinam level) (1971), and rainfall near the dam is 2000–3000 mm/yr. The length of the main dam is 1913 meters; the height is 54 meters. Total power (six turbines) is 180.000 kw, and the yearly capacity is 1 billion kw hr. The dam was closed on February 1, 1964. In November 1965 the level of ±38 meters NSP was reached, and the plant was ready for operation. Full use of the turbines will be possible at the level of +47 meters NSP. The Department of Public Works and Traffic in Surinam kindly provided the following data on fluctuations in water level for 1970: average water level, +43.5 meters; maximum, +45.0 meters; and minimum, +42.0 meters NSP.

SOCIAL ASPECTS

The lake area was inhabited by >5000 Bush Negroes in 34 villages. The transmigration preparations were started by the government in 1959. Upstream of the lake, 13 new villages were built; below the dam, 10 were built; and 1 was built at the end of the railroad near Brownsweg. The lake is uninhabited now, and, as the borders are not easily accessible, it will remain so in the near future. To meet the demands of transportation of the lake, a motor launch was introduced, since navigation in the common 'corjals' became a dangerous and time-consuming job.

The lake is situated about 110 km from Paramaribo, and a road leads to the dam. There are plans to make accommodations for tourism. However, the inaccessibility of the lake borders, the difficulty of navigation because of the presently drowned trees, and the voracious 'pirengs' are no invitation. There is no interest in the fishery potentialities of the lake.

MEDICAL ASPECTS

The disturbance of the biological equilibrium in the original tropical forest and the formation of the lake environment have not resulted in explosions of diseases such as malaria, filariasis, and bilharzia. The aspects of this medical problem have been considered in reports from parasitologists from the University of Leiden.

Van Thiel [1962] studied the occurrence of *Anopheles darlingi* and the possibilities of the lake as an environment for the larvae. Also, filariasis was studied, and a report was given to the Surinam-Netherlands Institute for Public Health (Sunevo).

During dam construction, contacts between townspeople and Bush Negroes and measures of prevention were of special interest. Actually, it proved to be impossible to clear the shore region (2000 km!) of trees, and thus the development of breeding places for mosquitoes could not be avoided.

In the area of floating water hyacinths, many larvae of mosquitoes are present, but young fish and other predators are also present. As the lake is uninhabited at present by people, infection will be limited. Bilharzia, which occurs in Surinam only in the coastal regions, is also no problem in the lake. In the Amazon region, *Sioli* [1964] found no bilharzia either, because of the absence of the carrier in the acid waters. The water of Lake Brokopondo also is acidic. Snails are rare or absent, and this sort of rare occurrence is also the case in the inland parts of the rivers of Surinam. Thus we may expect that in the future, because of the establishment of an acid oligotrophic environment and the low concentrations of people, bilharzia will be no problem.

The study on the present bottom-living organisms (such as snails, mosquito larvae, insect larvae, and crustaceans) is important not only in medical terms but also in fish-food relations and biological control. For the species found in the rivers and the lake region, I refer to the publications of *Demoulin* [1966] and *Leentvaar* [1964, 1965, 1966*a*, *b*, 1967, 1969].

OPERATION GWAMBA

During the first filling of the lake the rescue of animals was undertaken by the foundation 'Tjali oede Gwamba' with the aid of the International Society for the Protection of Animals in Boston. John Walsh and his cooperators rescued 9737 animals in this period, and the results are published in the book *Time Is Short and the Water Rises* [*Walsh and Cannon*, 1967]. The animals were released around the lake, and hunting was forbidden until 1969.

Operation Gwamba is interesting from a scientific point of view, since no data were available on the density of different species in this tropical rain forest. Walsh estimates that, in the lake area of about 150,000 ha, 1000 animals drowned or died and an equal number escaped. A list of the species rescued is given at the end of the book, and it is interesting to give some of the data: 2104 three-fingered sloths (*Bradypus tridactylus*), 1051 nine-banded armadillos (*Dasypus novemcinctus*), 973 tortoise (*Testudo denticulata*), 927 porcupines (*Coendou prehensilis*), 840 two-fingered sloths (*Choloepus didactylus*), 671 deer, 528 monkeys, 518 bristle porcupines (*Coendou insidiousis*), and many others. There was a total of 43 species. The value of the rescue is debatable, since much depends on the method of catching and the ability of the species to flee. It is interesting that we had not known that two species of porcupines existed in Surinam.

BOTANICAL RESEARCH

Botanical research in the lake region started in 1964 when the lake began to fill. It was not easy to identify the trees in the inland forest, even with the help of a dendrologist from the forestry service, since there were various species that are seldom seen or that are unknown in the north of Surinam. *Van Donselaar* [1969*b*], the botanist of our team, mentions that about 90% of the 2213 samples collected in the lake area were identified. These species include about 70 new records for Surinam and many second and third records. Thus the scientific value of the preimpoundment research in relation to botany is illustrated, but, as we will see, several unknown or rare species were recorded in the other disciplines as well. It must be regretted that research was started only a short time before the inundation, since we shall never know what exactly was living in this rain forest. *Van Donselaar* [1968, 1969*a*] mentions that there was a unique opportunity to collect the epiphytic species from the dead tree tops after the drowning of the forest. He collected 39 species of orchids and several Bromeliaceae, Cactaceae, ferns, and mosses. During his visit in 1969 to the lake he reexamined the permanent sample plots in the marginal zone of the lake, which were fixed to follow the changes resulting from the inundation. Several plots, however, were not reached by the water. This finding illustrates the difficulty of predicting the exact shoreline of the lake.

In his work, *van Donselaar* [1968] carefully followed the development of the water and marsh plants in the lake. During the first 3 years the water hyacinth (*Eichnornia crassipes*), two floating ferns

(*Ceratopteris pterioides* and *C. deltiodea*), two duckweeds (*Lemna valdiviana* and *Spirodela biperforata*), two bladderworts (*Utricularia gibba* and *U. hydrocarpa*), and *Jussiaea natans* were recorded. The water hyacinth and the water fern were mapped. Both plants were scarce in the Suriname River, but after stagnation of the water they expanded swiftly. In 1964 the water hyacinth covered an area of 5000 ha; in 1965, 17,900 ha; and in 1966, 41,200 ha or 40% of the surface. Also *Ceratopteris* was mapped as shown in Figures 1, 2, and 3. In 1964, *Ceratopteris* covered an area of 1200 ha; in 1965, 11,700 ha; and in 1966, 17,000 ha. Since September 1966 the amount of water hyacinth has decreased as a result of chemical control, which was carried out by Suralco. A special service was set up with the advice of L. W. Weldon, and 15 spraying crews operated from camps in the lake. In 1965 a spraying campaign with 2-4-D from an airplane was started. Information from 1970 indicates that

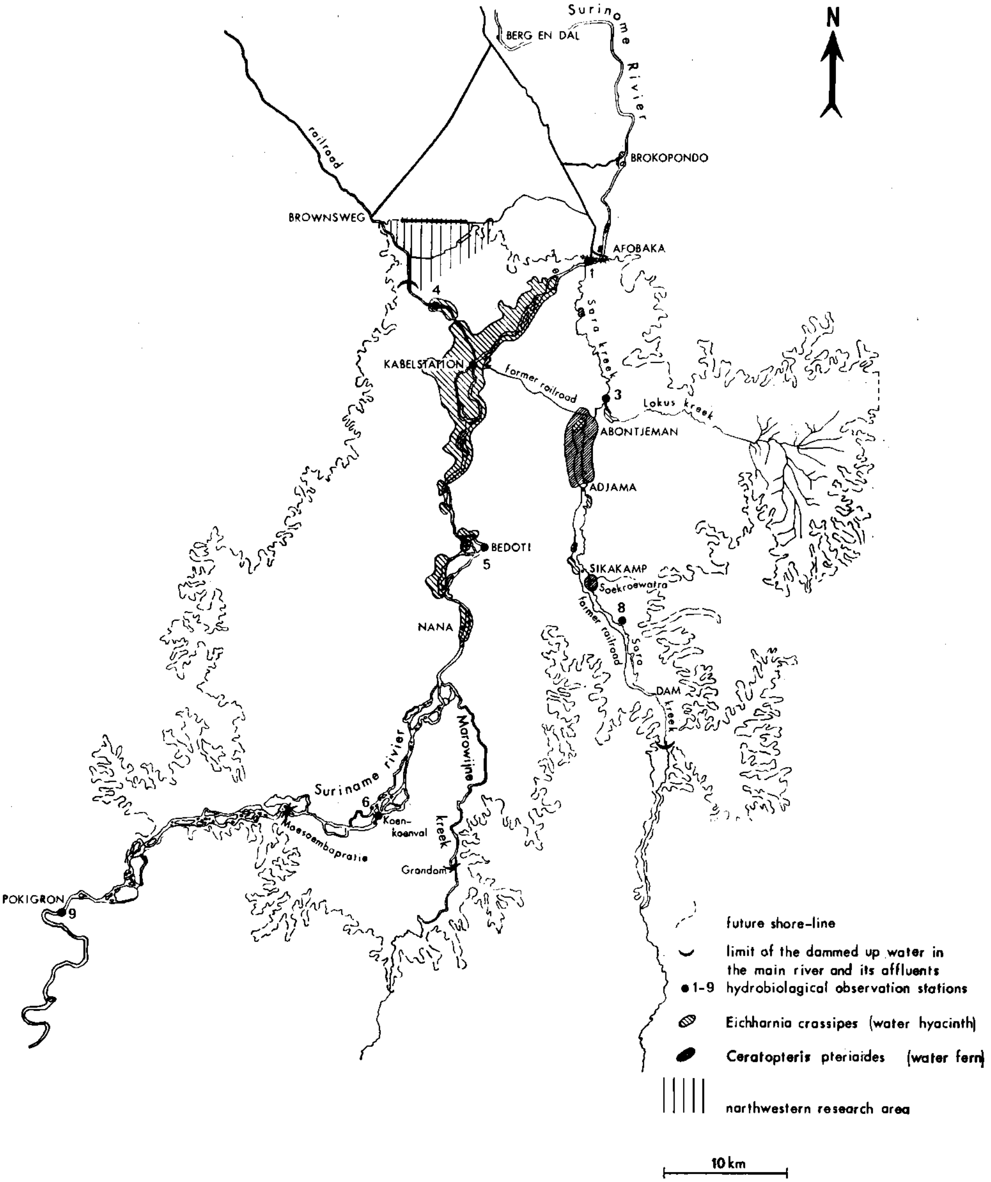


Fig. 1. Distribution of dominant water plants in Lake Brokopondo, 1964.

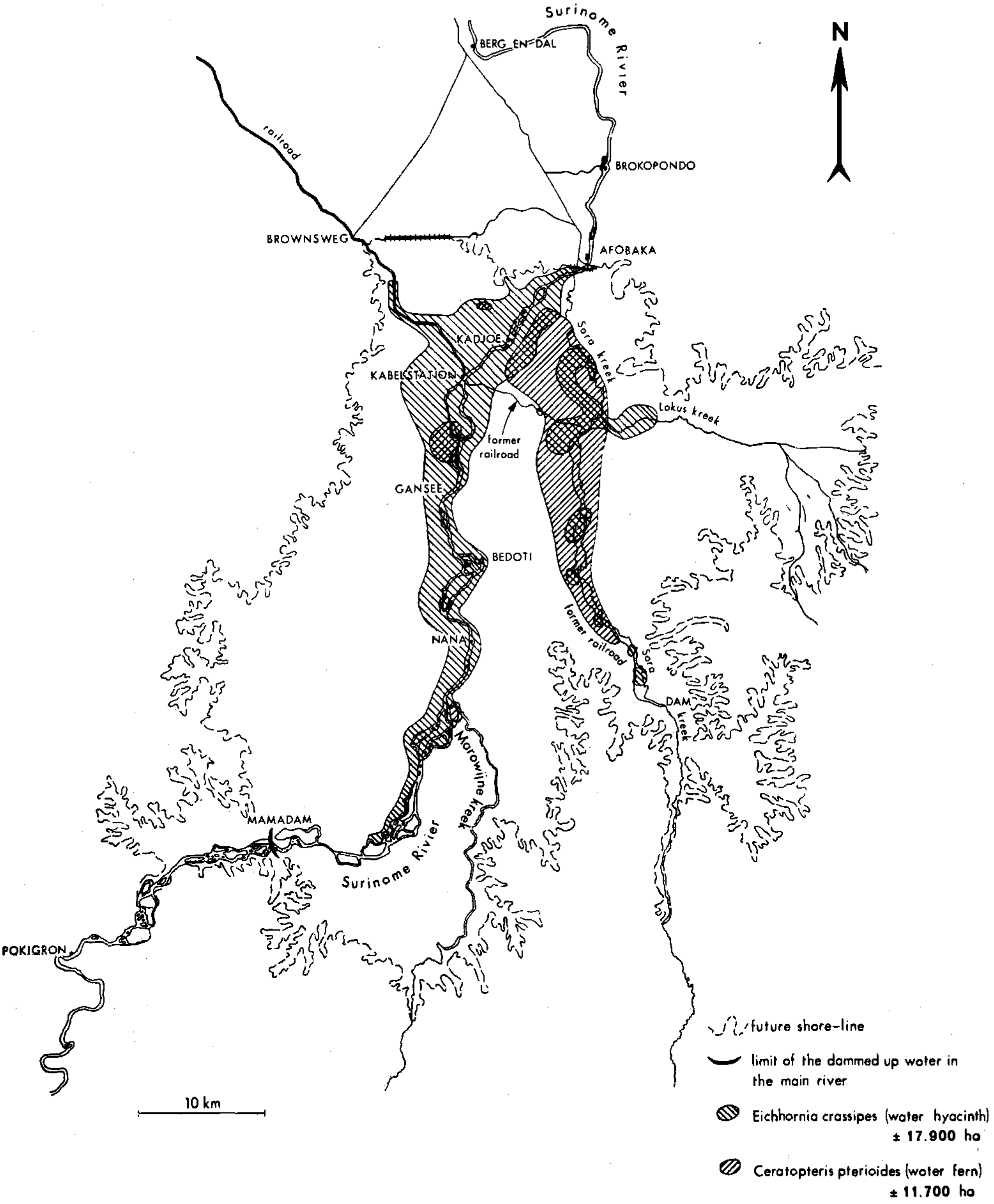


Fig. 2. Distribution of dominant water plants in Lake Brokopondo, June 1965.

the water hyacinth is absent now, and control was stopped for 1 year to observe regrowth, if any. The water fern also decreased in amount, probably in this case by the increase of direct light.

As the chemical control of water plants is undesirable in the environment, attention was paid to the presence of insects. The leaves of the water hyacinth in the lake are eaten by a kind of grasshopper and sucked by a cicada. Also, beetle larvae were found and were identified by W. H. Anderson as a species of *Epipagus* (*Pyraustidae*). Van Donselaar reported that the insects only locally had a noticeable influence on the amount of water hyacinth.

Other water plants such as duckweed developed in great numbers during the first period of filling. This development must be correlated to the high content of organic matter in the lake water. It is

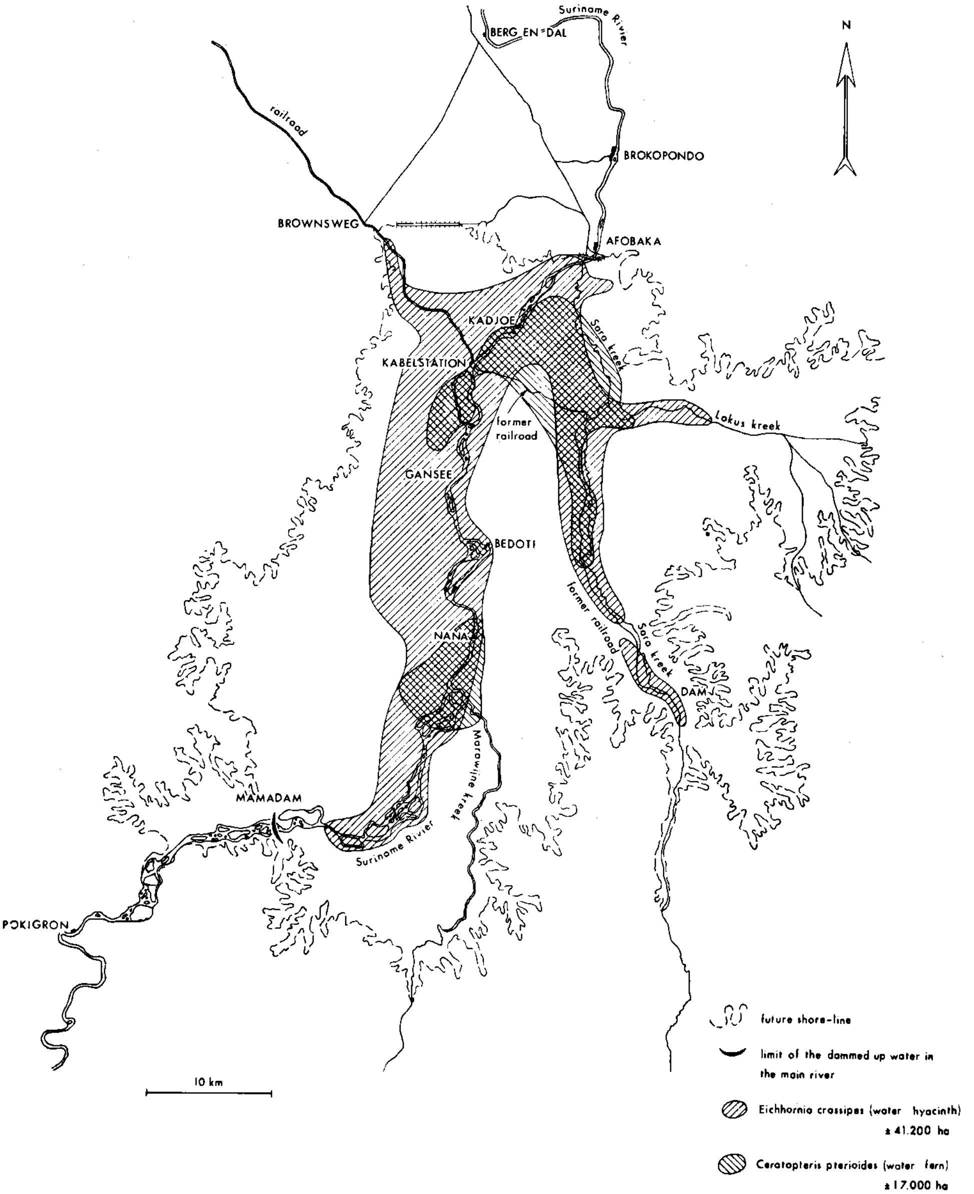


Fig. 3. Distribution of dominant water plants in Lake Brokopondo, April 1966.

known that duckweeds all over the world develop in water with a high content of organic matter. After the establishment of the lake environment in the water, the plants decreased in number. *Utricularia* is the most common plant in the lake now. It is found attached to dead trees and among the roots of water hyacinths.

No mention has been made so far of the effects of the water hyacinth on the evaporation of water. As the filling of the lake took much longer than was calculated, the causes were related partly to the evapotranspiration of the mats of the water hyacinth and partly to the occurrence of a relatively dry year. In this connection we must note that insufficient data on rainfall for inland Surinam were available and that insufficient experiments were carried out to measure evaporation of free water surfaces. No attention was paid to the possible growth of the water hyacinth in the lake and the related water losses by evapotranspiration. For this reason the commission Netherlands for Research on Impoundments in Surinam discussed the importance of new research.

Since 1968, rainfall stations have been established in the lake, and measurements of evaporation and evapotranspiration have been carried out in experiments by the Department of Hydraulics and the agricultural station in Paramaribo [*van der Weert and Kamerling*, 1968]. It now appears that the ratio of evapotranspiration of the water hyacinth to evaporation of the free water was 1.4 : 1, which is much lower than that found by H. Timmer and L. W. Weldon in experiments in Florida.

Recent information and general climatological data are given in reports by *van Loon* [1970] and *Breeveld* [1971]. The rainfall was measured at seven different stations around the lake in the period 1960–1970, and these authors deduced that the influence of the lake on the weather is limited to a rather small surrounding area. The northwest area of the lake seems to be drier, whereas the southeast and west are wetter than before. They conclude that the average yearly rainfall at the lake is of the same order as the transpiration of the free water surface. The observation that the yearly discharge of the Pikien Saramacca, a river flowing near the lake border, has increased considerably since 1966 whereas the discharge of other rivers has not changed is interesting. Because we lack sufficient measurement stations, we must be careful with the conclusions. It is clear that, in general, more data are needed from the different tropical regions on the subject of transpiration, evapotranspiration, and climate. For example, it has been stated by the U.S. Army Tropic Test Center in the Canal Zone that, if the vegetation of the Amazon basin is drastically changed by man (there are plans for damming the Amazon), the rainfall in other parts of South America may be influenced in the course of time.

FISH FAUNA

Since 1967, no regular observations on fish have been made. There is no interest in Surinam in the fishery potentiality of the lake. The ichthyologists of the Brokopondo team, M. Boeseman and G. F. Mees from the Rijksmuseum van Natuurlijke Historie at Leiden and H. Nijssen from the Institute of Taxonomic Zoology at Amsterdam, collected an estimated 60–70 thousand specimens during their stay in Surinam. It is not yet known which species were collected in the Suriname River and the lake, since these ichthyologists also carried out investigations in other parts of the country. The taxonomic studies will take a lot of time since few data were available. Some results are now published that show that about 400 species are recorded for Surinam, which is about twice as many as were recorded before the start of the Brokopondo research project.

As an illustration of the taxonomic difficulties, *Boeseman* [1968], in his publication on the genus *Hypostomus*, described 15 forms of which 10 are new species and two are new subspecies, and *Nijssen* [1970] revised the genus *Corydoras* and described 17 species and subspecies of which seven are new to science. At this point we may ask if a fish ecologist should not be added to the team, since the task was to investigate the changes in the fish fauna before and after the closing of the dam. It is clear that ecologists and taxonomists must work together. In this particular case, where little is known from the fauna and many endemic species occur, the ecologist cannot make sound conclusions unless primary taxonomic work has been done. On the other hand, a skilled field ecologist should have been able to carry out the scheduled task without deep taxonomic knowledge. We have not yet found the man for this task.

Nijssen [1969] gives some information on the changes in the fish fauna in the lake:

> By lack of data on the original fish fauna of the lake area it is difficult to make conclusions. However it is clear, that the fish fauna of the lake in comparison to that of the upper reaches of the Suriname River and other river systems, is rather poor in species. As a consequence of the oxygen deficiency in the lower layers and the disappearance of many niches (rapids, banks), many species could not survive. The dam will be fatal to many species which have to migrate for their reproduction. As we know very little about the ecology and reproduction habits of South American fish, it will be difficult to understand why certain species have disappeared.

In the lake, *Hoplias macrophthalmus* has disappeared, but *H. malabaricus* is caught in large numbers. The electric eel still occurs, and *Cichla ocellaris* and the 'pireng' (*Serrasalmus rhombeus*) are abundant. Other fish species occurring in the lake are *Acestrorhynchus falcatus, A. microlepus, Leporinus friderici, Curimatus schomburgki, C. spilurus,* many *Moenkhausia,* and *Creatochanes* spp.

Ichthyological research has yielded interesting results. The geographical distribution of the fish fauna in the different rivers of Surinam indicates that isolated rivers such as the Suriname and the Saramacca are inhabited by endemic species whereas other rivers such as the Corantijn are more related to the Amazon River system in occurrence of species. This information emphasizes that, in the planning of dams, biological knowledge should be included. If we had known before the construction of the dam in the Suriname River what a unique type this river represents, we might have promoted the location of the dam in another, biologically less valid region. As there are several other plans for dams in Surinam, it is necessary to carry out biological research in several rivers. In the preimpoundment phase a long period of research into the flora and fauna of the region should be conducted before an attack on our environment is made through construction.

LIMNOLOGICAL RESEARCH

The initial developments in physical, chemical, and plankton composition after the closing of the dam in 1964 were published in the London symposium on man-made lakes [*Leentvaar,* 1966*b*]. Continuous weekly sampling on fixed stations was carried out by J. van der Heide from the Vrije Universiteit at Amsterdam and H. Nijssen. After 1967 the research was continued by incidental visits to the lake, but thanks to the help of the Department of Public Works in Paramaribo a monthly sampling at a few stations was guaranteed. Unfortunately, no funds were available for the foundation of a permanent biological station at the lake. Limnological research is handicapped in this remote place in the jungle by lack of a well-equipped laboratory. Also, a university center in Surinam would have been helpful. In view of the new plans in Surinam it would be no luxury to found a permanent biological station with a special applied ecological task.

The observations in 1964–1967 have not been fully analyzed, but some of the results are presented here, together with the observations made by *Nijssen* [1970]. Figure 4 shows the temperature and oxygen content at different depths at the Kabel sampling station. The water stagnated here in March 1964, and in April the depth increased to 8.5 meters. Gradually, in 1967, a depth of 30.5 meters was reached. The temperature before stagnation was about 30°C from top to bottom; after stagnation the temperature of the deeper layers remained lower. Until the end of 1964, with the swift rising of the water level, the temperature in all layers gradually dropped. The lowest temperature of 26°C was found near the bottom. As the lake filled very slowly after 1964, the water gradually warmed up and showed the increasing influence of direct sunlight. In 1965 the layer at 2.5 meters together with the more superficial layers warmed up, whereas at 4.5 meters and lower the water warmed up less. The curves in Figure 4 show that only the layers below 18.5 meters were not affected in 1966 but that in 1967 even the bottom layers were warmed up. This tendency has continued. During my visit in 1958 the bottom temperature at Kabel was about 28°C in April; in April 1970, as measured by the Department of Public Works, it was 27.8°C. In general, the team concluded that in 4 years the water of the lake warmed from top to bottom. The heat balance of the lake may be stabilized now if we consider that the lake is filled and the trees are drowned and dead. The effect of the summer and winter seasons is visible in the higher and lower temperatures in the layers from 0 to 2.5 meters. The curves are influenced by the dry and wet periods, which correspond with winter and summer.

The oxygen content of the lake also is shown in Figure 4. In March, some weeks after stagnation, supersaturation of the water occurs. This supersaturation is caused by abiotic physical factors, since no sufficient assimilating phytoplankton are present at that time. Then a sharp drop in oxygen content in all water layers is seen; this drop is interrupted in June by the effect of a short wet period, which mixes the layers with colder, oxygen-rich river water. In the next years we see a parallel to the tendency in temperature: the oxygen content in the layers gradually increased. In 1964, large new wooded areas were inundated, and the oxygen was rapidly consumed. Below 2.5 meters the water was anaerobic with H_2S. The daily oxygen content fluctuated strongly, but the

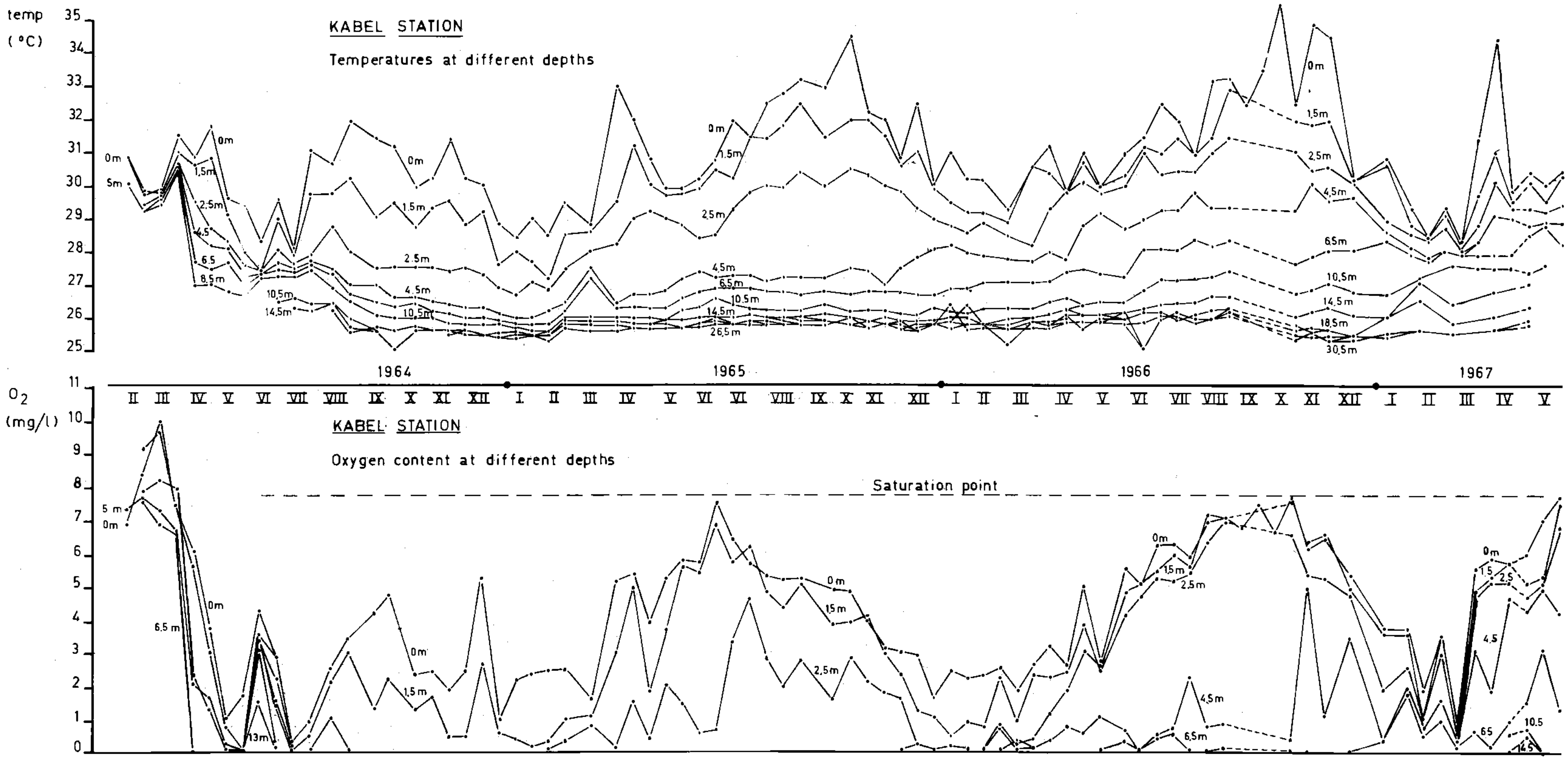


Fig. 4. Temperature and oxygen content at different depths at Kabel sampling station. This graph is presented in agreement with J. van der Heide.

development of plankton in the superficial layers from 0 to 2.5 meters caused the oxygen content to improve. In 1966 the layer from 0 to 2.5 meters was nearly saturated with oxygen, but gradually some oxygen was found in the anaerobic deep water at 4.5 meters and even 6.5 meters and in 1967 within deeper layers.

During winter when the temperature of the different water layers is more homogeneous, the water is mixed and the oxygen content drops. In summer, high oxygen contents are restricted to the superficial photosynthetic zone; in the aphotic deep water, oxygen is very low, but after each winter overturn an improvement is seen. This improvement indicates the gradual decrease of reducible substances derived from the drowned wood. The continuation of the mineralization was confirmed during my stay in 1968 when I found oxygen and even supersaturations at the bottom but also layers with low oxygen at the same time. Measurements at two stations every 2 hours showed that the vertical oxygen distribution was very unstable (Figure 5). This result was surprising, but my observations were sustained by the fact that plankton occurred at all depths and that living crustaceans were present only in the samples containing oxygen [*Leentvaar*, 1969]. The rapid change in oxygen content must be due to turbulence or undercurrents, which did not exist before 1968.

The remarkable daily fluctuations in temperature and oxygen just after stagnation in 1964 are described elsewhere [*Leentvaar,* 1967]. These occurred in the 2.5-meter layer only, and, in this period, wind action was almost absent. This occurrence demonstrated the effect of heat absorption in the absence of wind. If we realize that, by the weathering of the dead trees, more open water comes into existence and that this increase causes more wind action, we understand the increasing effect on the mixing of the water layers. Moreover, the radical control of the water hyacinth promoted the effect of the wind on the free water surface, so the high waves, caused by the wind at the beginning of rain showers, made navigation with the corjals dangerous. Short-duration heavy winds may cause temporary rapid mixing of the layers, even at 30-meter depths. The rapid mixing of a total water mass from 45 meters also has been observed in Volta Lake. Finally, the effect of the steady opening of the gates of the turbines in 1967 must have some effect on the water, but this effect has not been studied separately.

The picture will be completed by considering the measurements of the Department of Public Works in 1970. These investigators also found oxygen near the bottom (sometimes vertically irregularly distributed as in 1968), but, in general, they found much lower oxygen contents. Supersaturations did not occur. We must bear in mind that the enormous radical spraying of the water hyacinth resulted in the accumulation of many dead plants at the bottom, which consume oxygen. On the other hand, the spraying might have affected the development of plankton. Whatever the case may be, I observed that in the samples from 1970 that I received recently the amount of plankton was decreased considerably. This decrease might influence the amount of oxygen produced.

We hope that we shall have the opportunity to continue to study these interesting developments. For the present the lake is filled, and the water level is fluctuating. The heat balance might be stabilized, but the influence of increased wind action must be studied. The oxygen balance also might have obtained a stable character if no disturbances caused by control actions in lake management had interrupted the picture. The whole problem needs further study.

The scope of this paper allows no further details, but we may not finish without characterizing the lake as an environment. The electric conductivity at the surface is fairly constant between 20 and 25 $\mu\Omega^{-1}$; the pH varies between 5.5 and 6; and the transparency measured with the Secchi disk is about 3 meters. The water is acid and oligotrophic. These characteristics reflect the general quality of the waters in the Guianas and South America. At this moment, desmids are dominating; diatoms, blue algae, and green algae are practically absent; crustaceans and rotifers are present in great numbers. The succession of the most important plankters in the weekly samplings from 1964 until 1967, as analyzed by J. van der Heide, can be correlated with the mentioned changes in the physicochemical environment. After early 1964 the river plankton and the diatom *Eunotia asterionelloides* disappeared in the lake environment. In the transition period, blooms of filiform green algae and Euglenophyta occurred; their appearance indicated high contents of organic matter and extreme oxygen contents. The appearance of Ostracoda in the plankton was remarkable and may be related to the swamp character of the lake, caused by the abundant

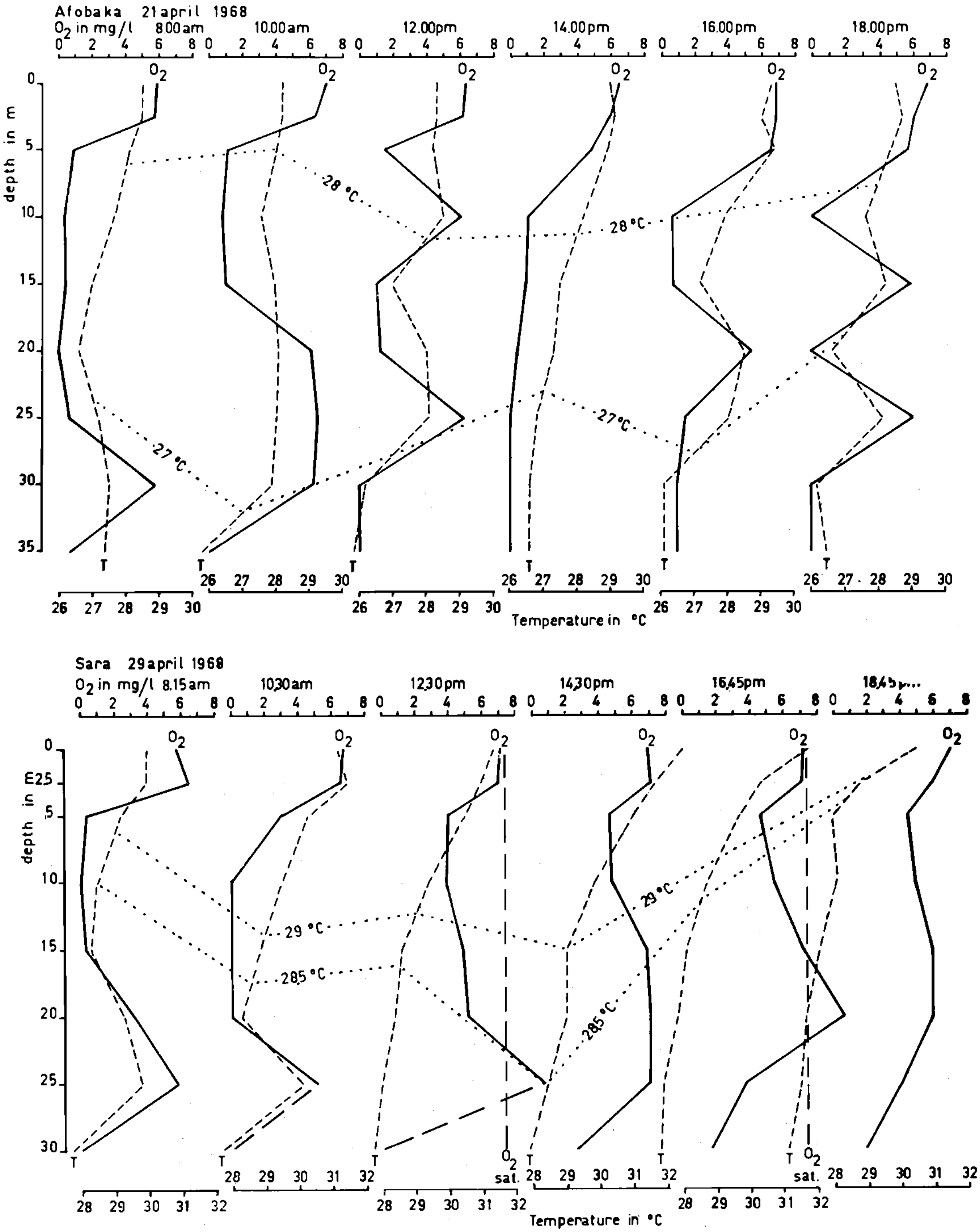


Fig. 5. Comparison of vertical oxygen distribution at two stations with measurements at 2-hour intervals in 1968.

water hyacinth mats in that period. In 1966 and 1967, species of desmids, typical for the lake environment, appeared, and they remain as the permanent plankters of the lake. After 1967 the bloom of *Volvox* and *Eudorina*, which gave the plankton the appearance of a thick green soup, diminished, and their decrease indicates that the lake tended to be more stable.

When may the lake be seen as a mature ecosystem? The diversity of the biocommunity must be studied further, but I am afraid that no definite conclusions can be made because of the side effects of sprayings and the other actions that will be carried out for the management of the lake.

REFERENCES

Boeseman, M., The genus *Hypostomus* Lacépède, 1803, and its Surinam representatives (Siluriformes, Loricariidae), *Zool. Verh., 99,* 89, 1968.

Breeveld, F., Hydro-meteorologisch onderzoek Brokopondo stuwmeer, report, Hydraul. Res. Div., Min. of Public Works and Traffic, Paramaribo, Surinam, 1971.

Demoulin, G., Contribution à l'étude des ephéméroptères du Surinam, *Bull. Inst. Sci. Nat. Belg., 41*(37), 22, 1966.

Leentvaar, P., Hydrobiological observations, Biological Brokopondo Research Project, Surinam, *Progr. Rep. 1,* pp. 5–10, Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1964.

Leentvaar, P., Hydrobiological observations, Biological Brokopondo Research Project, Surinam, *Progr. Rep. 1,* pp. 45–50, Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1965.

Leentvaar, P., The Brokopondo Lake in Surinam, *Verh. Int. Ver. Limnol., 16*(6), 680–685, 1966*a*.

Leentvaar, P., The Brokopondo research project, Surinam, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 33–42, Academic, London, 1966*b*.

Leentvaar, P., The artificial Brokopondo Lake in the Suriname River, Its biological implications, in *Atlas Sympôsio Biota Amazônica,* vol. 3, *Limnologia*, pp. 127–140, Consilho Nacional de Pesquisas, Rio de Janeiro, 1967.

Leentvaar, P., Hydrobiological observations, Biological Brokopondo Research Project, Surinam, *Progr. Rep. 4,* pp. 249–256, Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1969.

Nijssen, H., Final remarks and tentative list of fish species, Biological Brokopondo Research Project, Surinam, *Progr. Rep. 4,* pp. 240–246, Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1969.

Nijssen, H., Revision of the Surinam catfishes of the genus *Corydoras* Lacépède, 1803 (Pisces, Siluriformes, Callichthyidae), thesis, Univ. of Amsterdam, Amsterdam, 1970.

Schulz, J. P., Vergelijkend literatuuronderzoek inzake de ecologische consequenties van het 'Combinatieplan Surinamerivier' (with English summary), report, 124 pp., Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1954.

Sioli, H., General features of the limnology of Amazonia, *Proc. Int. Soc. Limnol., 15*(2), 1053–1058, 1964.

van der Weert, R., and G. E. Kamerling, Evapotranspiratie van water hyacinth, *Intern. Rapp. 211,* p. 49, Landbouwproefstation, Paramaribo, Surinam, 1968.

van Donselaar, J., Water and marsh plants in the artificial Brokopondo Lake (Surinam, S. America) during the first three years of its existence, *Acta Bot. Neer., 17,* 183–196, 1968.

van Donselaar, J., On the distribution and ecology of *Ceratopteris* in Surinam, *Amer. Fern J., 59*(1), 3, 1969*a*.

van Donselaar, J., Botanical observations, Biological Brokopondo Research Project, Surinam, *Progr. Rep. 4,* pp. 247–248, Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1969*b*.

van Loon, U. J., Hydrological data, Suriname River, report, Hydraul. Res. Div., Min. of Public Works and Traffic, Paramaribo, Surinam, 1970.

van Thiel, P. H., Malaria problems arising from the construction of a reservoir in the interior of Surinam, *Trop. Geogr. Med., 14,* 259–278, 1962.

Walsh, J., and R. Cannon, *Time Is Short and the Water Rises,* 224 pp., Dutton, New York, 1967.

Westermann, J. H., Een korte beschouwing over het Brokopondoplan Suriname, report, 16 pp., Found. for Sci. Res. in Surinam and the Neth. Antilles, Utrecht, Netherlands, 1956.

Westermann, J. H., Historisch overzicht van de wording en het onderzoek van het Brokopondo-stuwmeer, in *De Nieuwe West-Indische Gids,* Nijhoff, The Hague, 1971.

Kainji Lake, Nigeria

SALAH EL-DIN EL-ZARKA[1]

UNDP/FAO Kainji Lake Research Project, New Bussa, Nigeria

Kainji Dam, near Wawa and Kainji (Figure 1), on the River Niger in Nigeria is the first stage of a program to provide electric power for industrial expansion in Nigeria. The powerhouse at Kainji contains four 80-Mw generating sets, but provision has been made to increase the installation ultimately to 12 sets totaling 960 Mw. It is anticipated that this supply will be adequate for both domestic and industrial needs throughout the 1970 decade, near the end of which a new developmental program may be launched. In this new second stage a power station will be installed at Jebba, capable of producing 500 Mw; this station will be followed by a 480-Mw station at Shiroro Gorge on the Kaduna River (Figure 1). According to plans the three stations, totaling 1940 Mw, will function as an integrated system capable of sustaining a maximum demand of 1730 Mw.

Construction of Kainji Dam, which began in March 1964, was completed on schedule in December 1968 at a total cost of £87,650,000. It took about 20,000 men nearly 5 years to construct the main dam and ancillary projects, and it involved people of nine different nationalities.

The Kainji generating station was declared open officially on February 15, 1969. In addition to the power generation, other anticipated benefits from the project include (1) facilitation of navigation on the River Niger both upstream and downstream through the various improvement schemes (navigational locks, clearance of rapids, and regulation of flow at the dam); (2) control of floods of the River Niger to lessen the seasonal inundation of fadamas in the area and to allow thereby the expansion of agriculture; (3) provision of a large potential source of protein from fishing in the reservoir (Kainji Lake) upstream of the dam; and (4) improvement of road communication through the system of bridges at Kainji, which provides the only road crossing of the Niger upstream of Jebba.

HISTORY

The story of the Kainji hydroelectric project dates back at least to 1951. The demand for electricity had been rising faster than before along with the growth of industries and increased urbanization. The Electricity Corporation of Nigeria realized that a large and cheap source of power had to be found to satisfy this growing demand. As a result an examination was made of the hydroelectric potential of the River Niger above Jebba, but no further action was taken until 7 years later.

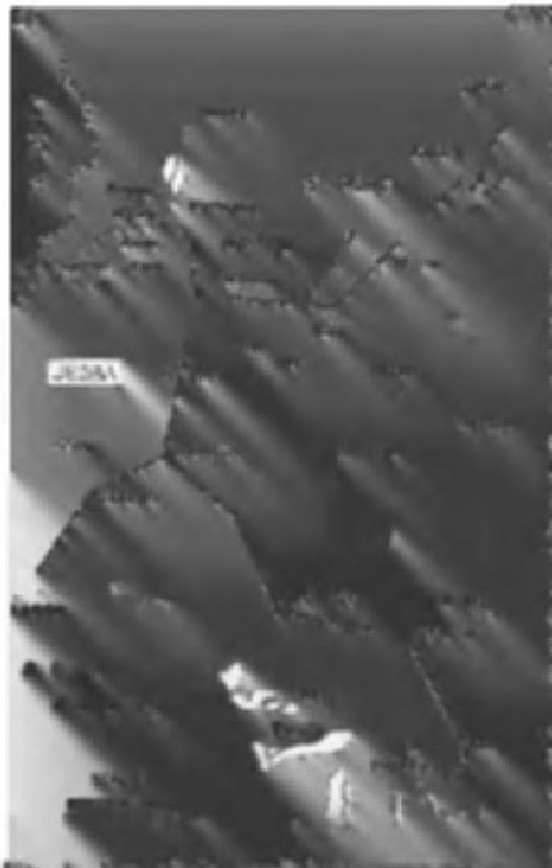
In 1958 the Electricity Corporation of Nigeria commissioned Balfour, Beatty and Company Limited of Great Britain to investigate the hydroelectric potential of the Niger in the vicinity of Jebba. A similar but separate investigation of the hydroelectric potential of the Kaduna River at Shiroro was also carried out at the request of the then Northern Nigeria government and the Electricity Corporation of Nigeria.

Earlier, in 1953, the federal government had commissioned the Netherlands Engineering Consultants (Nedeco) to carry out a hydrologic survey of the Niger and Benue rivers. The report of this survey, which was published in 1959, recommended, among other things, one or possibly two multipurpose dams on the Niger above Jebba.

At the request of the federal govenment and the Electricity Corporation of Nigeria, Nedeco and Balfour, Beatty and Company prepared a joint report. This report contained the recommendation that a dam be built upstream from Jebba to provide electric power, improve navigation, control flooding, and allow large areas of land downstream of Jebba to be cultivated. After further investigations, it was recommended that the first dam should be built

---

[1] Now at Near East Regional Office, FAO, Cairo, Egypt.



[illegible]

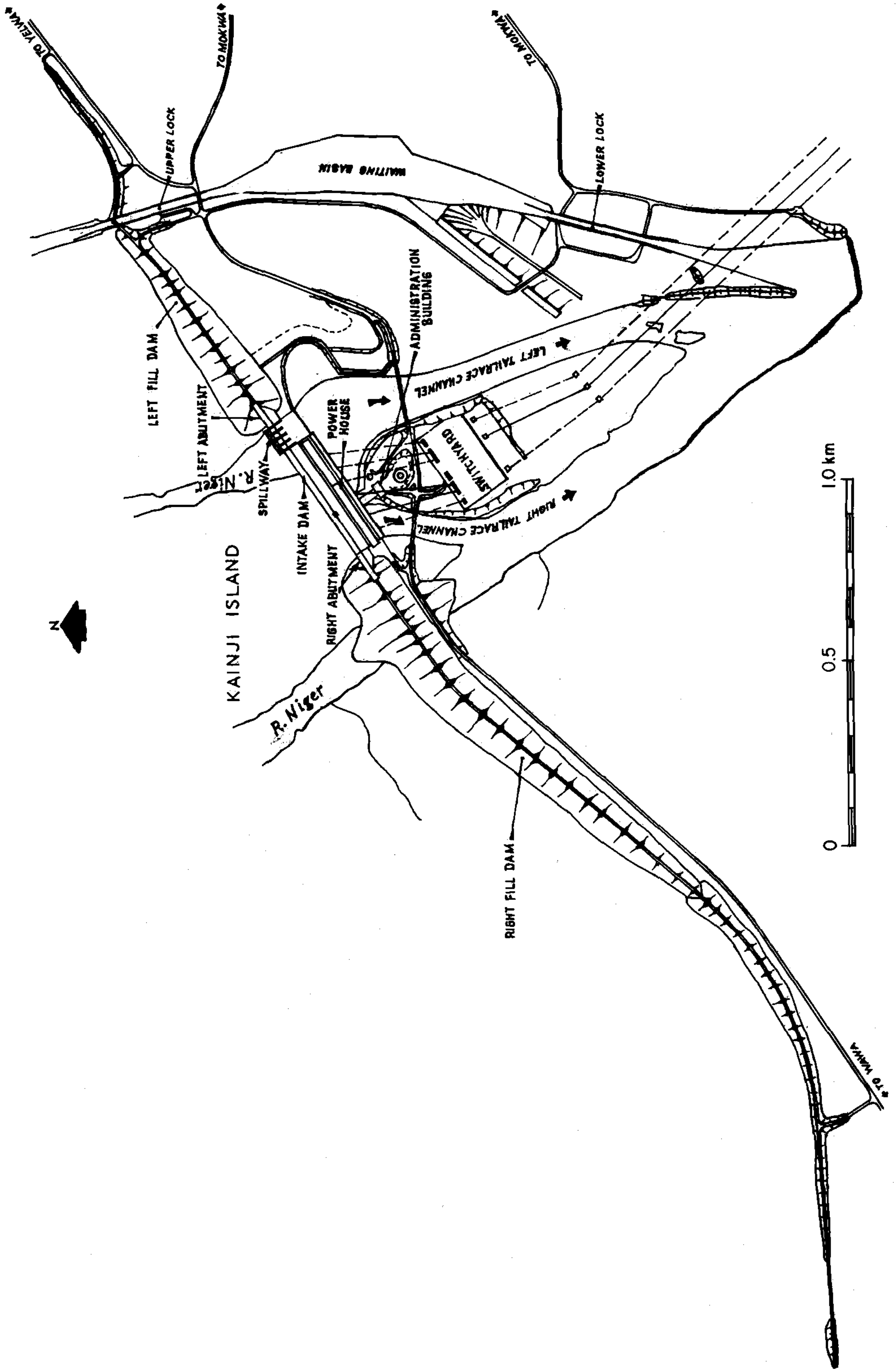


Fig. 2. Plan of Kainji Dam.

sisting of a pusher and four units of barges can be locked through in one operation. Each barge is 43.3 by 10 meters, and the train of four barges and a pusher approximates 200 meters in length. Each lock is 216.6 by 13.3 meters; it takes an hour for a barge train to pass through the two locks and the basin.

KAINJI LAKE

Kainji Lake is widest over inundated Foge Island (Figure 3), where its water depth ranges between 3.3 and 20 meters. The existence of trees and brush on the island was considered to be a major obstacle to the future development of the fishing industry in the new lake. As a result, 53,500 ha on and to the east of Foge Island were cleared along with fishing lanes to new villages and a navigation channel from the dam site. The work of clearing started in April 1966, and the last tree on Foge Island (the 5,300,000th!) was felled on October 21, 1967. About 70% of the future lake bottom was cleared.

Evaluation after early filling of the lake has indicated that there has been only little observable benefit from such a large costly clearance operation. In fact, the largest and most consistently high catches of fish to date have been taken in shallow waters where trees and brush were left standing. Present judgment is that the most useful type of clearance is the narrow strips, or farrows, that facilitate navigation and the setting of fishing nets.

Before inundation, plans were completed to resettle 42,500 people on higher ground around the new reservoir. Resettlement took place in 130 new villages and two towns comprising 5000 houses and 35,000 rooms. As of 1971, compensation in cash was still being paid to farmers for old farmland and economically valuable trees that had been destroyed as a result of the creation of the lake; thus far, a total sum of £296,000 has been paid out by the Niger Dams Authority. New farmlands have been sited around the lake. A new road has also been constructed near the west shore of the lake.

Besides resettlement, study and development of the natural resources of the lake area have been started. Fishing, farming, and the exploitation of wildlife are considered as principal components of the base for the regional economic development.

CHARACTERISTICS OF KAINJI LAKE

The River Niger rises in the Fouta Djallon Mountains of Guinea, about 150 airline miles from its mouth in the Atlantic Ocean, and flows in a large arc through Mali, Niger, along the northeastern border of Dahomey, and then through Nigeria to the Gulf of Guinea, a total distance of nearly 4183 km. Through the mid part of its course, very little water is added to the river, owing to very low regional rainfall; indeed, the river loses some 65% of its flow in this area [*Joint Consultants*, 1961].

There are two distinct periods of flood in the river in Nigeria. Local rains in the northern region of Nigeria and Dahomey (May through October) produce a flood beginning in mid-August with a peak flow of between 4000 and 6000 m^3/sec, whereas the rains upstream in Guinea produce a flood that reaches the Kainji area in November and extends to April with a peak flow consistently near 2000 m^3/sec (Figure 4). The annual flow into the basin of Kainji Lake may be around 80 billion m^3 in a year of high flow, of which 47 billion m^3 originates in the Nigerian basin (the 'white flood') and 33 billion m^3 originates in the Guinean basin (the 'black flood'). Of this 47 billion m^3, about 12 billion m^3 is stored annually in the lake. In years of low rain the white flood may be reduced to less than half, whereas the black flood is rarely reduced by $>10\%$. Little water enters the lake directly other than from the Niger (Figure 4). Of the several small tributaries to the lake the Malendo is the most significant; its peak discharge of around 700 m^3/sec occurs near the start of the white flood.

No very satisfactory estimates of evaporation from the lake area are available, although estimates of 150–200 cm have been made by extrapolation from scattered meteorological stations [*Joint Consultants*, 1961]. This estimate is nearly equal to the local annual rainfall.

The level of Kainji Lake rises and falls about 10 meters each year, and the volume and surface area change by factors of 4 and 2, respectively. The lowest level is reached in August, and the lake is essentially full from November to March (Figure 5). The discharge downstream has been rather irregular since the closure of the dam, particularly during the white flood. Because of this irregularity of the white flood the discharge schedule can only anticipate changes in inflow by a few days. In both 1969 and 1970 the discharge

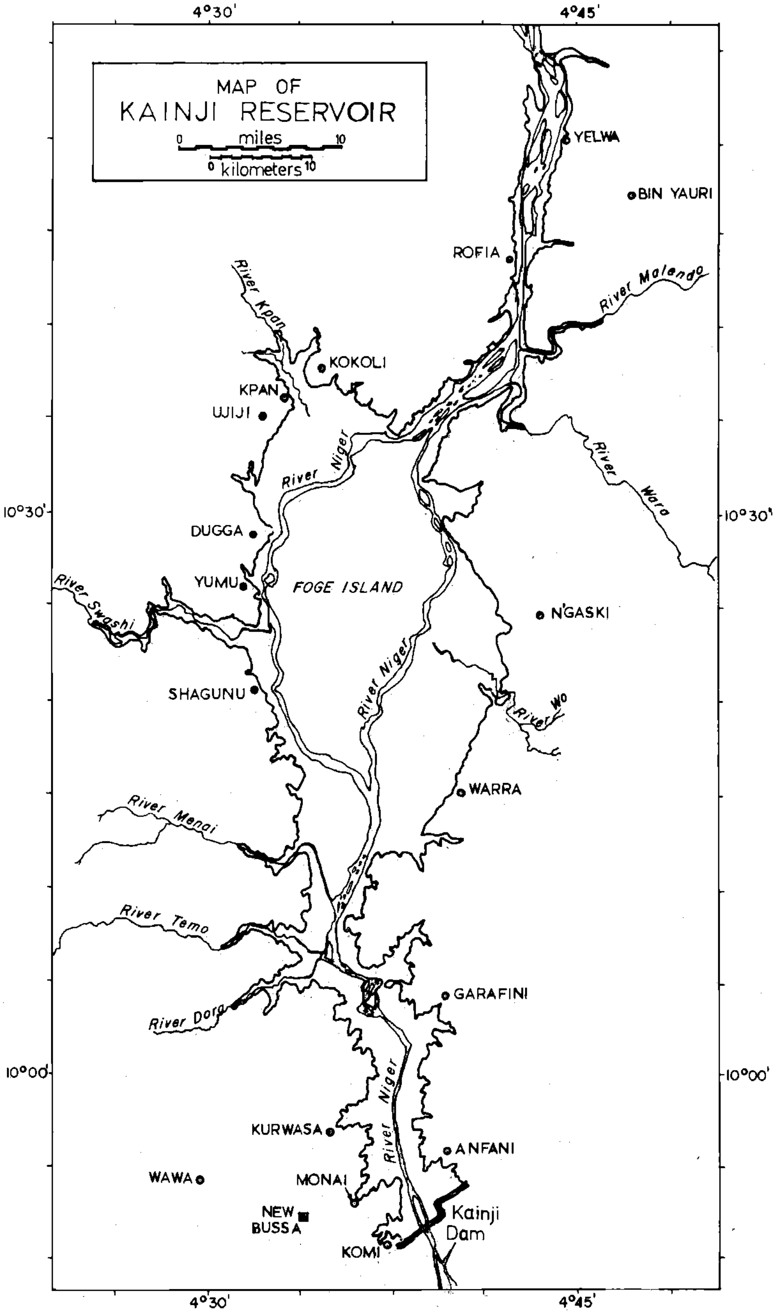


Fig. 3. Kainji Lake shoreline and inundated channel of the River Niger.

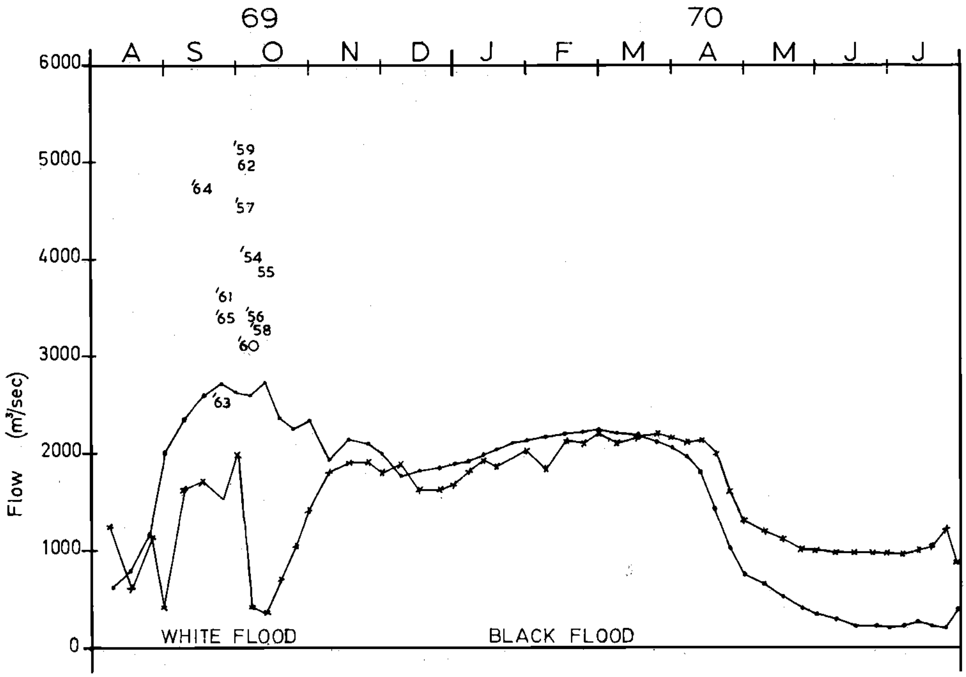


Fig. 4. Inflow (dots) and outflow (crosses) for Kainji Lake from 1969 to 1970 and peaks of the white flood from 1954 to 1965.

was reduced abruptly after the rise of the white flood; thus several 'floods' of the lower river were produced (Figure 4). After filling, however, the flow regime in the lower river closely follows the general pattern before inundation; however, there is a reduction in both maximum and minimum flow.

Limnological data from the River Niger prior to the Kainji impoundment are scarce. Studies on the geology by *Niehoff* [1917] and on the hydrology of the upper Niger by L. Feffay were mentioned by the *Netherlands Engineering Consultants* [1959] in their report on a study of possible improvement in the navigability of the Niger and Benue. The study by L. Feffay was the first comprehensive description of the hydrology of the Niger in Nigeria. Subsequently, the Nigerian government initiated a study of possible hydroelectric sites on the Niger and engaged Nedeco and Balfour, Beatty and Company for this study. Their reports [*Joint Consultants*, 1961] provided additional hydrologic information and proposed Kainji as one of three sites to be developed for hydroelectric power.

Realizing the potential for increasing the Niger basin fish catch through impoundment, the Nigerian government asked J. Daget to make a preliminary assessment of the fishery potential. His report [*Daget*, 1961] includes some limnological data for the river at the beginning of the harmattan season. A biological research team (from the universities of Liverpool and Ife) worked on the river from July through September of 1965 and reported data on ionic composition, turbidity, and plankton concentrations [*White*, 1966]. A. Imevbore (personal communication), a member of that team, has continued observations to date, particularly in limnochemistry. The Niger Dams Authority has continued detailed hydrologic study of the lake and the river above and below. The authority also obtains semiannual chemical analyses of the outflow. Recently, A. T. Grove, a member of the British Hovercraft expedition, obtained data on alkalinity, pH, and conductivity on a transect down the Niger from Bamako in Mali to its junction with the Benue.

The studies of *Holden and Green* [1960] on the plankton of the Sokoto River include information on a major tributary to the Niger above the lake. Beginning in early 1969, fishery biologists and limnologists of the Kainji Lake Research

Project have obtained monthly data that contribute to the general understanding of the limnology of the reservoir, particularly in relation to fishery development.

Physical and chemical characteristics. There are few known records of the temperature of the river prior to impoundment. It is thus necessary to infer the general seasonal pattern from present information obtained from the river above the main lake. From such data and the few records available, it appears that the river has a remarkably constant temperature (29°-30°C) from mid-March to December. This constant period is followed by a sharp drop, witnessed by *Daget* [1961], in mid-December to a low of about 22°C, which accompanies the harmattan season. The mean water temperature of the lake, taken from vertical profiles of volume and temperature, follows a very similar annual course, although the cycle shows a delay of about 1 month. The lowest mean monthly temperature is near 26°C, and the upper limit is 29°C (Figure 5). There is thus little overall effect of change in the climatological heat balance on water temperature.

Stratification of the lake, which is most pronounced from February to May, was not recorded or expected in the relatively fast-flowing river except perhaps in high-water swamps and pools. Diurnal heating of turbid surface water of the present lake, especially in areas of calm, can raise the surface temperature as high as 37°C. During stratification, bottom water does not go below 25°C. During periods of isothermal mixing, temperatures lie between 26° and 27.5°C. This lake temperature occurs at the same season as the thermal minimum of the river, and presumably both result from decreased incoming radiation and the cool, dry northerly winds.

The water of the river is typically turbid, owing to suspended silt and clay. This turbidity is most pronounced during the white flood, at which time Secchi disk transparency drops to about 10 cm (Figure 5). The Nedeco investigators concluded that the silt load of the Niger was very low in comparison with that of the other large rivers of the world. Their estimates suggest concentrations on the order of 100 mg/l. Grain size analysis showed that most of the silt was composed of particles from 10 to 30 μ in size. A clay fraction, with an average diameter of <1 μ, was suspected but not demonstrated. As the river water enters the lake, there is rapid, local sedimentation. Nevertheless, turbidity remains high during the months of September-December. This turbidity is now known to result from colloidal dispersion of negatively charged clays, mostly kaolinitic, brought into the lake with the white flood. The small size enhances scattering, particularly of

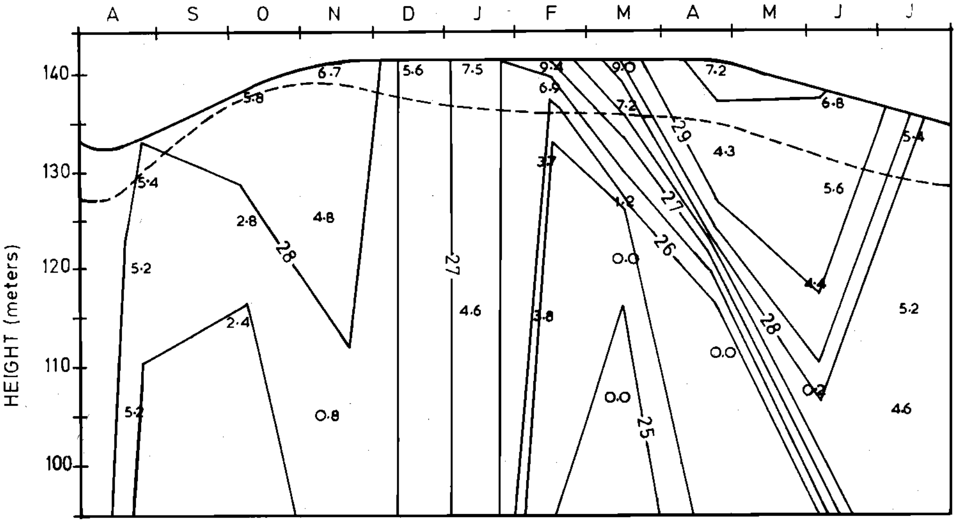


Fig. 5. Seasonal changes in water level, thermal and oxygen stratification, and light penetration from August 1969 through July 1970, 3 miles above the dam at Kainji Lake. Isotherms are drawn for each ½°C. Oxygen concentrations are shown in milligrams per liter at depth of sample. Dotted line is 2.5 times Secchi disk depth, or roughly the limit of the photic zone (1% of incident light). The height of the lake surface above sea level is given by uppermost solid line.

blue and green light. Secchi disk readings during this period are around 50 cm, whereas the actual clay concentration is on the order of 10 mg/l. Settling of this clay in the laboratory is extremely slow, i.e., <50% per month. The lake water clears rapidly at the drop of the white flood, presumably by washout with the much clearer black flood. This evidence, along with the evidence of isothermal structure at the start of the black flood, gives a convincing argument that the water of the white flood, which fills the reservoir to maximum height by November, is then completely replaced by the more than adequate volume of water of the black flood. Annual replacement of the whole volume of the lake ensures against nutrient depletion. It also suggests that long-term buildup of nutrients can only occur in the sediments.

Initial deoxygenation of the lake was much less pronounced than that expected from experience with other reservoirs, and concentrations in the upper waters never dropped below 20% of saturation (A. Imevbore, personal communication). However, during stratification, deoxygenation of hypolimnetic water occurred very rapidly. Even during periods of partial stratification, oxygen concentrations in the lower layers have dropped to <1 mg/l within a few days. Surface concentrations have remained near saturation at all times.

Further evidence of close resemblance in nutrient concentrations in the lake and river waters has been gained from studies of inorganic ions in the water. The conductivity of the lake water is low and ranges from 45 to 60 $\mu\Omega^{-1}$/cm. its average value differing little from that of the river prior to impoundment. The river showed somewhat more fluctuation with flow conditions than the lake. A. T. Grove, following the course of the black flood down the Niger, noted a gradual increase in conductivity downriver, presumably the result of ionic concentration due to evaporation. His data for alkalinity followed the same trend. The conductivity of the white flood undergoes rapid fluctuations associated with local rain [*White*, 1966] but falls within the same range as that of the black flood.

Until further year-round data are available, it is not possible to examine the changes in ionic composition in detail. Such data are available for the river at the rise of the white flood [*White*, 1966]. From these results it appears that calcium (0.21 meq/l), magnesium (0.15 meq/l), and sodium are more or less equal in abundance, whereas potassium (0.8 meq/l) is about half. Bicarbonate (0.54 meq/l) is the dominate anion, chloride being on the order of 0.01 meq/l and sulfate being even lower. Nitrate and phosphate were given as about 2.0 and 0.7 μg/l, respectively, and were quite variable. Silicate values were about 7–10 mg/l (original values are now thought to have been 4 times too large according to *White* [1966]).

Plankton. Although little work has been done on the plankton of the River Niger before the formation of the Kainji Lake, it has been found that the plankton population in the lake is greater than that in the river before impoundment. *Eaton* [1966] worked on the phytoplankton of the River Niger in 1965 before impoundment. A paper by A. Imevbore (unpublished manuscript, 1968) on the ecology of the newly formed Kainji Lake has a short paragraph on the plankton of the lake. *Holden and Green* [1960] included plankton in their River Sokoto study, and Green also wrote two papers (1960 and 1961) on the crustacean and rotiferan zooplankton of the Sokoto. A quantitative study of the Kainji Lake plankton was started by the Kainji Lake Research Project in March 1970 to trace the composition and seasonal variation and to discern the importance of plankton as fish food.

Phytoplankton abundance in the lake is inversely proportional to zooplankton abundance. The phytoplankton peak so far noticed is 2628 algae per milliliter, but the peak for the zooplankton is 4244 total organisms per haul. The phytoplankton peak was in July just before the lake level started to rise. This peak coincided with the condition in the Niger just before impoundment: the peak in the Niger (1030 algae per milliliter) occurred in July just before the rise in river level. The zooplankton peak in the lake occurred at the beginning of the rainy season toward the end of the black flood. In the Niger, before impoundment, the zooplankton peak (1557 organisms per haul) was noticed in August just at the beginning of the rise in river level. This occurrence may well coincide with the beginning of another rise in zooplankton abundance in the lake (1120 organisms per haul) in early September.

The low phytoplankton count (714 algae per milliliter) was in September and is thought to be due to the high turbidity of the lake water (Secchi disk reading was as low as 18 cm; River Niger inflow into the lake was as high as 2400 m^3/sec at this time).

A bloom of blue green algae has occurred in the lake in October of each year since impoundment. It consists mainly of *Microcystis* sp. and *Anabaena* sp. Such a bloom was never reported for the river before impoundment.

The dominant groups of phytoplankters in the river before impoundment between July and September were blue green colonial algae and diatoms. In the lake, diatoms were dominant from June to October, but in the southern basin of the lake the dinoflagellates dominated in September. Diatoms and blue green algae were equally abundant in the lake in October except for an area between the southern and middle basins of the lake where the blue greens were most abundant during this period.

The dominant group of zooplankters in the river before impoundment was *Cladocera*. In the lake the rotifers were dominant at the beginning of the rainy season but were superseded by *Cladocera* during the white flood as in the river before impoundment. The number of copepods increased during the white flood over their abundance in the river before impoundment. Adventitious zooplankton were also observed in the lake during the white flood; those found in the lake and not previously reported from the river include ostracods and coelenterates (*Hydra* sp. and medusae).

Aquatic weeds. The spreading of aquatic plants in the lake has been watched since 1969. The distribution of aquatic weeds shows striking differences between the northern part and other parts of the lake. In the northern arm of the lake (Yelwa area), there is certainly an increase in the size and number of sudds, both free floating and semiattached to the shores. The major constituents of these sudds are *Echinochloa stagnina*, *Polygonum senegalense*, *Jussiaea repens*, *Pistia stratiotes*, and *Utricularia inflexa*. By early 1971, they had not as yet formed a serious impediment to traffic or fishing. However, if the situation becomes worse, a mechanical removal of excess plants will be desirable. The use of herbicides or other chemicals is to be avoided because of the unknown side effects, including those on the fish population and other aquatic fauna. In the central part of the southern arm of the lake, small sudds with *Echinochloa stagnina* sometimes appear owing to wind action. The number and size of these, however, are negligible; if they increase, simple mechanical removal near the dam should be sufficient control.

The formation of sudds on the eastern bank of the central part of the lake is less than that in the northern arm, possibly owing to wind action. The sudd-forming plants are those that were previously reported in the River Niger before the construction of Kainji Dam [*White*, 1966]. Other undesirable species such as *Salvinia auriculata* and *Eichhornia crassipes* have not yet been recorded in Nigeria, although both species are present in Congo and invasion is possible [*White*, 1966]. It is thus deemed desirable continually to monitor the spread of aquatic weeds. It will also be advantageous to distribute illustrations of these plants and to explain their potential danger.

DEVELOPMENT OF NATURAL AND HUMAN RESOURCES

It was realized that building Kainji Dam and the creation of the lake would have major effects on the potentialities and natural resources of the area. Among these effects are the displacement of approximately 50,000 people, the development of a new fishery resource, changes in the hazards of public health, reduction of land area for agriculture and grazing, and provision of new opportunities in game management, including those for the establishment of new game reserves.

To help overcome postimpoundment problems and to assist in the development and the use of these resources, an intensive research program was initiated in 1967 by the multidisciplinary Kainji Lake Research Project. This project has had financial and technical support from the United Nations Development Program (UNDP), the Food and Agriculture Organization (FAO), and the World Health Organization (WHO).

The following summary of research activities in the Kainji area covers the period until 1970. Research programs have concentrated on fisheries, socioeconomics, public health, and wildlife. An agricultural program has been planned.

FISHERY RESOURCES

Among the benefits to Nigeria from the construction of the dam is the use of Kainji Lake as a substantial inland source of fish. The yield from the lake has been estimated to be capable of reaching >10,000 metric tons of fish per year. This forecast is based on estimates of the current number of fishermen and their catch, the catch from the River Niger before inundation, and the fishing success in other man-made lakes in Africa.

A reliable estimate for sustainable fishery yield from Kainji Lake probably will not be attainable until the lake reaches a more or less stable condition several years hence. An example of the early underestimates of catch potential can be shown from Volta Lake, Ghana, among others. The earliest estimate of the possible catch from that lake was 10,000 metric tons. But after a statistically designed subsampling procedure was applied, the actual catch was estimated to be 60,000 metric tons. Such a change over the preliminary forecast might or might not come to pass for Kainji Lake since the physical and biological conditions here are quite different.

To estimate the fishery potential of Kainji Lake and to determine the factors that might affect the productivity of the lake, several studies have been initiated both during the preinundation period and after the formation of the lake. Such studies are essential for the proper management of the fishery in the future, although a proper biological management of the fishery will be of minor significance during the initial 5 years. However, the management of social and economic restraints on the development of the fishery has been discerned to be of immediate pertinence.

Several studies on the fish population of the River Niger in the Kainji area were conducted before and during the early stages of inundation by *White* [1966], *Motwani and Kanwai* [1970], *Imevbore and Bakare* [1970], *Bakare* [1970], *Imevbore* [1970*a, b*], and *Reed* [1970]. These studies have subsequently made it possible to follow the ecological changes that happened after lake formation.

The Kainji Lake Research Project has been investigating the fisheries of the lake since 1968. The investigation includes studies of fish population, dynamics, stock assessment, and natural history of the economically important species.

Fish population. A regular fish-sampling program has been conducted every 6 weeks to obtain a seasonal picture of fish distribution and abundance in Kainji Lake. Seventeen stations throughout the lake are the basis of this program, and series of gill nets of different mesh sizes are used. Other types of gear have also been engaged to extend the sampling and include electrofishing and lift nets with light attraction.

The fish catch has changed considerably since preimpoundment studies, as is shown in Table 1. Impounding the River Niger has produced changes in the fish population as reflected in the catch. Before inundation, fish of the families Citharinidae and Characidae were the most abundant and were followed by Mormyridae and Mochokidae; Cichlidae comprised 3% of the catch [*Banks et al.*, 1966; *Motwani and Kanwai*, 1970]. Since lake formation (1969) the fish population has been dominated by Citharinidae and Characidae. Fish of the family Centropomidae constituted 1% of the catch before inundation but now comprise 13%. In contrast, representation of the family Mormyridae dropped drastically from about 20% during the preinundation period to 1% after lake formation; representation of the family Cichlidae dropped correspondingly from about 4% to 1%.

Changes such as the foregoing in the fish population can be expected to continue for some time depending on the degree of biological and physical stability of the lake and on the rates of selective exploitation. Unlike other man-made lakes in Africa, Kainji Lake had a small representation of bream (*Tilapia* spp.) in the first years of impoundment, but, in 1970–1971, tilapia fry appeared in the lake, especially among the aquatic plants of the shore areas. This appearance indicates that breeding places of *Tilapia* have become available and that the species may become abundant.

TABLE 1. Percentage Composition of Major Fish Families by Number

	Preimpoundment		Postimpoundment	
Family	1965*	1966†	1968§	1969¶
Citharinidae	6	24	34	36
Mochocidae	18	20	17	11
Mormyridae	21	18	15	1
Schilbeidae	8	6	8	9
Characidae	36	5	16	18
Cyprinidae	3	3	1	9
Bagriidae	7	3	4	2
Clariidae	...	3	...	...
Centropomidae	...	1	2	13
Cichlidae	...	4	3	1
Other families	1	14	...	...

**Banks et al.* [1966].
†Motwani and Kanwai [1970].
§Lotic areas around Yelwa.
¶Other lentic areas.

Another important change in the fish population after impoundment is the ratio of predatory to nonpredatory fish. Before impoundment the predators comprised 4.5–5.0% (by number) and 15–17% (by weight) of the catch from the river. Since impoundment the percentage by weight has increased to 18–31% in the lake. The lowest percentage of predators (18% by weight) was recorded in the upstream, nearly lotic, section of the lake. The percentage of predators has also shown an increase in deep water (15 meters and more) and in the shallow and cleared middle parts of the lake, respectively, to 31 and 29% of the catch by weight. Likewise, the predators constitute 28% of the catch by weight from the submerged brushy parts of the lake. Thus it has been possible from experimental fishing to obtain a picture of the distribution and composition of the fish catch according to feeding habit and habitat (Table 2).

Stock assessment. An estimate of the actual catch that the fishermen can expect to take from the lake has not yet been finalized. However, a preliminary estimate has been calculated to range from 4.667 to 8.265 metric tons per boat per year. The catch figure is most likely to be increased when (1) improved fishing gear and methods are adopted, (2) fishing operations are extended to all parts of the lake instead of being concentrated in the northern part of the lake between Rofia and Yelwa, and (3) appropriate statistical sampling methods have been applied to collect catch data.

Estimates of fish stocks differ with principal habitat in the lake on the basis of experimental fishing with standard fleets of gill nets of different mesh sizes. The following estimates were made:

1. In medium uncleared deep water (not more than 15 meters) the catch reached 30 kg per fleet of nets per night.
2. In the cleared areas of Foge Island (depth not exceeding 15 meters) the catch averaged 25 kg per night.
3. In deep water above and around the old river channel (15 meters and more) the catch averaged 18 kg per night.
4. In Yelwa area, where the lake is under the influence of inflowing water, the catch did not exceed 15 kg per night.

The catch per unit of effort also differed in the different habitats from 14.3 kg per set of gill nets at the surface to 9.3 kg per set of gill nets on the bottom (Table 3). Members of the families Citharinidae and Characidae are mostly represented among the surface catch, and to a lesser extent the families Centropomidae and Mochokidae are represented. Among the bottom catch, Cyprinidae is dominant and is followed by Bagridae and Mochocidae.

As regards the seasonal variation in abundance of fish, the catch per unit of experimental fishing effort was highest in August (45.3 kg), dropped

TABLE 2. Percent Distribution of Fish According to Food Habit and Habitat

Food Habit	Lotic Conditions	Deep Water (≥15 meters)	Cleared Areas on Foge Island	Shallow Water and Submerged Brush
Detritus, periphyton, phytoplankton (generally herbivorous)*	19	6	56	61
Zooplankton and insect larvae†	59	60	10	9
Fish (carnivorous)§	18	31	29	28
Uncertain or very diverse (omnivorous)	4	3	5	2

**Alestes macrolepidotus*, *Distichodus* sp., *Synodontis schalli*, *Labeo* sp., *Citharinus* sp., *Auchenoglanis* sp., and *Synodontis membranaceous* (seasonally).

†*Eutropius nilotica*, *Chrysichthys* sp., *Alestes baremose*, *A. dentex*, *A. nurse*, *Heterotis (Clupisudis) niloticus*, *Synodontis membranaceous*, *S. resupinatus*, *S. sorex*, and *Schilbe mystus*.

§*Lates niloticus*, *Hydrocynus* sp., *Clarotes laticeps*, *Bagrus* sp., *Clarias lazera*, and *Heterobranchus* sp.

TABLE 3. Comparison of Surface and Bottom Gill Net Catches

Family	Mean Catch, kg per set of nets	
	Surface	Bottom
Mormyridae	...	0.1
Characidae	3.6	0.5
Citharinidae	5.4	0.4
Cyprinidae	0.6	3.1
Bagridae	0.1	1.9
Schilbeidae	0.5	0.2
Mochokidae	1.7	1.6
Centropomidae	2.4	0.9
Others	...	0.7
Total	14.3	9.3

Data from J. L. Turner (unpublished manuscript).

progressively from September (39.5 kg) to January (15.1 kg), and then rose from January to June when it was up to 27.0 kg (J. L. Turner, unpublished manuscript, 1970). The foregoing seasonal differences in the catch per unit of effort are related to environmental changes. The most obvious environmental change was an increase in the water level from a low in August of 145 meters to its maximum level in November of 155 meters.

The experimental fishing with gill nets of different mesh sizes disclosed both species and size selectivity of these nets. Part of the aim of the experimental fishing was to obtain information on the mesh sizes that will have maximum efficiency without affecting the future fish stocks. This information will be a keystone in the future management of the fishery. Related data are also being obtained on the comparative selectivity of multifilament and monofilament gill netting.

Natural history studies of the economically most important fish are under way, and spawning, food, habitat, and age and growth are included. The results of these studies will be applied to the management of the lake fishery.

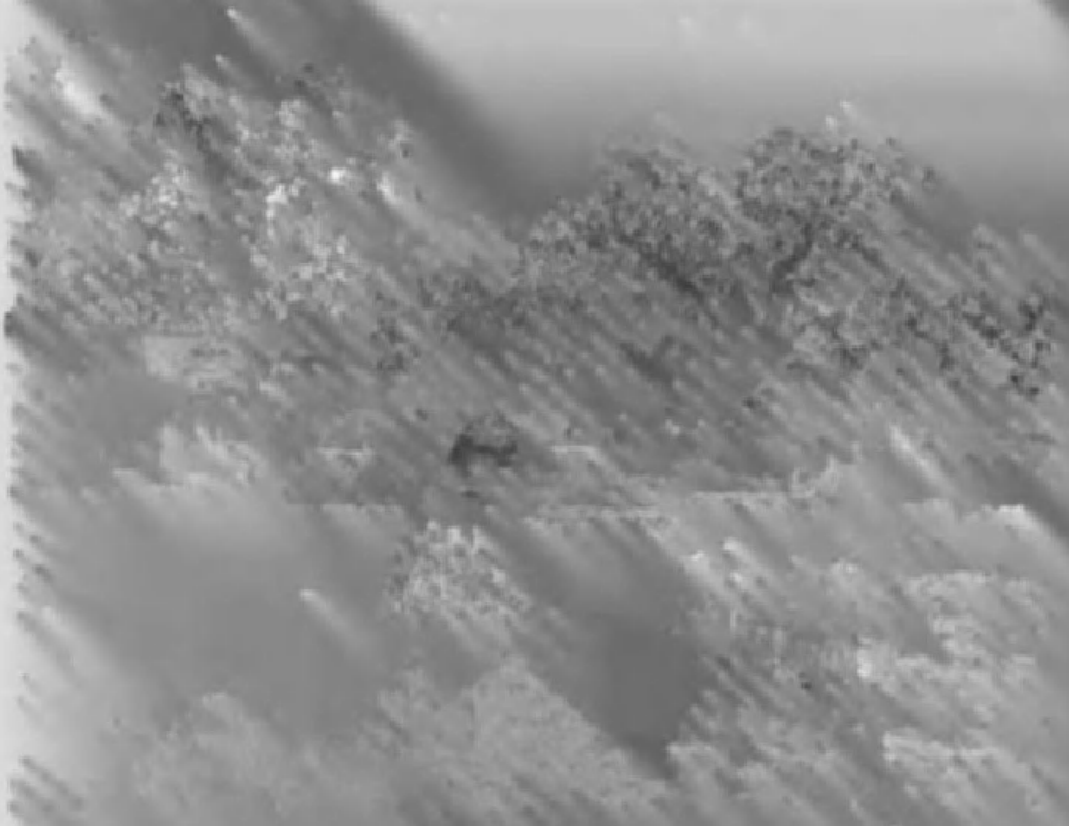
Sampling of larval fish (<5 cm in length) from the lake has revealed that the majority of larvae are present in October. However, young of the clupeids, *Barbus*, *Chrysichthys*, *Physailia*, and *Tilapia* are present all year round. The seasonal follow-up of development in the gonads of fish has shown that a maximum of maturation stages exists during months of rising water level in the lake and that the opposite exists during periods of drawdown.

SOCIAL AND ECONOMIC DEVELOPMENT OF THE FISHERY

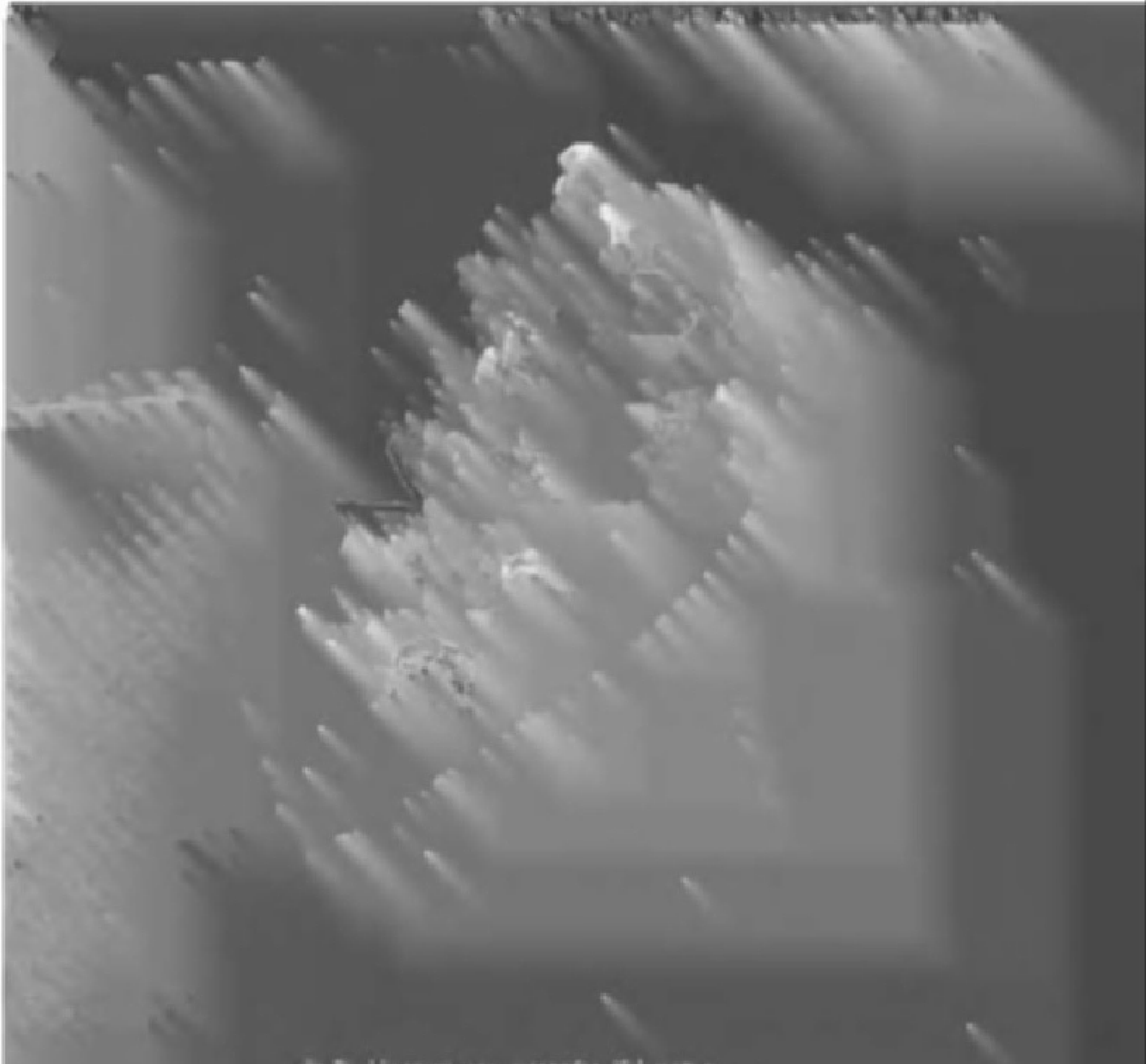
A broadly objective effort has been initiated to increase the quality and quantity of fish harvested from the lake. Included in this effort have been socioeconomic studies of the fishing community around the lake, which have revealed that the following major problems compose a significant restraint on the development of the fishery in Kainji Lake:

1. Fishing effort declined 60% in certain areas owing to the rise of water level above that to which the fishermen had become accustomed.
2. There is a transportation bottleneck with reference to both fresh and smoked fish.
3. Most of the canoes and boats in use are in poor repair and unsuitable for fishing on the lake (Figure 6).
4. Most of the gill nets used by the fishermen are inefficient in catching fish in the new environment.
5. Fish processing in most of the fishing centers falls below necessary standards of efficiency and quality.

To overcome the deficiency in boat quality and supply for fishing and transport on the lake, a boatbuilding program was started in January 1970. Initially, a survey was conducted of all fishing centers around the lake to evaluate the existing fishing canoes and boats and the requirements of the fishermen. As a result, two prototypes of boats were constructed either at the project site or at Yelwa (the major boatbuilding center on the lake) and were demonstrated around the lake or were loaned to fishermen for reactions. One prototype was a simple 8-meter planked canoe capable of using a small outboard engine and costing £41.16.3. The other prototype was a 6-meter boat built at a cost of £32.8 each and designed basically for paddling. The reaction of the fishermen led to the construction of another model, the 7.3-meter canoe. This canoe was built at a cost of £38.1.3. Also constructed was a 13.3-meter transport boat to be powered with a small diesel or an outboard engine; the unit hull cost was £381.9.6 (Figure 7). Altogether, eight demonstration boats were built during the 1-year boatbuilding program: three 6-meter boats, three 6.6-meter boats, one 8-meter boat, and one 13.3-meter boat.



[illegible]



[illegible]

[illegible]

ing group, each such group having two to 23 members including one to nine men. All members of the group above 10 years of age work at farming. Laborers from among relatives or others are also hired. The size of a group farm holding ranges from 1.9 to 36.8 ha; the larger the size of the group, the larger the size of the farm.

Roder also discovered that there is very little seasonal underemployment, so any new development program that aims at employing unused labor would be threatened with failure. The most promising development opportunities should be to provide more profitable substitutes for present activities.

The creation of the lake would bring hardly any significant benefits to these upstream irrigation farmers other than the possible improvement of product transport. Resettlement of lake-displaced persons could be a hindrance rather than an aid to these farmers.

The agricultural extension officers have been working effectively among these farmers. However, Roder pointed out that these officers could benefit from added training and encouragement because of mass illiteracy among the farmers.

Opportunities were discerned for the introduction of mechanical repair services into the area for the small petrol irrigation pumps that should be introduced increasingly into the system. The provision of market facilities and suitable boats for transport is anticipated.

The second FAO study was that of *Jenness* [1970] on the fishermen of the Kainji basin. As a sociologist, Jenness described in detail the social structure of the riverine communities including their religions, social stratification, geographic location, occupational specialization, and so on. He discovered that only 500 of the 50,000 displaced by the lake were professional fishermen.

It was noted that fishing is an occupation of commoners and is not associated with wealth. Men whose families do not fish do not aspire to learn the trade. There are three basic patterns of fishing: low-grade upland creek fishing, more advanced marginal fishing, and professional river and swamp fishing. The first of these patterns is for domestic use, whereas the second and the third involve selling and are therefore of a larger scale. Gill netting has been adopted by the Gungawa, Lopawa, and Shangawa tribesmen who practice the second pattern, and they are expected to play a major role in the new reservoir fishery. Most of them even use imported boats.

The Sarkawa, Sorko, and Kyedyawa tribespeople are noted for professional fishing; they offer no competition to the farmers. Therefore they are welcome everywhere to make their fishing camps.

Cooperation among fishermen is based on kinship and friendship, but among professionals it is also based on a sense of occupational solidarity that involves hospitality. On the whole, Jenness found out that the organization of the fishery was capable of taking on immigrant fishermen smoothly. This finding was held to be especially true if the newcomers concentrate on offshore fishing.

The fishermen generally work alone and use members of their family as helpers; only occasionally are they in pairs. They use only small quantities of gear. The catch is sold fresh, smoked, or salted and dried. Smoked fish are carried in baskets by fish traders, mostly Hausa and Zambrama from the Niger Republic, for distant trade. In contrast, women take an active part in the local fish trade. There is essentially no specialization, large-volume bulk handling by cooperative formations, or large capital investments.

Jenness saw a possible advantage in setting up a commission to control the Kainji fishery. Commission members would be selected by the various unit governments involved. He also saw advantage in numbering and taxing boats in the lake along with the formation of a fishery development field organization. He warned against permitting an influx of commercial fishery firms on the lake and judged that local professional fishermen should be encouraged first.

There is opportunity for improving fishing gear in use and for encouraging each fisherman to use several different fishing methods and gear. The handling of the catch also showed opportunity for improvement, and it was thought that development of a processing industry and offshore fishing deserved encouragement. To facilitate fishery development, it was held that native authority stores should consider selling fishing and boat and engine repair materials to make them as inexpensive as possible and easily available for the fishermen. To improve marketing, provisions of road access or cheap water transport were identified as being needed along with storage and smoking facilities at key shipment points. To afford fair trading, weighing machines and open publication of prices were seen as being required.

The third study was a survey by *Anthonio* [1968] on fish marketing in the Kainji basin. His survey was limited to Yelwa area and aimed at appraising the existing distribution of the fish catch in the area to identify any bottlenecks to the fullest expansion of the lake fishery.

He found that improvements were urgently needed in the provision of facilities, processing, storage, grading, packing, and transportation. Markets had no durable stalls and very few stores. He advised therefore that not only durable stalls but also storage facilities should be provided. The construction of comfortably large market sites in the area would help not only the fishery industry but also trade in onions, beans, and rice.

Anthonio determined that smoking was a desirable and economic processing method for fish to be exported. However, there was room for improvement. He recommended group smoking in central fly-proof smokehouses and storage sheds in each village or fish-landing site. In addition, value was seen in an extension service to teach the fishermen how best to use these facilities and how best to upgrade their products.

Packaging for transport of processed fish is done in cheaply made large baskets called mankaras. If packaging were standardized, it would facilitate marketing. Smaller packages could be introduced, but some type of box with high sides, which could be stronger, might be a greater improvement in spite of the initial costs. At least secondary infestation by insects could be avoided.

Anthonio noted that transportation problems are basically external to the fishing industry but that they needed correction. He recommended the formation of cooperatives for wholesaling and marketing, smoking and storage, and financing.

The fourth study [*Oguntoye*, 1968] concerned occupations in Old Bussa; this study had a view to provisions requisite for resettlement at New Bussa. The major occupations were farming, craft industries, trading, and fishing.

Traditional farming varied considerably in size from 0.05 ha to about 8 ha. All farms were owned by men, and none was >4.8 km from the owner's home. Basically, the farming was for subsistence, and many such farmers were part time, their major occupations usually being with the federal or state governments, native administration, or firms. Oguntoye recommended that the poorer land around New Bussa should be allocated to this class of farmer.

Craft industries were few and scattered, and the traditional ones were family monopolies. Oguntoye predicted that this pattern would change when the people become established in their new resettlement homes. The modern crafts like carpentry and tailoring would also have an opportunity to expand, and the barter system in marketing would change.

Oguntoye recommended that (1) special accommodation be provided near the market for specific industries like dyeing and the actual houses of weavers, blacksmiths, and the like should be near the market; (2) a government estate be built for traditional craftsmen; and (3) spinners, who are mostly women, be given space in the compound of influential citizens like the Obandoma.

Fishing was found to be practiced only a little by the Busawas but was mostly practiced in the region by migrant fishermen. Oguntoye recommended that these migrant fishermen be encouraged to continue at New Bussa, which, in spite of the native attitude, is likely to become a fishing center. The need to allocate space along the shores of the lake near New Bussa for fishing activities with a fishing instructor was recognized, and Oguntoye thought that a cooperative fishery organization should be encouraged.

Trading seemed to be specialized by tribes, e.g., the Busawas on agricultural products, Hausas on kola nuts, and Yorubas on clothing. Marketing was noted to have social importance too. Hence Oguntoye recommended that an open space near the central market be provided for an open market on specified dates.

The last study was that of M. Babalola (unpublished report, 1970) on the roads around Wawa. Many of the roads are third class, i.e., highly inadequate especially during the rainy season. Some villages are cut off by streams. Other roads are very narrow and poorly constructed and maintained. The result is that there is slim contact between people and local administration. Babalola also learned that transporters were stressed by import restrictions. He pointed out that, if these two major difficulties could be solved, transportation and communication would improve.

PUBLIC HEALTH STUDIES

Between flooded Kainji Island at mid lake (Figure 1) and Yelwa at the northern end of the new lake, the southern half of the Niger Valley was very sparsely populated. From Bussa upstream to Kainji Island, about 25 miles, there was sparse population mostly in 10 small riverside villages. North of Bussa the population was more dense, especially in the vicinity of Yelwa (always a thriving river port and center of fishing and farming, including onion growing).

The health services of the area consisted of a small mission hospital (35 beds) at Yelwa and six scattered dispensaries. There is now a modern 110-bed hospital at New Bussa, which is the property of the Niger Dams Authority. With such minimal health services, there is on record only a little statistical information about health conditions in the rural areas. Epidemics of smallpox and cerebrospinal meningitis occurred from time to time, but sleeping sickness was not endemic. *Budden* [1956] reported a high prevalence of onchocerciasis (river blindness) in the Bussa-Kainji area.

When it became known that the Kainji Dam was to be constructed, H. Thomson of the Northern Region Rural Health Service visited the area. He confirmed (unpublished data, 1959) the prevalence of onchocerciasis and found that schistosomiasis (bilharzia) was everywhere endemic. In an area of rural west Africa such as this, it could be assumed that malaria was already holoendemic and would not be affected one way or the other by the creation of a lake. B. Waddy visited the area twice (in 1960 and 1964) as a health consultant to the Joint Engineering Consultants for the Niger Dam. One of his main recommendations was that control of the blackfly, *Simulium damnosum*, which was breeding very freely in the main river and several of its tributaries, should be undertaken to protect the labor force from onchocerciasis and the nuisance of fly bites. Consequently, this and other potential disease vectors, including mosquitoes and tsetse flies, were controlled, and high sanitary standards were maintained throughout both senior and junior labor camps. As a result the health record of the labor force was very good; there were no disease epidemics. Among an expatriate labor force that amounted to 800 at its peak (with families in addition), there was relatively little malaria, and only one man was known to have become infected with onchocerciasis.

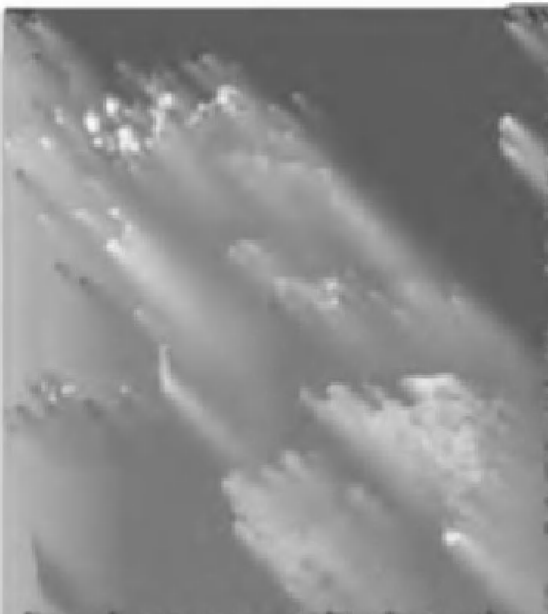
Resettlement. Resettlement of the communities displaced by the lake has been remarkably free from the disastrous side effects that sometimes accompany such projects. Nutrition may have suffered for 2 years, especially in the Yelwa area where the valuable onion crop was disrupted wholly for 1 year and partially for 2 years; farming is now going on normally all over the resettlement area.

Onchocerciasis. Because the vector *Simulium damnosum* breeds only in running water, the potential transmission of onchocerciasis has ceased around the lake area except in relation to three tributaries, the Oli and Kontagora (which enter the river below the dam) and the Malendo (which enters the east bank of the lake a few miles south of Yelwa). A program of control operations, in the form of periodic application of larvicides in the Oli and Kontagora throughout the rainy season, was almost completely successful in keeping Kainji and New Bussa free from *S. damnosum* through the rains of 1970. Below the dam, routine spillway manipulation results in changes of river level that prevent *Simulium* breeding.

Onchocerciasis and the pestilential biting of *S. damnosum* are now accepted as some of the most important causes of depopulation of river valleys in tropical Africa [*Waddy*, 1969]. The removal of these hazards to health and comfort must be at least partly responsible for the dramatic rise in population around the southern half of the new lake. Where there was a total of 10 small riverside villages along this stretch of the old Niger, there are now 67 fishing villages or camps.

The precise extent and seriousness of onchocerciasis in the lake area were investigated in 1969–1970 by B. Waddy. He found 176 blind persons among 2846 examined (6.1%). Established onchocerciasis can continue to advance after transmission has ceased, and the treatment of ocular onchocerciasis is presently under study. Considerable improvement of vision, even in subjects who were actually blind, is possible in some cases (Figure 8) [*Waddy*, this volume].

Schistosomiasis. It is still too early to estimate the effect of creating the lake on the transmission of schistosomiasis. Vector snails have made their appearance at danger points of water contact such as the Rofia ferry. A WHO consultant spent 3 months (May–July 1970) conducting a survey of schistosomiasis and its vector snails at several places by the lake, including Yelwa, its neighboring villages, and Shagunu. He found that infection with *Schistosoma haematobium* was prevalent in up to 70% of the population in some localities, *S. mansoni* and *S. intercalatum* being present but rare in some but not all places. In contrast, he found that the people in certain resettled villages were less exposed to infection than they were in their old sites. At



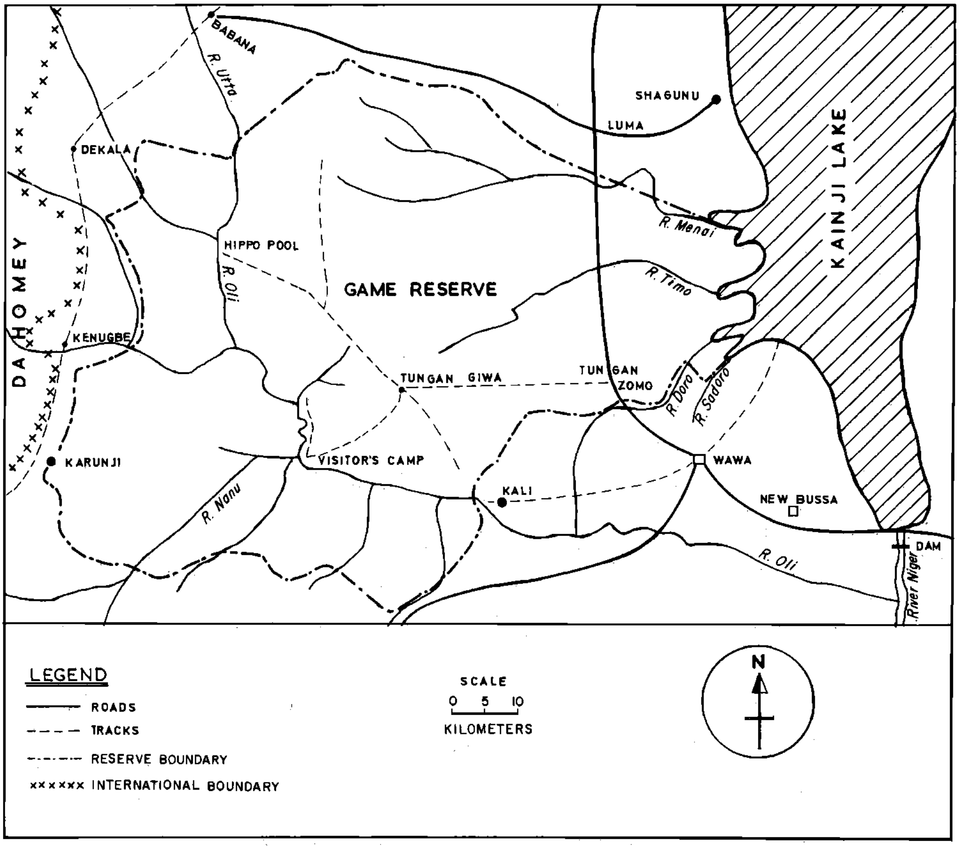


Fig. 9. Borgu Game Reserve and Kainji Lake.

Wawa-Agwara road, which traverses the eastern part of the reserve.

The original and largest part of the area was established as a game reserve during 1962–1963. When Kainji Lake was formed, the reserve was extended easterly to include a part of the new lakeshore.

The prior study of the wildlife of the area was made by *Howell* [1968*a*, *b*, 1969]. His fieldwork was carried out between 1962 and 1966 and included intensive observations in a well-protected study area in the reserve. Howell estimated the populations of some of the large mammals in the reserve together with an indication of their population trends. He also made suggestions for future management of the reserve as a viewing area for game.

A further survey of the mammals of the reserve was made by D. Brown (unpublished manuscript, 1967), working with the game preservation unit of the Kwara State Forestry Department. He made observations in several parts of the reserve and also estimated the densities of various species in sample areas. Extrapolations of these estimates were made to obtain estimated populations for the whole reserve. Brown also used the ratio of the number of young animals seen to the number of adult animals seen to obtain percentage 'increases' of some species.

The vegetation of the reserve was the subject of a study by *Charter* [1970], senior ecologist of the Federal Department of Forest Research. From his preliminary findings he has speculated on factors that have given rise to the present pattern of vegetation. He has proposed a different classification of vegetative subtypes in the reserve from that adopted by *Howell* [1968*a*, *b*, 1969].

Wells and Walsh [1969] included the game reserve in their study of the birds of northern and central Borgu. This work provides a checklist of the birds of the area together with basic information on their status and ecology.

TABLE 5. Estimates of Roan and Hartebeest Densities from Counts made in July and August 1970

Transect No.	Length, km	Hartebeest Densities per km^2 Method 1	Hartebeest Densities per km^2 Method 2	Roan Densities per km^2 Method 1	Roan Densities per km^2 Method 2
1	25.6	0.36	0.48	0.08	0.12
2	18.9	1.15	0.85	0.15	0.23
3	16.2	1.01	1.06	0.73	0.30
4	16.5	0.51	0.84	0.05	0.15
Mean		0.76	0.81	0.25	0.20
s.d.		0.38	0.24	0.41	0.08

The FAO wildlife ecologist made preliminary visits to the project during the first part of 1970 and subsequently moved to New Bussa in June to organize a program of field studies to obtain data for the development of a management plan for the Borgu Game Reserve. A parallel consideration is to set up long-term studies to monitor trends in the fauna and flora of the area.

Fauna

Species list. A preliminary list of the large mammals of the Borgu Game Reserve has been completed (Appendix 2). Records for the orders Insectivora, Chiroptera, and Rodentia are very incomplete and have not been included at this stage. It is hoped that the necessary equipment to complete the survey of these groups will become available shortly.

Population dynamics. The only practical way of attempting to assess the densities of the larger mammals in the reserve with the staff and equipment available is to make use of line transects. One of the principal difficulties with this technique, which has been described as a 'pseudo sample census' by *Overton and Davis* [1969], is to determine the area being sampled.

In consideration of the nature of the cover in the reserve, it was decided to adopt the 'mean visibility' method described by *Hirst* [1969]. A range finder was available for measuring distances, which were verified periodically with a steel tape.

Four line transects were selected and ranged in length from 16.1 km (10.1 miles) to 25.6 km (16 miles). From the end of June 1970, these transects were run whenever the availability of transport, weather conditions, and other factors permitted.

The results of counts made in July and August were used to compute densities for hartebeest and roan antelope (Table 5). In estimating the densities, two different approaches have been tested. In the first, the individual animals have been used as the counting unit; in the second, herds have been counted, and a mean herd size has been calculated to express densities in terms of individuals [*Rodgers*, 1969]. A crude extrapolation of the mean of the estimated densities from the four transects to the whole reserve (3900 km^2), along with the data of D. Brown (unpublished manuscript, 1967) and *Howell* [1968*a*, *b*, 1969], discloses a substantial population of both hartebeest and roan (Table 6).

A fifth transect was located adjacent to and roughly parallel with the Oli River. Results of three counts along this line were also used to estimate densities for the kob. A crude estimate of the number of kob in the reserve has been computed by extrapolating the mean densities to the estimated area of kob habitat in the reserve for comparison with the values obtained by D. Brown (unpublished manuscript, 1967) and *Howell* [1969] (Table 7).

There was a steady decline in the number of animals sighted per unit length of transect over the period under review by the project staff. By the end of August, sightings were too few to be of quantitative use. The number of sightings declined, of course, because of the increasing growth of vegetation as the rainy season proceeded; this vegetation reduced the effective area covered during line transect counts. It is felt that running the transects did not cause the animals to move away.

The results to date show a high proportion of the smaller size and younger age classes in the populations of hartebeest, roan, and kob. This result is taken to indicate an expanding population and probably represents a reaction to the effective control of poaching.

Flood habits. Direct observations of the feeding of animals have been made, but it is likely that the accumulation of data by this method will

TABLE 6. Mean Densities from Table 5 Extrapolated to Whole Reserve and Compared with Other Estimates

Species	Method 1	Method 2	Brown*	Howell†
Hartebeest	2970	3180	1464	250 to 300
Roan	1000	790	1171	220 to 250

*D. Brown (unpublished manuscript, 1967).
†*Howell* [1968*a*, *b*, 1969].

TABLE 7. Estimates of Kob Densities per Square Kilometer

Date	Method 1	Method 2	Brown*	Howell†
7/10/70	6.27	10.01		
7/27/70	10.89	9.99		
8/5/70	10.87	16.63		
Mean	9.34	12.18		
Total	1868	2436	350	1500 to 2200

*D. Brown (unpublished manuscript, 1967).
†*Howell* [1969].

be a slow process owing to the nervous disposition of most animals under sustained observation. Indeed, the majority quickly resort to flight in these circumstances.

Collections of elephant dung were made from various parts of the reserve each month. These have been dried and roughly sorted into four components: woody matter, dicotyledonous leaves, grass, and seeds. As this sampling proceeds, the seasonality of food pattern should emerge.

Notes are being made and measurements are being taken of all trees that are found to have been used by elephants. In practice, trees that elephants are seen to be working on or that have been used within the previous 2 or 3 days (indicated by spoors) are recorded. Samples of bark, leaves, and roots that have been used or chewed and ejected have been collected. Chemical analysis of these is planned.

Habitat

Plant collection. Plants are being collected in the reserve as they come into flower. Specimens are deposited in the herbarium of the Federal Department of Forest Research. These specimens will form the basis for the establishment of a working herbarium.

Productivity. A series of 5- × 5-meter plots within various grass types in the reserve has been established. These have been clipped and production determined as dry matter. This clipping is to be continued, and the investigation of the products is to be extended. The dividing of samples into the stem and the green and dry leaf will be undertaken at various times of the year, and crude protein determinations will be made. It is planned later to study the effect of various combinations of burning, grazing, and protection.

Fire. An early season burning policy was instituted in the Borgu Game Reserve. There were two main reasons for this policy. First, early burning ensures that all grazing is not burnt off in a single conflagration as might happen with a late burn. Second, the heat of an early burn is less intense and therefore less damaging to trees.

In practice, it is extremely difficult to implement controlled burning schemes even on a limited experimental scale. Fires can be swept into an area from a distant source by high winds and can jump firebreaks, people may be careless with campfires or cigarettes, and even fires deliberately set in carrying out a controlled burning policy all too often get out of hand.

Controlled burning in the reserve is planned experimentally to (1) check bush encroachment and improve grazing and visibility, (2) provide complete protection of patches of closed woodland and riverine forest, and (3) attract and concentrate animals at places accessible for game viewing by controlling the timing and locality of limited burns.

APPENDIX 1: PARTICULARS OF KAINJI LAKE AND DAM

Name of lake: Kainji Lake
Country: Nigeria
Coordinates of latitude and longitude: 10°00′–10°55′N, 4°20′–4°50′E
Height of dam: 65.5 meters (215 feet)
Date of completion: February 15, 1969
Type of dam: concrete and earth fill
Mean water level and elevation: 139.7 meters
Date of first full stage: October 19, 1968
Mean water volume: 13.2 × 10^9 m^3
Mean surface area: 1.18 × 10^9 m^2 (118,000 ha)
Mean annual evaporation: 2.5 × 10^9 m^3
Installed capacity: 320 Mw
Mean annual discharge: 67 × 10^9 m^3
Average annual output: 140 Mw
Mean annual fluctuation in reservoir level: 10 meters
Other use: fisheries, irrigation, navigation
Operating authority: Niger Dams Authority
Post office address: P.M.B. 1111, New Bussa, Kwara State, Nigeria

APPENDIX 2: PRELIMINARY LIST OF MAMMALS OCCURRING IN THE BORGU GAME RESERVE EXCLUDING THE ORDERS INSECTIVORA, CHIROPTERA, AND RODENTIA

Pholiodota
Manis gigantea (giant pangolin)

Primata
- *Galago senegalensis* (galago or bush baby)
- *Cercopithecus aethiops* (green monkey or tantalus guenon)
- *Erythrocebus patas* (red patas monkey)
- *Papio anubis* (baboon)

Lagomorpha
- *Lepus capensis* (hare)

Carnivora
- *Canis adustus* (side-striped jackal)
- *Lycaon pictus* (hunting dog or wild dog)
- *Mellivora capensis* (honey badger or ratel)
- *Aonyx capensis* (clawless otter)
- *Viverra civetta* (civet)
- *Genetta genetta* (common genet)
- *Mungos gambianus* (Gambian mongoose)
- *Ichneumia albicauda* (white-tailed mongoose)
- *Crocuta crocuta* (spotted hyena)
- *Felis serval* (serval)
- *F. caracal* (caracal or lynx)
- *Panthera leo* (lion)
- *P. pardus* (leopard)

Sirenia
- *Trichechus senegalensis* (manatee)

Tubulidentata
- *Orycteropus afer* (aardvark)

Hydracoidea
- *Procavia capensis* (rock hyrax)

Proboscoidea
- *Loxodonta africana* (elephant)

Artiodactyla
- *Hippopotamus amphibius* (hippopotamus)
- *Phacochoerus aethiopicus* (warthog)
- *Tragelaphus scriptus* (bush buck or harnessed antelope)
- *Hipotragus equinus* (roan antelope)
- *Kobus ellipsiprymnus* (waterbuck)
- *K. kob* (kob)
- *Redunca redunca* (reedbuck)
- *Alcelaphus buselaphus* (hartebeest)
- *Cephalophus rufilatus* (red-flanked duiker)
- *Sylvicapra grimmia* (Grimm's common or crowned duiker)
- *Ourebia ourebia* (oribi)
- *Syncerus caffer* (buffalo or bushcow)

Acknowledgments. I am indebted to all my colleagues in the project who furnished the basic information for this report: Dr. F. Henderson and Mr. H. A. Adeniji, limnology and plankton; Dr. A.Lelek, fishery; Mr. C. D. Nordlund, boatbuilding; Dr. B. B. Waddy, public health; Mr. G. S. Child, wildlife; and Mr. F. P. A. Oyedipe, socioeconomics. I am also grateful to Alhaji S. O. Olagunju, Public Relations Office, Niger Dams Authority, for his assistance in obtaining the material concerning the construction of Kainji Dam.

REFERENCES

Anthonio, Q. B. O., Fish marketing survey in the Kainji Lake basin, Yelwa area study, report, Nigerian Inst. of Soc. and Econ. Res., Ibadan, Nigeria, 1968.

Bakare, O., Bottom deposits as food for inland freshwater fish, in *Kainji, A Nigerian Man-Made Lake*, edited by S. A. Visser, pp. 65–85, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Banks, J. W., M. J. Holden, and R. H. McConnell, Fishery report, in *The First Scientific Report of the Kainji Biological Research Team*, edited by E. White, University of Liverpool, Liverpool, 1966.

Budden, F. H., The epidemiology of onchocerciasis in northern Nigeria, *Trans. Roy. Soc. Trop. Med. Hyg.*, *50*, 366–378, 1956.

Charter, J., The vegetation of Kainji with special reference to the Borgu Game Reserve, paper presented at Symposium on Ecology of Kainji Lake, Univ. of Ife, Ife, Nigeria, June 1970.

Daget, J., Report on the Kainji Dam project (fisheries), Hydrobiology and inland fisheries, Fourth symposium, *Publ. 76*, Sci. Coun. for Afr. S. of the Sahara, London, 1961.

Eaton, J. W., Algal investigations, in *The First Scientific Report of the Kainji Biological Research Team*, edited by E. White, pp. 8–16, University of Liverpool, Liverpool, 1966.

Hirst, S. M., Road-strip census techniques for wild ungulates in African woodland, *J. Wildl. Manage.*, *33*(1), 41–48, 1969.

Holden, M. J., and J. Green, The hydrology and plankton of the River Sokoto, *J. Anim. Ecol.*, *29*, 65–84, 1960.

Howell, J. H., The Borgu Game Reserve of northern Nigeria, part 1, *Nigerian Field*, *33*(3), 99–116, 1968*a*.

Howell, J. H., The Borgu Game Reserve of northern Nigeria, part 2, *Nigerian Field*, *33*(4), 147–165, 1968*b*.

Howell, J. H., The Borgu Game Reserve of northern Nigeria, part 3, *Nigerian Field*, *34*(1), 32–35, 1969.

Imevbore, A. M. A., Some general features of the Kainji Reservoir basin, in *Kainji, A Nigerian Man-Made Lake*, edited by S. A. Visser, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970*a*.

Imevbore, A. M. A., Some preliminary observations on the sex ratios and fecundity of the fish in the River Niger, in *Kainji, A Nigerian Man-Made Lake*, edited by S. A. Visser, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970*b*.

Imevbore, A. M. A., and O. Bakare, The food and feeding habits of non-Chichlid fishes of the River Niger in the Kainji Reservoir Area, in *Kainji, A Nigerian Man-Made Lake*, edited by S. A. Visser, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Jenness, J., Fishermen of the Kainji basin, Kainji Lake

Research Project, *Work. Pap. 1,* Dep. of Fish., Food and Agr. Organ., Rome, 1970.

Joint Consultants (Nedeco and Balfour, Beatty and Company, Ltd.), *Niger Dams Project,* vol. 1-7, Federal Government of Nigeria, Lagos, 1961.

Motwani, M. P., and Y. Kanwai, Fish and fisheries of the coffer-dammed right channel of the River Niger at Kainji, in *Kainji, A Nigerian Man-Made Lake*, edited by S. A. Visser, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Netherlands Engineering Consultants, *River Studies and Recommendations on Improvement of Niger and Benue*, North-Holland, Amsterdam, 1959.

Niehoff, K., Oberflächen Gestaltung, Niederschlag und Abfluss des Nigers, *Mitt. Deut. Schutzgebeiten, 30*, 1917.

Oguntoye, O. A., Occupational survey of Old Bussa, report, Nigerian Inst. of Soc. and Econ. Res., Ibadan, Nigeria, 1968.

Overton, W. S., and D. E. Davis, Estimating the numbers of animals in wildlife populations, in *Wildlife Management Techniques*, 3rd ed., edited by R. H. Giles, the Wildlife Society, Washington, D. C., 1969.

Reed, W., Fishery technology in the Kainji Lake, in *Kainji, A Nigerian Man-Made Lake*, edited by S. A. Visser, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Roder, W., The irrigation farmers of the Kainji Lake region, Nigeria, Kainji Lake Research Project, *Work. Pap. 2,* Food and Agr. Organ., Rome, 1970.

Rodgers, W. A., Miombo research center, *Annu. Rep. 2,* Min. of Agr., Food and Coop., Dar es Salaam, Tanzania, 1969.

Waddy, B. B., Prospects for the control of onchocerciasis in Africa, *Bull. WHO, 40*, 843–858, 1969.

Waddy, B. B., Health problems of man-made lakes: Anticipation and realization, Kainji, Nigeria, and Kossou, Ivory Coast, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Wells, D., and F. Walsh, Birds of northern and central Borgu, *Nigerian Ornithol. Soc. Bull., 6*(21/23), 1969.

White, E. (Ed.), *The First Scientific Report of the Kainji Biological Research Team,* University of Liverpool, Liverpool, 1966.

Lake Mead, A Case History

DALE A. HOFFMAN AND AL R. JONEZ
Bureau of Reclamation, Denver, Colorado 80225

Lake Mead was formed by impounding the Colorado River by Boulder Dam in the Black Canyon, approximately 676 km (420 miles) upstream from the river's mouth in the Gulf of California. The dam was dedicated in 1935 and started impounding water at that time. In 1947 the name of the dam was changed to Hoover Dam.

At the time of its construction, Hoover Dam was the highest dam in the world, 221.4 meters (726.4 feet) from bedrock to crest; it also formed the largest man-made lake. Discharges are made to the power plant turbines through two gates in each of four towers. The upper gate with a sill elevation of 308 meters (1045 feet) above mean sea level is no longer used; all present discharges are through the lower gate with a sill elevation of 273 meters (895 feet).

When filled to its maximum operating level (374 meters, or 1229 feet, above mean sea level), Lake Mead has a depth of 180 meters (589 feet) above the original stream bed, a shoreline of 885 km (550 miles), and a surface of 660 km^2 (255 mi^2); it extends upstream 183 km (115 miles). At an elevation of 374 meters (1229 feet) above sea level the total capacity is 36×10^9 m^3 (29,755,000 acre-feet), and the total storage below the permanent spillway crest elevation of 366.4 meters (1205.4 feet) is 22×10^9 m^3 (26,086,000 acre-feet) [*Lara and Sanders*, 1970]. The dam has provided the following benefits: flood control, irrigation, domestic and industrial water supply, generation of power, navigation, recreation, fish and wildlife conservation, and sediment control.

GEOLOGIC ASPECTS

The geologic history of the Lake Mead area accounts for its present morphology of a series of steep narrow canyons separating wide sloping basins. The Colorado River cut through the hard rock ridges to form deep narrow canyons, but it eroded away the softer material from the intervening valleys and left wide sloping basins. The major reaches of the reservoir from the upper end to Hoover Dam are Pierce basin, Iceberg Canyon, Gregg basin, Virgin Canyon, Virgin basin, and Boulder basin, the Overton arm extending northward from Virgin basin (Figure 1). Lake Mead is located in an area that slowly subsided during the Paleozoic and Mesozoic eras. During this time the resulting basin formed the floor of an ancient lake in which sedimentary deposits accumulated. These accumulations formed layers of limestone, shale, and sandstone, which in turn were buckled by mountain uplifting. Debris and sediments from the eroded mountains formed deposits between the uplifted ridges. Later, volcanic activity and further uplifting added to the complexity of the geologic setting. Layers of limestone interbedded with beds of gypsum, borate minerals, dolomite, and rock salt are found in the Virgin basin, Overton arm, and Boulder basin reaches. Many of these outcroppings were submerged by Lake Mead. Low-grade deposits of manganese dioxide are also found in the Las Vegas wash area of the lake [*Smith et al.*, 1960].

EARTHQUAKE ACTIVITY

Investigations have been made to determine if filling Lake Mead caused earthquakes. J. P. Rothé reported on work by D. S. Carder done in 1945 that showed that, although no earth tremors had been recorded from the Hoover Dam area during the 15 years previous to construction, shocks were felt in 1936 and numerous tremors were felt in 1937. After 1938, when seismographs were installed at the dam, thousands of tremors were recorded. The seismic activity reached a maximum in May 1939, about 10 months after Lake Mead reached a depth of 145 meters (475 feet) [*Rothé*, 1968]. Subsequent bursts of activity were observed following periods of overfilling. Carder concluded that the seismic activity was

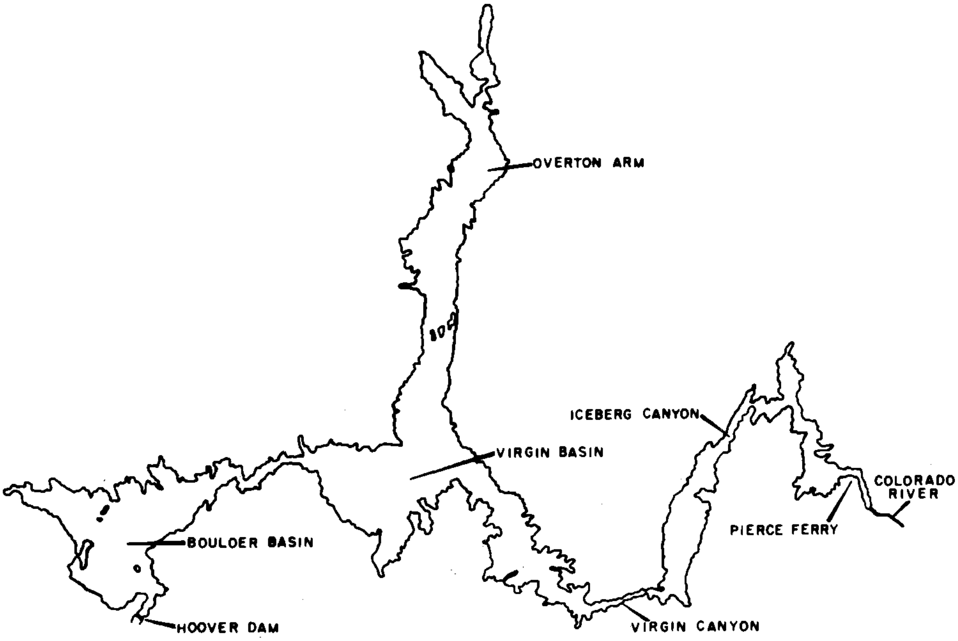


Fig. 1. Lake Mead.

caused by the overload of Lake Mead water, which reactivated faults that had been stable since the Pleistocene era. It is interesting to note that, during the period when water was spilling over Hoover Dam in 1941 and 1942, the dam vibrated in a period of 0.8–0.9 sec with an amplitude of 80 μsec [*Carder,* 1965].

CLIMATE

Lake Mead is located in an arid region with an annual precipitation of <12.7 cm (<5 inches) and an annual mean temperature of 19°C (66°F). Maximum temperatures of 43°C (110°F) occur in July and August, and minimum temperatures of −1°C (30°F) occur in January [*Harbeck et al.,* 1958]. Studies of wind patterns at Boulder basin indicate that the winds are highly variable and have pronounced diurnal fluctuations brought about by the topographic configuration of the surrounding terrain and temperature differences between the land and water areas. The general circulation pattern is northeasterly in winter and southerly in summer. The average wind speed in 1951 ranged from 7.6 km/hr (4 knots) in October to 21 km/hr (11 knots) in May. Studies during 1952–1953 indicate that the annual evaporation from Lake Mead during water year 1953 amounted to 217 cm (85.6 inches), equivalent to 1 $\times 10^9$ m^3 (875,000 acre-feet) [*Harbeck et al.,* 1958]. It is interesting to note that during 1965–1969 the evaporation was 191 cm (75.2 inches). The reduction is probably due to releases of cooler water from Lake Powell after the Glen Canyon Dam power plant started operating.

PHYSICAL LIMNOLOGY

Surveys were conducted to determine various aspects of the limnology of Lake Mead in 1948–1949, 1964–1966, and 1968. The 1948–1949 work was oriented toward determining the circulation patterns affecting the transport of sediment [*Smith et al.,* 1960]. The 1964–1966 and 1968 work was oriented toward determining the chemical and physical limnology of the lake and had an emphasis on the Boulder basin reach of the lake [*Tramutt,* 1965; *Hoffman et al.,* 1967]. The following general description of Lake Mead is compiled from the above-mentioned surveys.

The annual cycle of events in Lake Mead can be divided into the four seasons as follows: winter is January, February, and March; spring is May and June; summer is August, September, and October; fall is November and December. The months of April, July, and October are typical of transition periods. Of course, these general divisions can vary from year to year. The following description of the circulation patterns in the lake is based on data collected before the impoundment of water upstream by Glen Canyon Dam.

At the end of the winter the lake is nearly isothermal, the temperatures ranging from 11.1°C (52°F) at the bottom to 12.2°C (54°F) in the surface waters. In April the air temperatures begin to increase, and the surface waters take on heat. Also, at this time the spring runoff of snowmelt enters Lake Mead from the Colorado River. This water is low in total dissolved solids (220 ppm) in comparison with lake water (650 ppm) and has warmed during its course through the desert to near the temperature of the lake surface waters at the upper end. Being less saline, the river water flows downlake on the surface and can be detected at Virgin basin. A sharp salinity gradient occurs at the upper end of Lake Mead (220 ppm at the surface and 600–700 ppm near the bottom), whereas at Virgin basin the gradient is less sharp (350 ppm at the surface and 600–650 ppm near the bottom). At this time the salinity gradient at Hoover Dam is uniform, i.e., approximately 600–640 ppm from surface to bottom. The force of the surface flow creates a countercurrent moving uplake along the bottom in the upper reaches of the reservoir. The resulting countercurrents aid in mixing the winter water from the lake depths with the inflow from the Colorado River; Figure 2 shows the relationship of the current and the Colorado River inflow.

As the season progresses into summer, stratification begins. Also, during this period the flow from the Colorado River decreases, and its salinity increases to >1000 ppm. The denser inflow sinks down into the lake to a depth of about 24.4 meters (80 feet) where it spreads out over the more dilute but colder water of still greater density that remains from the spring inflow. This tongue of higher saline water will extend downlake to Virgin basin, and will gradually mix with the spring inflow water en route (Figure 2).

As the season progresses into fall, the Colorado River becomes colder and increases in salinity. The tongue of inflow water sinks deeper into the lake and sets up a surface uplake counterflow and a deepwater uplake counterflow (Figure 2). At the point where the river inflow sinks beneath the lake surface, a very sharp convergence line is marked by an accumulation of debris on the lake surface. Within a few hundred yards of this line, salinities will range from >1000 ppm in the river to 700 ppm in the lake [*Smith et al.*, 1960].

The temperature stratification becomes less sharp as the epilimnion cools and begins to mix

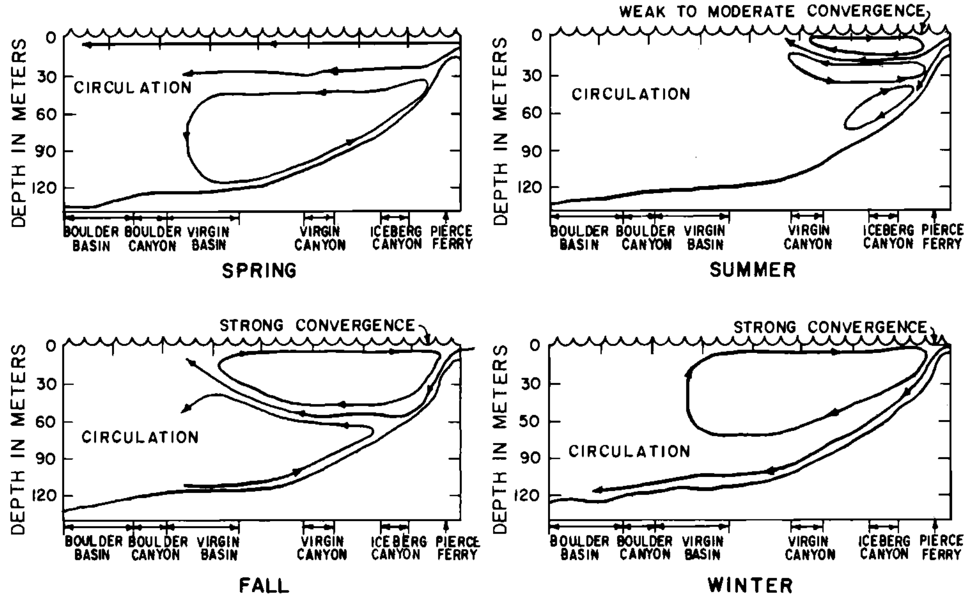


Fig. 2. Circulation patterns in Lake Mead. Figure is taken from paper by *Smith et al.* [1960].

with the thermocline. As the temperatures decrease, stratification gradually disappears, and the lake is once again isothermal during the winter. During this season the cold incoming water sinks to the bottom of the lake and may extend downlake into Boulder basin.

Studies of the lake indicate that Virgin basin acts as a 'mixing bowl' for the incoming Colorado River water and the lake waters. Thus the sources of water flowing into this basin are more variable than those in Boulder basin. The effect of this difference on the rate and magnitude of chemical changes between the two basins is not known.

As discussed previously, Lake Mead is nearly isothermal during the winter but becomes strongly stratified during the summer. The development of stratification is shown in Figure 3. During stratification the epilimnion consists of 19°-32°C (47°-90°F) water at the surface down to the thermocline at approximately 15-30 meters (50-100 feet) where the temperature ranges from 12° to 18°C (54° to 66°F); at the same time the hypolimnion, which begins at approximately 61 meters (200 feet), will have temperatures between 11° and 12.8°C (53° and 55°F). This type of temperature cycle is classified as being warm monomictic, i.e., directly stratified in the summer, freely circulating above 4°C during the winter, and never falling below 4°C [*Hutchinson*, 1957].

CHEMICAL LIMNOLOGY

The temperature regime of a reservoir, in turn, influences the dissolved oxygen pattern. A negative heterograde dissolved oxygen cycle is characteristic of Lake Mead (Figure 3). During stratification, dissolved oxygen values range from 4 to 5 mg/l in the epilimnion, 0 to 4 mg/l in the thermocline, and 1 to 5 mg/l in the hypolimnion. During the winter, oxygen values range from 6 mg/l in the bottom to >11 mg/l in the surface.

Two probable causes for this type of dissolved oxygen distribution have been suggested by *Hutchinson* [1957]. In one case, organic material such as algae is produced in the epilimnion and sinks down to the thermocline where it is oxidized. Another suggestion is that the depth of the oxygen minimum corresponds to a shelf in the bottom contour. In Lake Mead, sources of organic material include the debris brought in by the spring runoff as well as algae. Although Lake Mead is considered a canyonlike reservoir, Boulder and Virgin basins have flat contours that are shelflike. Work by F. D. Sisler showed that large numbers of bacteria were found in the sediments collected near Hoover Dam [*Smith et al.*, 1960]. Such a bacterial population could be a source of oxygen depletion. A. H. Wiebe reported that low dissolved oxygen values at the thermocline in Norris Reservoir were due to organic-rich inflows moving downstream as water was withdrawn [*Hutchinson*, 1957]. How-

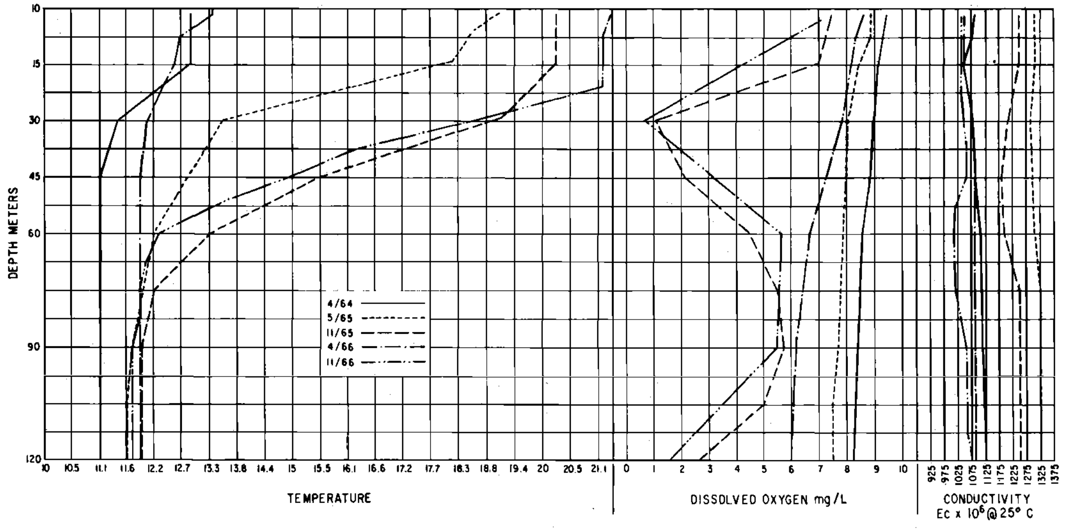


Fig. 3. Temperature, dissolved oxygen, and conductivity data for station 1, Lake Mead.

ever, at this time the cause of the depletion is not known and remains a challenge for future research.

As would be expected, the carbon dioxide pattern in Lake Mead is nearly inverse to the dissolved oxygen pattern. Figure 4 shows the relationship between carbon dioxide, *p*H, and alkalinity at the Hoover Dam station. During stratification, carbon dioxide values are higher in the thermocline than the other zones. Total alkalinity is higher in the epilimnion during stratification than during the periods when the lake is not stratified.

The impoundment of the Colorado River by Hoover Dam has changed the quality of water downstream. The water released from Lake Mead has shown a concentration of dissolved solids that is higher than the average for the inflows. The greatest increases are found in sulfates, chloride, sodium, and calcium. A comparison of the chemical quality of the Colorado River at Grand Canyon with that at Hoover Dam is shown in Table 1. The increases are due to concentration by evaporation and dissolution of salt from the reservoir bank. However, there has been a large decrease in bicarbonate due to precipitation. Although the dissolved solids have increased in the outflow, the wide variation in amounts has been reduced. Even though the inflow loadings of dissolved solids range from 200 to >1700 ppm, the releases average 684 ppm [*U.S. Department of the Interior,* 1967]. This stabilization of salt loadings in the releases enables water of lower salinity to be delivered to irrigators during the irrigation seasons.

During March 1963, when water was being impounded in Lake Powell, the flow down the Colorado River to Lake Mead was reduced, and the level of Lake Mead dropped (Figure 5). At that time the principal effect of filling Lake Powell on the water quality in Lake Mead was the increased salinity due to the solution of salt from the new reservoir (Figure 6). Increases in temperature and alkalinity were also noted [*Hoffman et al.,* 1967].

HYDROLOGY

The Colorado River originates in the high mountains of the state of Colorado. Its main tributaries are the Green, Gunnison, and San Juan rivers, all of which have large impoundments. Glen Canyon Dam, which impounds Lake Powell, is 595 km (369.8 miles) upstream from Hoover Dam and has an influence on Lake Mead that has not as yet been completely determined.

The average annual flow during 1941–1964 from the Colorado River into Lake Mead was 13.4×10^8 m^3 (11,190,000 acre-feet). During the

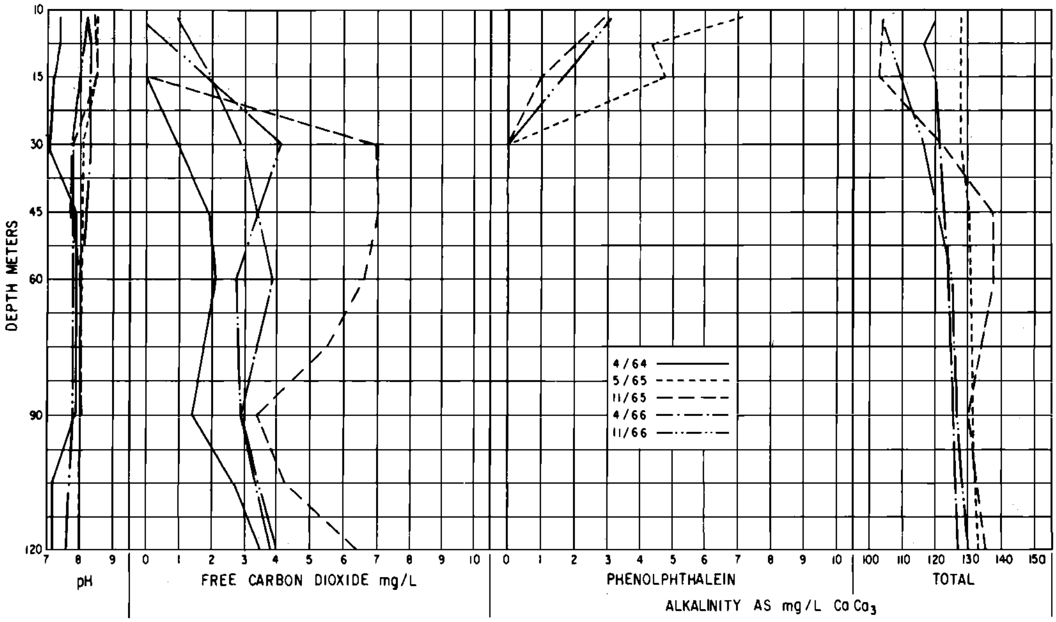


Fig. 4. Relation between carbon dioxide, *p*H, and alkalinity from station 1, Lake Mead.

TABLE 1. Mean Dissolved Constituent Loads of the Colorado River, 1941 to 1964

	Ion Constituent, metric tons						
	Ca	Mg	Na	HCO_3	SO_4	Cl	TDS,* ppm
Grand Canyon	57	28	50	47	63	26	610
Hoover Dam	62	30	54	36	82	29	684

Table is adapted from a report by the *U.S. Department of the Interior* [1967].
* Total dissolved solids.

same period the average annual release from Hoover Dam was 13.7 × 10^8 m^3 (11,156,000 acre-feet). The general pattern of operation at Lake Mead has been to raise the level during the spring and early summer and then to lower it during the fall and winter. The reservoir has been successful in handling floods. Colorado River flows of 3453 m^3/sec (122,000 ft^3/sec) in 1941 and 1952 were reduced to 990 m^3/sec (35,000 ft^3/sec) and 877 m^3/sec (31,000 ft^3/sec), respectively [*U.S. Department of the Interior,* 1961].

DENSITY CURRENTS

Lake Mead is well known as the first large reservoir where density currents were described. The first and best evidence of density currents flowing through the reservoir was obtained during the first 15 months of operation of Hoover Dam, when the reservoir was only 80–112 km (50–70 miles) long. Underflows are the dominant type of density current that transports sediment in Lake Mead. The turbid water sinks down near the bottom and follows the submerged channel of the Colorado River. Usually, the underflows do not reach the western part of the lake, but at least 12 conspicuous ones have been noted between 1935 and 1948. These flows were determined by relating measurements at the Grand Canyon gage upstream from Lake Mead with increases in the thickness of the silt deposit at Hoover Dam or by observation of turbid water passing through the outlets [*Smith et al.,* 1960]. Turbid flows are no longer detected at Hoover Dam.

SEDIMENTATION

A full-scale survey of Lake Mead was run in 1963–1964. The results of both the geodetic and the hydrographic surveys [*Lara and Sanders,* 1970] as well as those of an extensive sediment-sampling collection program were reported.

The geodetic survey showed that most of the reservoir area subsided (lowered) an average of 118 mm during the 1935 and 1963–1964 interval. Results of the hydrographic survey were used to compute a reservoir capacity of 36 × 10^9 m^3 (29,755,000 acre-feet) at an elevation of 375 meters (1229 feet). The reservoir surface area is 660 km^2 (255 mi^2) at this elevation. The results also showed that sediment accumulations in Lake Mead amounted to 3.35 × 10^9 m^3 (2,716,000 acre-feet) since the dam was closed in 1935. This result computes to an average sediment accumulation rate of 1.13 × 10^8 m^3/yr (91,450 ac ft/yr). This rate, however, has been substantially diminished with the closure of Glen Canyon Dam on the Colorado River about 595 km (370 miles) upstream from Hoover Dam. In view of this reduced sediment inflow rate the life of Lake Mead is expected to be increased by at least another 500 years.

Analyses of the sediment samples collected indicated a unit weight of 0.961 g/cm^3 (60 lbs/ft^3) as being representative of the deposited sediments. Representative size gradation of the accumulated sediment was computed to be 60% clay, 28% silt, and 12% sand.

TERRESTRIAL ECOSYSTEM ASSOCIATED WITH LAKE MEAD

Lake Mead is located within the Lower Sonoran life zone. The dominant forms of plants

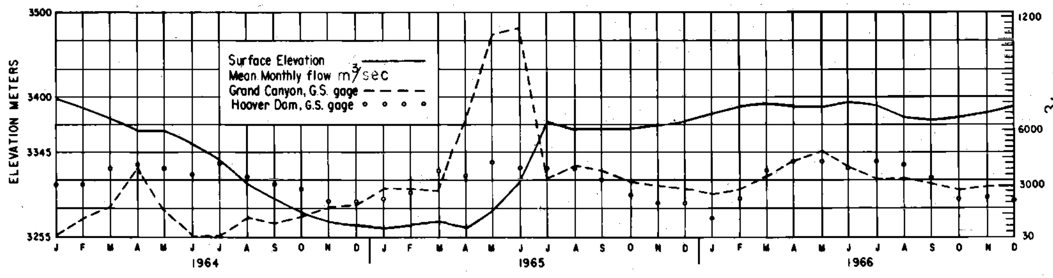


Fig. 5. Flow of Colorado River and Lake Mead elevation from station 1.

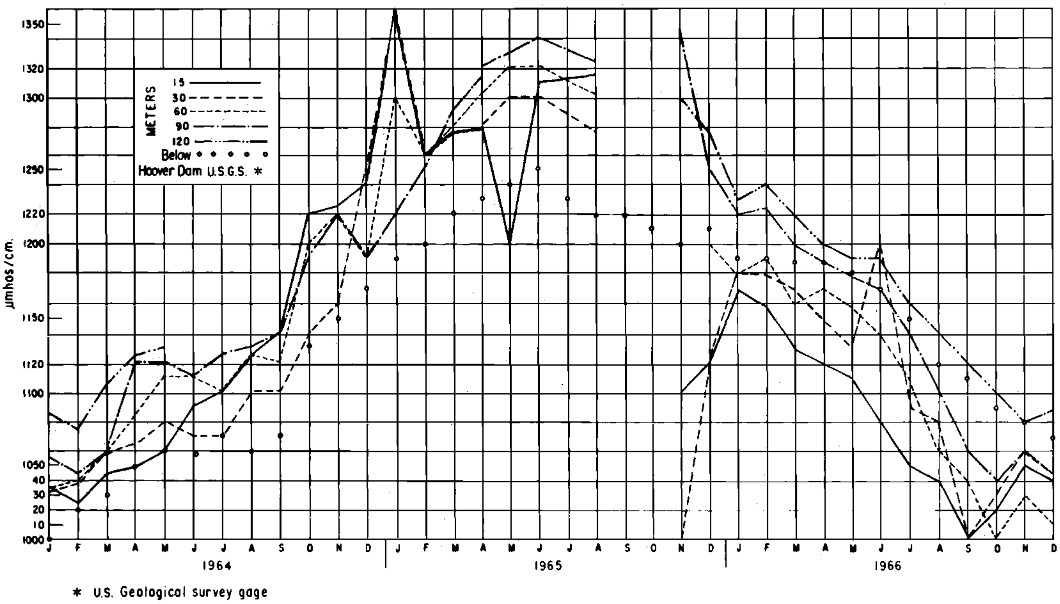


Fig. 6. Electrical conductivity (at 25°C) from station 1.

found there are perennial shrubs. Some of the more typical plants include the creosote bush, mesquite, erigonum, saltbush, arrowweed, barrel cactus, catclaw, desert tobacco, and desert willow (common and scientific names are given in the appendix). An exotic shrub that has invaded much of the lakeshore is the tamarisk, or 'salt cedar.'

Flowering plants can become quite showy in the late spring or early summer months when the Lake Mead area is favored with above average rainfall. The beaver tail cactus, aster, desert chicory, globe mallow, and sand verbena bloom profusely.

About 60 species of mammals are found around the Lake Mead area, the desert bighorn sheep being the most prevalent big game animal. Other mammals found are the bobcat, coyote, gray and kit foxes, badger, and ringtail cat. Cottontails, jackrabbits, and a host of smaller rodents are also found.

More than 250 species of birds have been seen in and around the area. The Gambel's quail is the most common upland game bird, and more than 60 species of waterfowl and wading birds can be seen in the Lake Mead National Recreation Area, especially during the winter migration period.

The casual visitor to the recreation area would undoubtedly consider the desert devoid of life and very harsh. Unless the visitor were quite perceptive, much of the animal and plant life listed above would go unnoticed.

HUNTING

Hunting is allowed in the Lake Mead National Recreation Area during the legal hunting seasons of the states of Arizona and Nevada. The prized desert bighorn sheep is hunted within the recreation area, and hunters have taken trophy heads in the past years. The seasons have been generally held in the winter months when the pelage is at its best. The lake has also provided a way for the fisherman or visitor to view the desert sheep from boats. The desert bighorn sheep is native to the Colorado River area and was pushed out of the river bottom when Lake Mead filled. The lake has since provided a permanent source of water throughout the many miles of its irregular shoreline. The annual plants that grow around the shore provide a source of food for the desert sheep.

Gambel's quail are found around the shoreline, especially in the larger washes. The quail population fluctuates quite drastically depending on the success of the annual plant growth. The rains that produce good flower displays in the spring of the year usually produce good-quality crops in the fall. On these above-average moisture years, it is not unusual to see the quail population increase a thousandfold.

Waterfowl hunting around Lake Mead is a popular winter sport. The Overton Wildlife Management Area is a public hunting area administered by the Nevada Department of Fish and Game and is located on the Overton arm of Lake Mead.

The Overton Wildlife Management Area is located on reclamation-withdrawn or reclamation-acquired land and is under a long-term lease to the Nevada Fish and Game Commission, the National Park Service, and the Bureau of Reclamation. One of the main purposes of the area is to provide a source of winter food for the ducks and geese that winter along the lower Colorado River each year. The 257 ha (560 acres) of improved feeding grounds produced each year feed several hundred thousand waterfowl during the winter migration period. Many ducks and geese return each winter to stay in the Overton Wildlife Management Area. Public hunting is allowed on the area, but, because of its close proximity (96.54 km, or 60 miles) to the Las Vegas area, the hunting days and number of hunters are restricted. The Overton Wildlife Management Area is also popular with school children from the Las Vegas area, and many field trips are made to observe the ducks and geese that spend the winter near the reservoir.

AQUATIC ECOSYSTEM

Prior to the formation of Lake Mead the silt-laden Colorado River overflowed its banks in the spring and early summer and then dried to a trickle in the fall and winter; the result was either too much or too little water. Catfish and native squawfish were taken by the early day anglers. With the filling of Lake Mead starting in 1935 and concurrent releases of bass and sunfish, this lake soon gained a nationwide reputation as a place to catch record largemouth black bass.

Until 1965, rooted aquatic plant life was a rarity because of the extensive annual fluctuations (nearly 15 m/yr, or 50 ft/yr). Since 1965 the lake level has not fluctuated significantly because of another major dam upstream, Glen Canyon Dam. Rooted aquatic plants came into Lake Mead in most of the coves and large bays. Spiny naid is the most common aquatic plant, and pondweed is the second most common.

Cattails are common in many coves, and, because of the rising of the reservoir level, they have grown to a height of 6 meters (20 feet) or more. The rooted aquatics and the cattails provide much needed cover for fish and other aquatic life in the reservoir. Lake Mead does not contain an abundance of insect life. However, midges, damselflies, and dragonflies are common. Crayfish have been seen on several occasions and are an introduced species. The soft-shelled turtle is common in Lake Mead but is not often seen by the visitor to the lake. A freshwater clam is now quite common in the lake, as is an introduced species from Asia.

N. Wood and D. Lockhard (unpublished report) reported that during the late summer and fall of 1962 the medusa form of the Hydrozoa *Craspedacusta sowerbyi* Lankester became abundant in the Vegas wash and Boulder basin areas of Lake Mead. This small freshwater 'jellyfish' averaged approximately 2 cm in diameter and was easily seen in most of the protected coves in Lake Mead [*Deacon and Haskell,* 1967].

FISHING

The native fish found in the Colorado River before Hoover Dam was constructed were the Colorado River squawfish, the humpback sucker, and the bonytail chub. Carp were introduced into Nevada by 1881 and were present throughout the lower Colorado River prior to the formation of Lake Mead.

The largemouth black bass has been the most important game species in Lake Mead throughout the lake's history. Other game species are the channel catfish, black crappie, bluegill, green sunfish, and rainbow trout. Recently, silver salmon and striped bass have been introduced to see if a winter trophy fishery can be developed. The threadfin shad was introduced in 1955 to provide a forage fish for the game species in Lake Mead.

Fishing success was fair to excellent in the early years of the reservoir. In 1941, however, local sportsmen were concerned about the apparent poor condition of bass and complained that the bass seemed to have lost their 'gameness.' *Moffett* [1943] conducted an investigation of the Lake Mead fishery during 1941 and 1942. He noted that there was an absence of aquatic vegetation, that plankton was none too plentiful, and that the production of bottom organisms was poor. He also noted that the 1941 spawning season was considered a phenomenal success. It is interesting to note that this success coincided with the highest surface elevation of the Lake Mead waters and that wide expanses of new, brush-covered shores were inundated.

Another slump in the Lake Mead fishing occurred in 1950. Consequently, in 1951 the Nevada Fish and Game Commission initiated a 3-year investigation of the Lake Mead fishery. The purpose of the study was to examine and evaluate the ecosystem and make recommendations for future management of the fishery (A. R. Jonez and R. E. Summer, unpublished report, 1954).

High values for Lake Mead fishing success were observed following the 1952, 1957, 1958, and 1962 high runoff years, which caused a tremendous rise in the surface elevation of the reservoir. Between these peaks were periods of declining fishing success.

Lake Powell behind Glen Canyon Dam started to fill in 1963 and, as Lake Powell received its initial supply of water, the Lake Mead fishery was declining. The low point came in 1967, the lowest fishing success year recorded since 1952.

It became apparent that the fishery in Lake Mead historically reflected very closely the fluctuation pattern of the lake. The history of the fishery as illustrated in Figure 7 bears this relationship out. The direct correlation between reservoir fluctuation and fishing success was noted as early as 1954; however, it was considered virtually impossible at that time to manipulate the reservoir for the benefit of fish life, because the reservoir water level was at the mercy of the snowpack and resulting runoff each spring.

However, owing to the construction of Glen Canyon Dam, flows to the lower basin are now regulated. By 1967 it was apparent that the man-controlled fluctuation pattern of Lake Mead was affecting the fishery and that fishing success was declining. Reservoir manipulation to benefit fish life was requested by the fish and game agencies of Arizona and Nevada. In 1968, 1969, and again in 1970 the reservoir levels were adjusted to benefit fish life.

Recommendations were made to hold the reservoir level steady during the months of April, May, and June and then to raise the water level into the terrestrial vegetation from July through September to aid the escape of the young of the year bass from the larger fish. Normally, by July the young bass have left the protection of the male bass and can be found around the shoreline in very shallow water. If we raise the water level during the late summer months, the young bass find optimum escape cover in the recently inundated terrestrial plants (Figure 8).

Another factor in the success of bass spawning is the occurrence of cold spring weather. Largemouth bass spawning usually starts in April

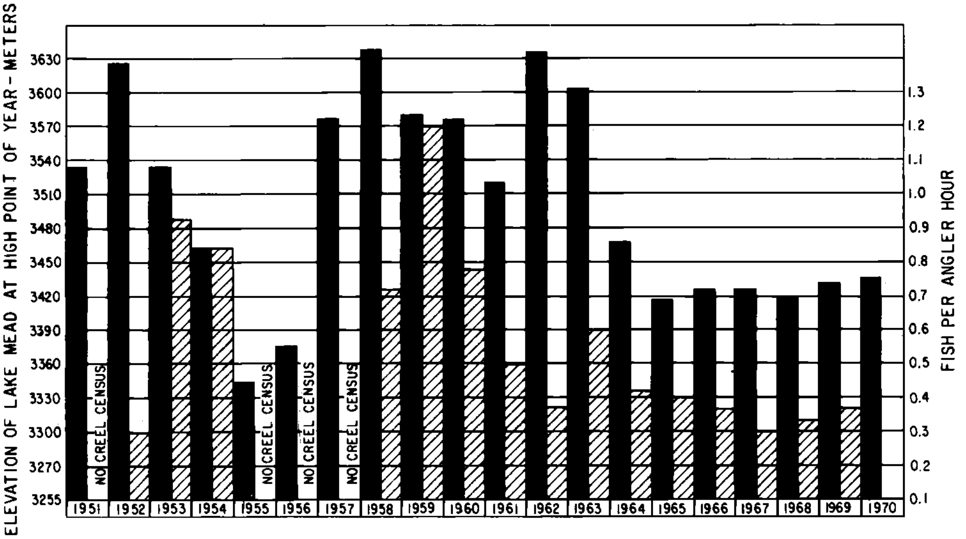


Fig. 7. Yearly Lake Mead fluctuation pattern in relation to fishing success and angler use. Elevation is indicated by darkened bars; fishing success is indicated by shaded bars.

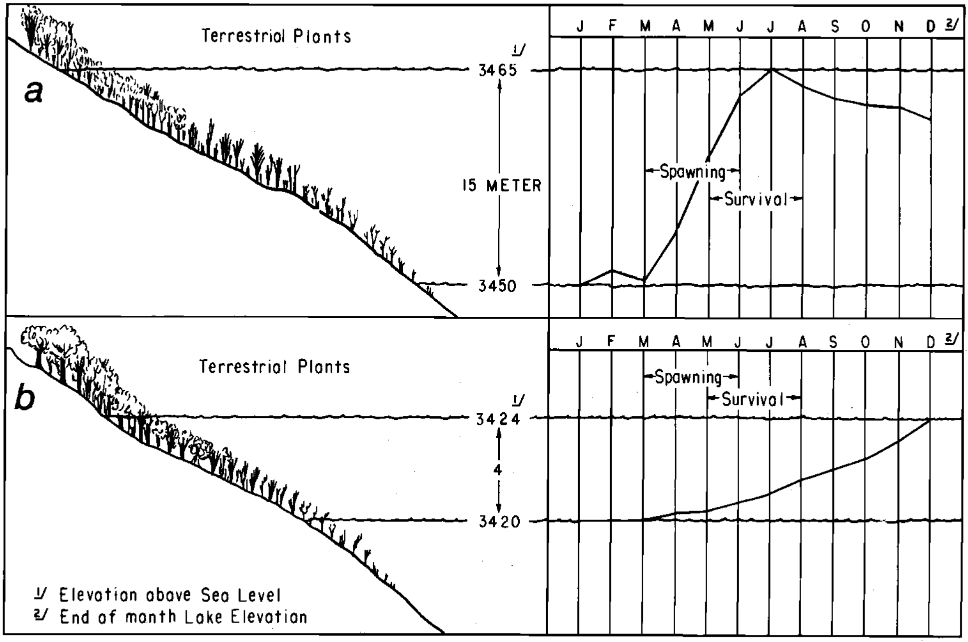


Fig. 8. (*a*) Outstanding bass spawning and survival conditions on Lake Mead during 1962; (*b*) fluctuation pattern that helped bass spawning and survival in 1969.

when the surface water temperature reaches 15.6°C (60°F). When the surface water temperature reaches 18.3°C (65°F), the spawning is in full swing. At least half of the time the Lake Mead area can be subject to cold spring weather, and, when this weather occurs, the spawning is delayed at least a month or more. Besides the delay of spawning the cold spring weather (with high winds) has caused significant mortality to bass eggs in the nests. Underwater observations with the aid of scuba gear have allowed a close look at this mortality. Cold winds in April seem to cause the most mortality, and it is not uncommon to find an abandoned nest with 50–60% of the eggs destroyed. It is apparent that early spawning results in failure when cold winds prevail for any length of time (Figure 9).

We cannot expect the large flows from high-runoff conditions similar to those in the years 1952, 1957, or 1962 to reach Lake Mead with any regularity now that Glen Canyon Dam and Lake Powell are in existence upstream from the Lake Mead. The water delivered to the lower basin is regulated by the Colorado River Compact. The lower basin receives 92×10^9 m^3 (75 million acre-feet) in a 10-year period, and, unless Lake Powell is abnormally full during a high-runoff period and has to release water to make room for flood control, the lower basin can only expect approximately 10×10^9 m^3/yr (8.3 million ac ft/yr).

The Bureau of Reclamation has established the following guidelines to benefit the fishery in Lake Mead:

1. Try to preclude a drawdown during the months of April through June. A relatively stable or rising reservoir provides the better spawning conditions.
2. Try to provide at least a stable or preferably a rising reservoir level during June through September. The rising water level inundates terrestrial vegetation and provides more living space and escape cover for the young of the year game fish.

The above guidelines may be altered when further research indicates that other fluctuation patterns should be tried.

RELATION TO MAN

Ancient. Archaeological expeditions to obtain information about the history of man in the area inundated by Lake Mead were conducted in the 1920's and 1930's. The most thoroughly studied excavations that pertain specifically to

Lake Mead are those in the Overton arm reach where the Muddy and Virgin rivers joined. These sites, near the old town of St. Thomas, are known as the Lost City sites.

The earliest evidence of man in southern Nevada was at Tule Springs, a few miles west of present-day Las Vegas, Nevada. Radiocarbon dating of charcoal deposits from the site indicates an age of 28,000 years. However, the specific relationship between the charcoal and artifacts and bones found there has not been established to everyone's satisfaction.

The next evidence of man was from a gypsum cave just north of Las Vegas and dates to about 8000 B.C. The next group to occupy the area were the Basket Maker people whose beginnings are undetermined but who lasted until 500 A.D.

The first evidence of man in the Muddy and Virgin rivers area was during the Basket Maker period. Subsequent phases were the Muddy River phase from 700 to 1100 A.D. and the Mesa House phase from 1100 to 1150 A.D.

Probably one of the principal attractions for settling here was the nearby large deposits of salt. These deposits interestingly enough were also one of the principal reasons for settlement by modern man.

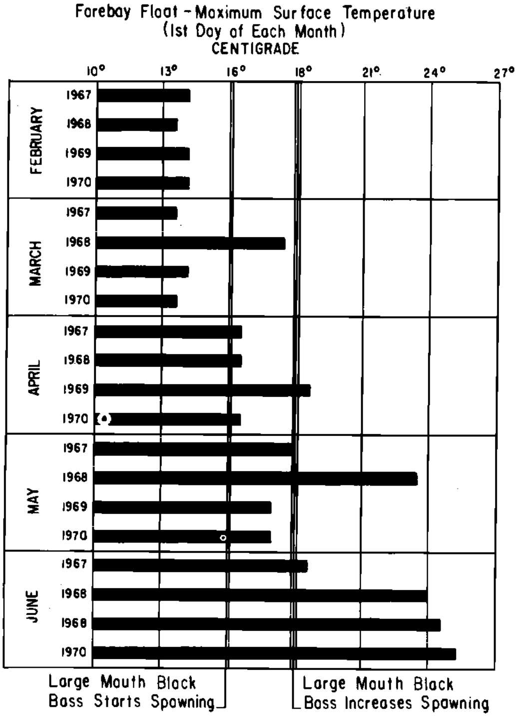


Fig. 9. Bass spawning and temperature relationship on Lake Mead.

During the Muddy River phase the early Basket Maker people wandered about the area near the rivers depending on wild foods and hunting, whereas those people of the Lost City and Mesa House phases depended more on irrigated crops and built more permanent types of structures. Small brush dams and ditches were probably used to irrigate their crops.

The last period of occupation of southern Nevada by Pueblo-type people was during the Mesa House phase. For some unknown reason the sites were abandoned, and the people apparently moved east and became the ancestors of the present-day Hopi. Since they were dependent on the Muddy and Virgin rivers, a period of increased drought would have reduced agricultural endeavors. The consequent reduction in size of the villages would have made them more vulnerable to the depredations of the Paiute Indians from the north. These circumstances may have been sufficient to convince the Pueblo people to leave the area.

During the Lost City phase the Southern Paiute entered southern Nevada, and evidence of their presence is found throughout the subsequent phases. They were more like the early Basket Maker people in that they used wild foods more than the Pueblo people. Thus, not dependent on any one resource, they scattered throughout the territory and did not establish a social organization [*Shutler,* 1961].

Recent. The Gulf of California was discovered by the Spanish explorer Francisco de Ulloa in 1539. Although he was not able to reach the mouth of the Colorado River because he was driven back by the bore of the river, the amount of turbidity and debris convinced him that a great river entered the head of the gulf. Another expedition led by Hernando de Alarcon attempted to move up the river with supplies for Francisco Vasquez de Coronado's cross-country expedition in 1540. Although he did not contact Coronado, Alarcon was able to go up the Colorado River as far as the present Blythe, California. After 1774 the Spanish gave up exploration in this region because it was too dangerous, and it was not until the early 1800's that American frontiersmen visited the Colorado River basin.

During the following 50 years the region gradually became better known through the travels of trappers and traders and through more formal expeditions such as those by John C. Fremont in 1842–1846. The California gold rush in 1849 attracted thousands of fortune seekers who crossed the Colorado River at Yuma, Arizona, on their way to the gold fields. However, it was not until the expedition of John Wesley Powell in 1869–1872 that the Colorado River was accurately described. His reports suggested the possibilities for an irrigated agriculture in the southwestern United States [*U.S. Department of the Interior,* 1948].

During the middle 1800's, attempts were made to navigate the Colorado with steamboats. One of the first, in 1857, was the *Explorer* under the command of Lieutenant J. C. Ives, which passed through the present Lake Mead site and almost got to the Virgin River. In spite of Ives' discouraging reports, other boats attempted the journey. One of the most dangerous and main obstacles to navigating the river was a series of rapids downstream from the present site of Hoover Dam. A simple, but ingenious, scheme was developed to help move the boats through the rapids. Large ringbolts were attached to the canyon walls. To aid boats moving upstream, one end of a cable was attached to the ringbolt, and the other end was attached to a winch on the boat. The boat would pull itself up through the rapids by winding the cable on the winch. The reverse procedure was used to let the boat slowly downstream through the dangerous rapids. In spite of the difficulties of navigation on the Colorado River due to fluctuating flows, shifting sandbars, and rapids, riverboats operated on a regular schedule as late as 1910.

During the development of its new colony near the Great Salt Lake, the Mormon church decided it would be less dangerous to bring their new converts from Europe up the Colorado River rather than by wagon across the United States. Thus it was decided to establish a fort, later called Fort Callvill, on the Colorado River approximately 16 km (10 miles) upstream from the site of present-day Hoover Dam. The first building to be completed, a warehouse, was finished in the spring of 1865. Evidently, they built well, as some of the original buildings were still standing when they were submerged by Lake Mead 70 years later. The community was to be a port for receiving cargo, farm implements, and so on for the Mormon settlements and was to furnish an outlet for the surplus Mormon crops and salt from the nearby mines. However, as the railroads took over the freight hauling and passenger service, Callvill was abandoned.

Meanwhile, another Mormon community called St. Thomas was started near the junction of the Virgin and Muddy rivers, now under the water of the Overton arm reach of Lake Mead. In 1865 the townsite was moved north to a more hospitable spot. The town flourished and became the focal point for an extensive agricultural area, cotton being one of the main crops. In 1870, after a boundary survey determined that St. Thomas was part of the state of Nevada and not Utah, many Mormon settlers packed up their worldly possessions and moved back to their home state. In spite of this setback the town continued to grow and was well known in the early 1900's as a sort of oasis for motorists crossing the desert. When the main highway was rerouted north of town, the economy suffered, and the population decreased.

When word of the construction of Boulder Dam reached St. Thomas, few could conceive that the water would back up as far as their town. On June 11, 1938, as water began to lap at the buildings, postmaster Leland Whitmore and his father Rox raced frantically against time cancelling thousands of 'last day' envelopes. As a final gesture, Whitmore threw the stamp into the rising waters. St. Thomas was not seen again until 1946, when Lake Mead dropped enough for some of the buildings and dead trees to be seen.

One of the few people to remain at St. Thomas when the others returned to Utah was Daniel Bonelli. Recognizing the potential of a trading center at the junction of the Virgin and Colorado rivers, he established a settlement there and called it Rioville. However, it was better known as Bonelli's Ferry. It became an important port for riverboats bringing up supplies for the mines and settlers and hauling out rock salt and agricultural products. However, due to competition of the railroads the riverboats quit coming to Rioville, and it gradually died [*Ashbaugh,* 1963]. When Lake Mead filled, the towns of Rioville and Callvill were already ghost towns; St. Thomas was still inhabited, and the buildings were purchased by the government.

During the late 1800's, efforts were made to develop an irrigated agriculture in the Imperial, Yuma, and Coachella valleys on the lower Colorado River. Numerous successful ventures were made, but none reached full potential because of the problems of floods and silt from the Colorado River compounded by periods of drought.

During the severe drought of 1904 a cut was made in the bank of the Colorado River to let more water flow to the irrigated fields. Unfortunately, the drought broke with a series of floods from the Colorado and Gila rivers, which washed into and widened the cut. As a result the Imperial Valley was flooded, and the Salton Sea was formed. In the following years, more floods occurred, and attempts to close the cut were not successful until 1907.

This series of disasters gave rise to a series of attempts to control the Colorado River floods by levees and dikes. The lack of success with these methods gave rise to thoughts of building a large dam to control the river; these thoughts culminated in the construction of Hoover Dam [*U.S. Department of the Interior,* 1948].

VISITOR USE

The Lake Mead Natural Recreation Area has always been a popular water sport area. Swimming, boating, water-skiing, and fishing are an important part of visitor use of Lake Mead. Sight-seeing is by far the most popular visitor activity. Guided tours through Hoover Dam have remained popular over the years, and over 615,000 visitors were shown through Hoover Dam in 1969.

The Lake Mead Recreation Area is administered by the National Park Service, which has provided 14 boat-launching ramps and two supervised swimming beaches and has 12 concessions operating in the area. There are 17 campgrounds and 24 picnic shelters around the lakes. Visitor use of the Lake Mead National Recreation Area in 1969 was over 6 million visitors. The visitor use has doubled in the past 12 years and is still rising.

TOURISM

Las Vegas, Nevada, is the largest population center near Lake Mead. This tourist-oriented community has always capitalized on the fact that Lake Mead is the water sport playground of southern Nevada. The large hotels in Las Vegas all have large boats berthed on Lake Mead and treat their guests to a trip on the lake. The Chamber of Commerce and the Las Vegas Convention Bureau have played up the water sport aspect of a trip to Las Vegas.

FUTURE RESEARCH

1. Although Lake Mead was impounded in 1935, there is comparatively little known regarding the biology and ecology of the reservoir. There is a need for information regarding productivity and resulting food web relationships.
2. Now that Lake Powell is in operation, there is a need to determine the present-day circulation patterns, especially in reference to the study by E. R. Anderson and D. W. Pritchard in 1948 [*Smith et al.,* 1960].
3. The cause and regime of the low dissolved oxygen layers during stratification also should be determined.
4. The effect of development in the Las Vegas wash and Virgin River basins on the water quality of Lake Mead must be determined.

APPENDIX: COMMON AND SCIENTIFIC NAMES

Creosote bush, *Larrea divaricata*
Mesquite, *Prosopis pubescens* (Bentham)
Erigonum, *Eriogonum* spp.
Saltbush, *Atriplex* spp.
Arrowweed, *Pluchea sericea* (Nuttall) Coville
Barrel cactus, *Echinocactus* spp.
Catclaw acacia, *Acacia Greggli Gray*
Desert tobacco, *Nicotiana* spp.
Desert willow, *Chilopsis linearis* (Cav.) Sweet
Tamarisk, *Tamarix pentandra*
Beaver tail cactus, *Opuntia basilaris* Engelmann and Bigelow
Aster, *Aster* spp.
Desert chicory, *Chickorium* spp.
Globe mallow, *Sphaeralcea* spp.
Sand verbena, *Abronia* spp.
Desert bighorn sheep, *Ovis canadensis nelsoni* Merriam
Bobcat, *Lynx rufus pallescens* Marble
Coyote, *Canis latrans estor* Merriam
Gray fox, *Urocyon cinereoargenteus scottii* Mearns
Kit fox, *Vulpes macrotis arsipus* Elliot
Badger, *Taxidea taxus berlandieri* Baird
Ringtail cat, *Bassariscus astutus nevadensis* Miller
Cottontail, *Silvilagus audubonii arizonae* Allen
Blacktail jackrabbits, *Lepus californicus*
Gambel's quail, *Lophortyx gambelii gambelii* Gambel
Rainbow trout, *Salmo gairdneri* Richardson
Largemouth black bass, *Micropterus salmoides* (Lacepede)
Channel catfish, *Ictalurus punctatus* (Rafinesque)

Black crappie, *Pomoxis nigromaculatus* (Lesueur)
Bluegill sunfish, *Lepomis macrochirus* Rafinesque
Green sunfish, *Lepomis cyanellus* Rafinesque
Spiny naid, *Najas marina* L.
Pondweed, *Potamogeton* spp.
Cattail, *Typha* spp.
Midge, *Tendipedids* sp.
Damselfly, *Odonata*
Dragonfly, *Odonata*
Crayfish, *Asticus* spp.
Emory soft-shelled turtle, *Amydaemory* spp.
Asiatic clam, *Corbicula* sp.
Freshwater clam, *Cambera* sp.
Colorado River squawfish, *Ptychocheilus lueius* Girard
Humpback sucker, *Xyrauchen texanus* (Abbott)
Bonytail chub, *Gila elegens* Baird and Girard
Silver salmon, *Oncorhynchus kisutch* (Walbaum)
Striped bass, *Morone saxatilis* (Walbaum)
Threadfin shad, *Dorosuma petenense* (Gunther)
Carp, *Cyprinus carpio* Linneaus

Acknowledgments. The authors wish to express their thanks and appreciation to other Bureau of Reclamation personnel, especially those in the region 3 headquarters, whose aid and information contributed to the paper. Thanks are also extended the National Park Service and Lake Mead National Recreational Area staff for information on the history and use of the Lake Mead area.

REFERENCES

Ashbaugh, D., *Nevada's Turbulent Yesterday,* pp. 59–74, Westernlore, San Francisco, Calif., 1963.

Carder, D. S. (Ed.), Earthquake investigations in the western United States, 1931–64, *Publ. 41-2,* 264 pp., Coast and Geod. Surv., U.S. Dep. of Commer., Washington, D. C., 1965.

Deacon, J. E., and W. L. Haskell, Observations on the ecology of the freshwater jellyfish in Lake Mead, Nevada, *Amer. Midl. Natur., 78*(1), 155–166, 1967.

Harbeck, G. E., et al., Water-loss investigations: Lake Mead studies, *U.S. Geol. Surv. Prof. Pap., 298,* 100 pp., 1958.

Hoffman, D. A., P. R. Tramutt, and F. C. Heller, Water quality study of Lake Mead, *Chem. Eng. Rep. ChE-70,* 1953 pp., Bur. of Reclam., U.S. Dep. of the Interior, Denver, Colo., 1967.

Hutchinson, G. E., *A Treatise on Limnology,* vol. 1, *Geography, Physics, and Chemistry,* 1015 pp., John Wiley, New York, 1957.

Lara, J. M., and J. I. Sanders, The 1963–64 Lake Mead survey, *Rep. REC-OCE-70-21,* 172 pp., Bur. of Reclam., U.S. Dep. of the Interior, Denver, Colo., 1970.

Moffett, J. W., A preliminary report on the fishery of Lake Mead, *Trans. N. Amer. Wildl. Conf., 8,* 179–186, 1943.

Rothé, J. P., Fill a lake, Start an earthquake, *New Sci., 39*(605), 75–78, 1968.

Shutler, R., Jr., Lost City, Pueblo grand de Nevada, *Anthropol. Pap. 5,* 80 pp., Nev. State Mus., Carson City, 1961.

Smith, W. O., et al., Comprehensive survey of sedimentation in Lake Mead, 1948–49, *U.S. Geol. Surv. Prof. Pap., 295,* 254 pp., 1960.

Tramutt, P. R., Water chemistry survey of Boulder basin, Lake Mead, *Chem. Eng. Rep. ChE-46,* 36 pp., Bur. of Reclam., U.S. Dep. of the Interior, Denver, Colo., 1965.

U.S. Department of the Interior, Introductory, general history and description, part 1, final report, Boulder Canyon Project, 201 pp., Washington, D. C., 1948.

U.S. Department of the Interior, The story of Hoover Dam, *Conserv. Bull. 9,* 79 pp., Washington, D. C., 1961.

U.S. Department of the Interior, Quality of water, Colorado River basin, *Progr. Rep. 3,* 80 pp., Washington, D. C., 1967.

Lake Nasser

P. C. RAHEJA[1]

UNDP/FAO Lake Nasser Development Center Project
Aswan, Egypt

GEOGRAPHY

Aswan, the city, is 960 km south of Cairo and about 1200 km from Alexandria. The first cataract of the Nile is here, and Aswan is the site of a long, low dam built in 1902. This dam was subsequently heightened twice for flood storage. The new rock-fill Aswan High Dam, which now impounds Lake Nasser (Figure 1) in Egypt and Lake Nubia in the Sudan, was constructed in the period 1959–1969, 7 km south of the old Aswan Dam. The High Dam is 3600 meters long, 111 meters high above the riverbed, 980 meters wide at the base, and 40 meters wide at the top.

Lake Nasser is located within the latitudes of about 22°00'N and 23°58'N in Egypt; it extends southward into the Sudan (nearly to 20°N) as Lake Nubia. Mostly, the lake as a whole is surrounded by rocky terrain, chiefly piedmonts and peneplains of Nubian sandstone. To the west is the great Sahara Desert, and to the east is the Eastern Desert extending to the Red Sea.

The entire reservoir (Lake Nasser and Lake Nubia) has a gross capacity of 157,000 million m^3. The dead storage is about 30,000 million m^3 at 147 meters above mean sea level for operating the hydroelectric power station. The live storage between 147 and 175 meters is some 90,000 million m^3 and enables perennial irrigation for 0.7 million ha in Egypt. The maximum level of 182 meters is not likely to be reached until the 1980's. In Egypt the human population of the riverine flats in 44 villages (some shown on Figure 1) was resettled to Kom Ombo plateau, 46 km north of Aswan, east of the river.

PHYSICAL SYSTEM

Morphology. The shoreline of Lake Nasser at the 160-meter level is some 5416 km and at the 180-meter level is expected to be some 7875 km. For the entire reservoir the values at these levels would be nearer to 5960 and 8803 km, respectively. The ratio of the shoreline to the length of the entire reservoir is 18:1. The length of the eastern shoreline is almost double that of the western shoreline. The shoreline indices of the lake and entire reservoir in relation to surface areas of 160 and 180 meters above mean sea level are 30.05 and 30.45, respectively, and in relation to volume are 29.98 and 28.63, respectively.

The 1970 surface area of the entire reservoir was 3074 km^2 at the 160-meter level. When the reservoir is full at the 180-meter level it will have a surface area of some 6220 km^2. Thus with every meter rise in level above 160 meters the surface area will increase some 157 km^2. The major part of the reservoir is in Lake Nasser, where the surface area values at the 160- and 180-meter levels are 2581 and 5237 km^2.

The riverbed level at which the High Dam has been constructed is 99 meters above sea level. The mean depth of Lake Nasser at its 180-meter level is calculated to be 24.89 meters. Water depth at the dam would be 81 meters at the 180-meter level and would decrease to the south. The mean width of Lake Nasser at the 180-meter level approximates 17.95 km. Some of the arms (also called khors or lagoons) of the lake are >50 km long.

The volume of the reservoir at the 1970 level of 160 meters above mean sea level is 64.02 km^3. At 180 meters the volume would be 157.31 km^3. The volumes of the reservoir in the Sudan at the 160- and 180-meter levels are only 10.1 and 26.94 km^3, respectively. Thus the bulk of the volume is in Egypt.

Major khors, or arms, number 85, of which 48 are on the eastern shore and 37 are on the western shore. The shoreline length of these khors is 969.9

---

[1] Deceased.

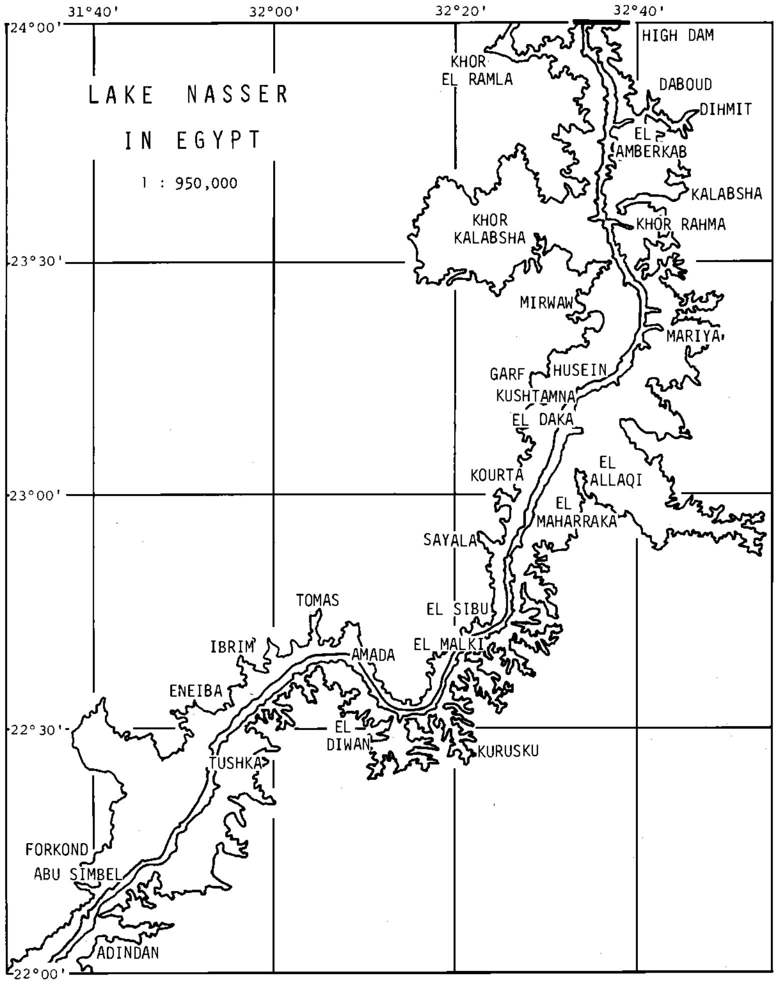


Fig. 1. Lake Nasser in Egypt with place names including those for a few of the major arms (khors).

km (576.33 km to the east and 393.57 km to the west). Cultivable lands are present at the heads of several of the khors, especially at Kalabsha, Wadi Al Allaqi, Kurkur, and Tushka (Figure 1).

Meteorology. The entire reservoir lies in an extremely arid environment. Although occasional showers may be received in any period of the year, there may be no rainfall at all in some years. Consequently, the mean relative humidity as recorded at Aswan is 13% in May–June, rises to 36% in December, and then falls off again. The mean monthly ambient temperature is near 34°C in the period from June to August, the lowest temperature of 15.8°C being recorded in January. The 'cool' season lasts from December to February with a mean air temperature of 16.5°C. Hot weather prevails from April to October with a mean of 31.1°C. The temperatures rise rapidly in February–March and decline steadily during November.

Occasionally, strong hot Sahara winds blow from northwest to southeast during the summer months of April to September. The north winds from the Mediterranean Sea reduce the temperatures whenever a high-pressure area is developed in the region. Except during khamsin periods the atmosphere remains clear, and the incidence of net energy is high.

Data recorded in June on the lake at 0700 hours indicated a small difference of −0.3 over the Aswan city temperature. The maximum difference of 6.0°C was recorded at 1800 hours when the

Aswan temperature was 37.0°C and the lake air temperature was 31.0°C. At 0700 hours the relative humidities at Aswan and the lake were 36 and 58%, respectively. The lowest values of relative humidity were recorded in June and were 3% for Aswan and 18% for the lake air.

Physical limnology. From November to April, no thermal stratification occurs in the lake water, which has surface to bottom temperatures of 17°–19°C. After April, when the surface water warms, stratification commences, and a thermocline then forms between 13 and 20 meters. With time the thermocline gradually presses toward the bottom so that the epilimnion, with temperatures between 25° and 27°C, is increased in depth by the incoming flood. At the end of the flood, near homothermy is reestablished, and, by the end of November, total circulation of water has occurred.

The flow of turbid water into the lake during the flood season reduced the transparency. In 1969–1970 the Secchi disk transparency was reduced to 20–25 cm near Adindan to the south in September, whereas it remained at 100–200 cm near the dam. By the end of September the transparency in the middle of the lake was 70–100 cm. Near the dam, transparency changed little throughout the year owing to flood materials. However, transparency was affected periodically by phytoplankton blooms that appeared to be related to floodwater. Near the High Dam and up to 40 km to the south the phytoplankton production was highest in spring and early summer. The density diminished progressively from September to December. In the central third of Lake Nasser the mass of plankton was higher than that in the northern third, particularly after the flood season. During the flood period the plankton density decreased rapidly.

BIOLOGICAL SYSTEM

Aquatic Ecosystem

Chemical limnology. In 1968 and 1969 the samples for chemical analyses of surface waters were drawn from 20 stations over the entire length of Lake Nasser. Vertical samples at 1-meter intervals were taken from one station near the High Dam. In 1969 and 1970, two khors were sampled at quarterly intervals, and two lake-wide surveys were conducted.

From January to March the difference in the hydrogen ion concentration declined from surface to bottom by about 1 *p*H unit. There was also a tendency of decrease in *p*H values from south to the north. Values of *p*H from March to August ranged from 7.8–9.1 at the surface to 7.6–7.8 on the bottom. The highest value, 9.35, was recorded in the middle section of the lake within the upper 10 meters. In the flood period the *p*H values tended to equalize as the water mixed, but they started showing differences again in November–December.

Carbonate in the first quarter of the year was present only down to 30 meters, and the maximum recorded value was 43 mg/l. Below 30 meters, free CO_2 was present in traces. The maximum amount of HCO_3^- observed was 185 mg/l near the southern end of the lake. In April to June the HCO_3^- was reduced and was present only in the upper 15 meters. There was further reduction up to mid-August. The concentration of HCO_3^- then increased slightly in the period from August to October and tended to decrease thereafter.

Chloride ions showed small local variations throughout the length and depth of the lake and ranged from 3.3 to 6.6 mg/l. The southern half of the lake throughout the year had a higher content of phosphate than the northern half, the values near the High Dam being lowest. The average PO_4^{---} content was 1.5 mg/l, and the inflow of floodwaters increased the level.

The amount of nitrates in water varied from place to place within the range of 0.05–0.55 mg/l. In the first half of the year a gradual increase in nitrate content with depth was recorded, and the nitrate content was highest in the flood season from September to November. Only small amounts of nitrite were present in the waters of the lake, the highest value being 0.1 mg NO_2^-/l.

The lake waters are rich in silicates throughout the length and depth of the reservoir; silicates increase in the flood season. In general, the lake is rich in organic and inorganic nutrients; for example, the ranges of values for Ca^{++} and Mg^{++} were 25–26 and 10–11 mg/l, respectively, throughout the length and depth of the lake.

Primary productivity. In April 1970 the primary productivity values were estimated to be at 15.5 g O_2/day/m² = 14.54 g glucose/day/m² = 5.82 g C/day/m².

Plankton production. Phytoplankton genera present include *Closterium. Pediastrum, Scenedesmus, Pooystis, Oscillatoria, Microcystis, Navicula, Nitzschia, Surirella, Bacillaria,* *Peridinium*, and *Ceratium*. Zooplankton recorded in abundance were *Daphnia* and *Cyclops* plus other copepods and cladocerans.

In a lake-wide survey in March, large colonies of *Volvox* made up 49.1% of the plankton samples near the southern end of Lake Nasser, and Cladocera and Copepoda formed 34.2 and 16.7%. The average values for the middle third of the lake for Cladocera, Copepoda, and *Volvox* were 42.6, 43.6, and 13.8%, respectively. The values in the northern third of the lake for Cladocera and Copepoda were 57.1 and 42.9%, respectively.

Fish fauna. The families of fish represented in the lake are Cyprinidae, Cichlidae, Contropomidae, Tetraodontidae, Mormyridae, Clariidae, Schilbeidae, Synodontidae, Bagridae, Malapteruridae, Characidae, and Polypteridae. The total number of species recorded so far is 53. The fish that make up more than 95% of the catch listed in order of their decreasing importance are *Tilapia nilotica, Hydrocynus forskali, Alestes dentex, Lates niloticus, Bagrus bayad, Clarias* spp., *Labeo forskali, Labeo niloticus, Synodontis schall, Barbus bynni, Schilbe uranoscopus*, and *Schilbe mystus.* The six most important of these (with metric tons landed in 1969 in parenthesis) currently are *T. nilotica* (1851), *Lates niloticus* (297), *Labeo* spp. (387), *Bagrus* spp. (113), *Synodontis* spp. (19), and *Clarias* spp. (37). The species generally salted (with the 1969 tonnage in parenthesis) are *Hydrocynus* spp. (4.8), *Alestes* spp. (1170.5), *Schilbe* spp. (48.3), *Labeo* spp. (582.2), and *Mormyrus* spp. (0.2).

Comparison of the annual fish catch for the years 1966 to 1969 indicates that the species composition is changing in favor of cyprinids and siluroids. The proportion of cichlids in the catch has decreased from slightly more than 80% in 1966 to about 60% in 1969.

Terrestrial Ecosystem

Biosphere. The land mass on both sides of the lake is devoid of vegetation except for a few xerophytes that have started to invade the heads of the khors or the piedmont and peneplain areas of the shore. Insects are abundant close along the shores, but the population rapidly decreases toward the desert areas. Resident and migratory birds, including egrets and pelicans, roost near the shores, and some subsist on fish and aquatic organisms. The migratory birds increase in number during the winter season and decrease in the summer. Toads are abundant in shallow waters and along the shore.

A few rodents occur in the adjacent desert. Of these, the desert rat (*Gerbilus gerbilus*) is the most common; they are most abundant in the interfluves and alluvial fans near the shore where they feed on the perennial vegetation that includes the following genera: *Aristida, Cenchrus, Cressa, Salsola*, and *Tamrix.* Some lizards and snakes sparsely populate a few of the habitats, particularly sandy dunes and slopes, and feed on microphytes and on insects that appear at dusk to dawn. The microphytes develop in the crevices of rocks and between sand particles and depend on the fall of dew during the autumn, winter, and spring seasons.

Gazelles are found, often in pairs, mostly at the heads of khors. Jackal and hyena are also present along with wildcat. Domesticated animals, especially goats, live with men in a few locations such as Aswan, Abu Simbel, and El Sibu, which are important archaeological centers. The sparse vegetation along the shore and in the desert does not support cattle, sheep, or goats.

RESERVOIR IN RELATION TO MAN

Fisheries

Production. The amount of fish landed from the lake at Aswan during the past 4 years has grown from 762 metric tons in 1966 to 4671 metric tons in 1969 (Table 1). Projections of these data suggest that the catch will increase for some years to come.

Fishing gear. The four types of fishing gear used on Lake Nasser are floating gill nets, trammel nets, sunken gill nets, and beach seines. Floating gill nets and trammel nets are used most frequently. The prevalent mesh size is between 3.5- and 5-cm-square mesh. Each net is about 30 meters long and 1.5–2 meters deep; usually several such nets are fished in a gang. Gill nets are typically set overnight, and the catch is gutted and salted. The predominant fish caught in gill nets are *Alestes* spp. and *Hydrocynus* spp.

Each trammel net is 30 meters long and 1.5 meters deep. The outside walls have a 30- to 40-cm-square mesh, and the inside wall has an 8- to 10-cm-square mesh. The fish caught are *Tilapia*, carp (Cyprinidae), and Nile perch (*Lates niloticus*). The catch in trammel nets is delivered as fresh fish.

Sunken gill nets are used on a semipermanent

TABLE 1. Landings of Fresh and Salted Fish at Aswan

Year	Fresh Fish Landed, metric tons	Salted Fish Landed,* metric tons	Total Landed as Fresh Fish, metric tons
1966	344.0	440.3	764.3
1967	789.3	633.1	1422.4
1968	1156.8	1162.9	2319.7
1969	2705.5	1838.9	4544.4

*These values are given in terms of fresh weight.

basis. Each has a length of 250 meters, depth of 3 meters, and mesh from 13 to 18 cm. The species usually caught are carp, catfish (siluroids), and Nile perch; these are delivered fresh. Beach seines are occasionally used during the daytime, but the catches are small.

Tests with floating gill nets 30 meters long and 3 meters deep with mesh sizes of 3, 5, 7, 10, 13, 16, 19, and 21 cm each showed that nets were most efficient at 7 cm for *Hydrocynus* whereas 10-cm mesh was most effective for *Lates* and *Tetraodon*. The fisherman's average catch per hour per net is 387 grams, whereas the project nets using 7-cm mesh gave an average of 1002 g/hr. The tilapias were caught least efficiently by small mesh sizes and best by 21-cm mesh. These fish were being underexploited by the mesh sizes used by fishermen.

Boats. The boats most commonly used by fishermen on the northern half of Lake Nasser are flat-bottomed, canoe-type Alexandrian wooden boats. As most of the fishing is carried out in the khors, these boats are safe enough, and repairs need to be made only infrequently. In the southern half of the lake, traditional Nile River boats of round bilge construction are used. These are heavy and beamy for their length and are hard to propel. They are operated in open waters, wind permitting. When the wind blows hard, the high freeboard and blunt bow make it impossible to row these craft. Consequently, much fishing time is lost. Each such boat costs about US$215. Both types of boats are constructed in Aswan, and the Alexandria type is becoming increasingly popular since the average cost for one is about US$135. The number of boats registered on Lake Nasser up to March 1969 was 1086, of which 984 were in use for fishing.

In 1970 a boatyard was being built to make ferrocement boats of 7.5 and 10 meters in size. These boats are expected to be relatively inexpensive and useful for deepwater fishing.

Under a project of the Food and Agriculture Organization (FAO), Freedom from Hunger Campaign (FFHC), motorization of boats with 15-hp outboard engines began in 1970. A few of the boats immediately became engaged in collecting fresh fish from fishermen in the khors and delivering them to the carrier boats. For fishing, other motors have been distributed to enable operation of vessels in the unexploited offshore waters.

Fish collection and transport. The Southern Fishing Company and the Fishermen's Cooperative Society together own 32 carrier boats with the following capacities: two 50-ton boats, four 10- to 12- ton boats, six 6- to 8-ton boats, and twenty 3- to 4-ton boats. These carriers are used to transport fresh and salted fish from about 132 fishing bases in seven established fishing zones of Lake Nasser. The two 50-ton boats have mechanical refrigeration, whereas all the others use ice to hold the fish during transportation. In March of 1970, for example, these boats moved 650 metric tons of fresh fish and 393.5 metric tons of salted fish in tins. The salted fish did not require cooling during shipment. This fleet, well-scheduled, is foreseen as being adequate to service the fishery, including its projected growth, for yet a few years.

Ice for fish transport and holding has been short in supply during summer months. Difficulties are overcome by importing ice from Cairo. However, the purchase price of ice in Aswan is US$25.30 per metric ton, and in Cairo it is US$29.90 per metric ton. To reduce the cost of ice and ensure its ready availability, a 25-ton capacity block ice plant is required, costing US$64,400. Such a plant could reduce the price of ice at Aswan to US$11.50 per metric ton and would be amortized in 5 years.

Marketing of fish. The commercial catch of Lake Nasser is landed entirely in a fish harbor near the west end of the High Dam. The fish are unloaded from the holds of the transport boats in 15- to 20-kg baskets onto an old houseboat approximately 35 meters long and 5 meters wide. Here they are classified by species, weighed, and packed in wooden crates of 25-kg capacity. This handling has involved some spoilage. To speed up the handling process, five floating piers with belt conveyors and weighing shacks have been planned. This arrangement would also reduce time lost by transport boats and would cut down labor costs.

The wooden boxes filled with iced fish are stacked on top of each other in high piles on trucks for transport. The boxes are reiced at the marketing center before being transported in railroad cars to Cairo. Sometimes, fish are frozen and held for later transport. Plans have been advanced to substitute plastic or aluminum boxes to reduce spoilage and to facilitate iced rail transport. Regular scheduling of rail transport has also been recognized as a requisite of successful marketing of fish products of good quality.

Only a small part of the catch from Lake Nasser is consumed in Aswan; most is transported to Cairo and other towns in Lower Egypt. There is substantial unsatisfied demand for fresh fish in Cairo as there is in other parts of Egypt.

Trade of salted fish is in the hands of a few wholesalers who control prices paid to the fishermen. It has been suggested that, were the official Fish Marketing Company to take over the salted fish marketing system, a more favorable price would be enjoyed by the producers. Salted fish benefit from repackaging in insect-proof containers to prolong shelf life. A growing practice of inspection of fresh and salted fish products, along with sanitary and health inspection of the stores and licensed vendors, is foreseen as a means of improving and maintaining quality.

The market for fresh and salted fish in Cairo is unsaturated. Opportunity exists for systematizing distribution of fishery products in the city to facilitate convenient access by consumers. A survey of demand and of distribution requirements has been considered.

Fish processing. The wet salting of fish (mostly *Alestes, Hydrocynus, Labeo,* and *Schilbe*) is the most common practice of fish processing. It is also a very simple and primitive process. The fish are gutted, and salt is sprinkled inside and outside the fish. They are kept under cloth for curing for 3–7 days and then are packed into tins, each with a 20-kg capacity, for further curing and transport.

Salted fish contain about 50% water. According to the consumers' taste, the salted fish are graded in 10 subjective quality grades ranging from excellent to unacceptable. The basis of grading is color, smell, texture, flavor, insect damage, and acceptability by the consumer. In one study, samples drawn at random were regraded from the stocks of various species held by retailers. In general, the study graders were more perceptive of quality than those who had graded the fish in the market.

Fishermen. The number of fishermen registered with the Fishermen's Cooperative Society at the beginning of 1970 was 940. A lakewide census of 153 fishing bases indicated that 3441 fishermen were fishing. The average age of fishermen sampled was 35 years, and 79% were married. Literacy was low at 17%.

The fishermen of the northern part of the lake have largely migrated from the Sohag governorate. In the southern part, fishermen and hired laborers are from the Quena governorate. In the latter region a few large owners of several boats each control a substantial labor force that is feudal in character. The Gohena fishermen from Sohag generally have collective boat ownership, and their work is organized on a joint family and cooperative pattern. About 60% of the fishermen are of peasant origin and still own farmland. About 44% of the present population of fishermen on Lake Nasser have been engaged in fishing for >20 years.

The immigrant fishermen moved to the lake with a profit motive, and the big boat owners did very well. Most of the leaders of fishermen have succeeded in becoming boat owners, which number about 1000 on the lake. These owners usually are among the oldest and are capable, respected, and trustworthy. They are the representatives of the fishermen at each base.

More than two-thirds of the fishermen do not own boats or fishing gear. In spite of this fact and the hard living conditions in a hot climate, the fishermen would rather fish on the lake than work as farm laborers or till their meager fragmented lands in their home villages.

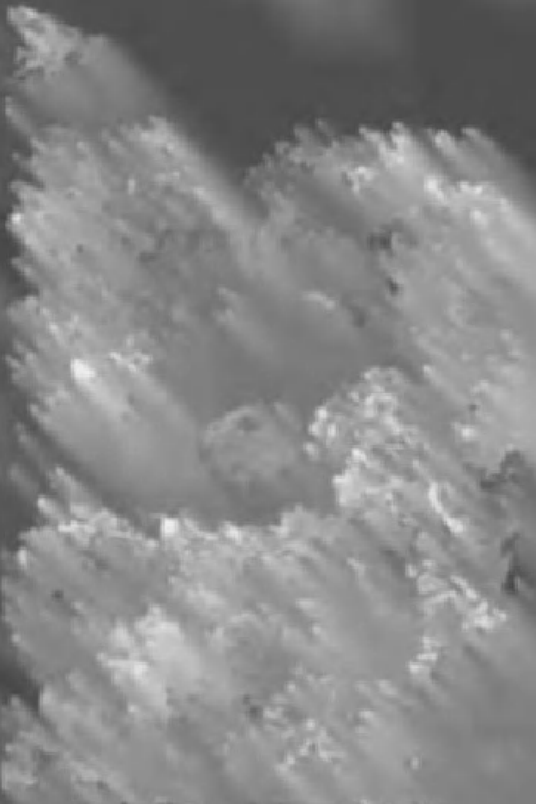
Resettlement of fishermen. At least 70% of the fishermen (married as well as bachelors) are willing to resettle around the lake. They would prefer to settle in the village made up of the groups from the same fishing ground. The majority of them would prefer to settle in large villages of a concentrated type with platform or one-floor houses joined to each other.

In consideration of the position of fishing bases in various zones, demographic features, and financial implications, plans have been advanced to set up 10 villages, each consisting of 300 houses for about 1500 people as a beginning. The first settlements have been suggested for the southern half of the lake. The first settlement will

[illegible]

[illegible]

[illegible]



[illegible]

the naturally available levels of nitrogen was shown in growth and development of fruits in the watermelon and sorghum crops.

Other studies in 1970 have included a cost analysis of cultivation of the foregoing crops, a survey of agricultural practices in vogue by the Nubian riverine population prior to flooding by the reservoir, and a determination of the consumptive need for water for a proposed 40-ha farm at Abu Simbel.

Public Health

Insect vectors. Two genera and six species of mosquitoes are common in the lake region and downstream: *Anopheles pharoensis, A. multicolor, A. coustani, Culex pipiens, C. univittatus,* and *C. theilesi.* In addition, there are the rarely encountered species of *Theobaldia* and *Aedes caspius.* In 1942, *Anopheles gambiae* invaded Egypt and caused a hundred thousand deaths. Of the mosquitoes now present, greatest concern exists over *Anopheles pharoensis, Culex pipiens,* and *C. univittatus.* Of these, the culicine species do not carry malaria gametocytes. They usually breed in unprotected cesspools, cesspits, and heavily polluted waters of the existing sewage system in Aswan and Abu Simbel.

Phlebotomus papatasii, a sand fly, breeds in the lake region. During 1968–1970, *Sergentomyia shewitzi* and *S. tiberiadis* were not observed, nor were sand flies of the *P. major* group (vectors of visceral leishmaniasis in the eastern Mediterranean) or *P. orientalis* (leishmaniasis vector in the Sudan). As was suggested by the World Health Organization (WHO), search for the *P. major* group was planned in outdoor surveys rather than in the system of indoor surveys that had been used. Preliminary observations by the WHO project epidemiologist did not disclose leishmaniasis in the area.

The vector of river blindness (onchocerciasis) is a blackfly, *Simulium damnosum.* So far (1970), this insect vector is absent, but it has been suggested that search for adults be undertaken below the old Aswan Dam where there are rocky rapids suitable for breeding.

Houseflies, *Musca domestica vicina* and *M. sorbens,* are abundant in the Aswan area because of the character of environmental sanitation. Chironomid midge flies breed in great abundance throughout the lake, and their larvae are extensively used as food by many fish.

Surveys. For vector surveys the lake and Aswan region and the suburbs have been divided into three sectors: sector 1 comprises Lake Nasser, sector 2 comprises the High Dam–Aswan Dam tract, and sector 3 comprises Aswan Dam to Aswan and its suburbs along the river. Furthermore, sectors 2 and 3 have been subdivided into 16 survey units. Sector 1 has been surveyed intensively once every 3 months, but sectors 2 and 3 have been surveyed monthly for anophelines, culicines, *Simulium damnosum,* and sand flies.

During the years 1967–1970 the number of houses surveyed for anophelines (the number of houses that were positive for adults of *A. pharoensis* are in parenthesis) were 4500 (1), 5950 (5), 9774 (36), and 4812 (2). The number of mosquito larvae examinations in the years 1967–1970 were 15,600, 19,500, 25,181, and 21,054, respectively. Of these numbers, larvae of *A. pharoensis* were found in only 13, 40, 60, and 37 examinations, respectively, for each year. However, in the Lake Nasser region, *A. pharoensis* was not found to be breeding during the period 1967–1970.

Of the culicines, the density of *Culex pipiens* was highest in all 4 years, particularly at Aswan, Abu Simbel, El Sibu on the lake, and at downstream areas. The density of *C. univittatus* was relatively low in comparison with that of *C. pipiens.* The number of rooms searched, respectively, in the years 1967–1970 in sectors 2 and 3 were 547, 4027, 3717, and 1936; the number of rooms positive for sand fly were, respectively, 68, 178, 182, and 83. The number of adults ranged from 6 to 12 per positive room control.

A mixture of 3% technical DDT plus 0.5% lindane in diesel oil has been sprayed for control at all potential and actual anopheline breeding habitats in the lake: High Dam, Aswan Dam, and other reaches of the Nile River and the river islands. All ships arriving from Sudan are similarly sprayed, but 0.1% pyrethrum is added to the spray mixture. Aircraft arriving from the Sudan are sprayed with pyrethrum (aerosol bombs) by the quarantine section hopefully to prevent the introduction of *Anopheles gambiae, Aedes aegypti,* or other insect pests. In the month of March a survey was made of the *A. gambiae* zone from Abu Fatma, 450 km from Adindan, the last outpost on the Egypto-Sudanese border. *A. gambiae* larvae were collected up to Dal, but, from Dal to Adindan, a distance of some 100 km, neither larvae nor adults could be found even in suitable breeding habitats. Similar surveys are projected for 6-month intervals to check on *A. gambiae* in the current malaria-free zone.

Public health administration. The control of public health in the Lake Nasser region is exercised by the director general of health services for the Aswan governorate in Aswan. In the town the General Hospital (338 beds), Chest Hospital (120 beds), and Eye Hospital (50 beds) serve the population of about 160,000. The General Hospital has 18 specialists; a blood bank; a combined laboratory of biochemistry, hematology, and bacteriology; a chemical laboratory for water and food analysis; and a physiotherapy department. The fishermen on the lake and residents of High Dam as well as the harbor area get their medical treatment here. In 1970, all the fishermen were immunized against cholera. There is a small hospital with 30 beds at Abu Simbel with a medical officer in charge of it. To facilitate medical treatment, a floating hospital has been suggested for the lake along with the establishment of health centers in the new villages proposed for fishermen and an improvement of the facilities at Abu Simbel.

Epidemiology. The incidence of a wide variety of diseases has been studied among the fishermen. The diseases include malaria, schistosomiasis, onchocerciasis, Bancroftian filariasis, ankylostomiasis, salmonellosis, shigeliasis, amoebiasis, leishmaniasis, leptospirosis, arbor viruses, guinea worm, sleeping sickness, infective hepatitis, nutritional deficiency diseases, allergic manifestations, and skin diseases. Of these the most important ones are schistosomiasis, malaria, and ankylostomiasis.

In a sample of 185 fishermen and 32 laborers, 39 cases of urinary bilharziasis were recorded in a lake-wide trip in March 1970. In April, on another trip, 16 cases suffering from the disease were observed from High Dam to Kalabsha. In an elementary school, among 312 children, 61 boys and 16 girls had the disease. In General Hospital in Aswan, 18 out of 40 fishermen examined had urinary schistosomiasis. The overall average incidence of infection for all the cases was 23%. The vector of this disease in the lake is a snail, *Bulinus truncatus*, the population of which at some loci was found to be as high as 500 per square meter and to be highly infected. In the lake-wide survey the infection rate of ankylostomiasis in a sample of 217 was found to be 23%.

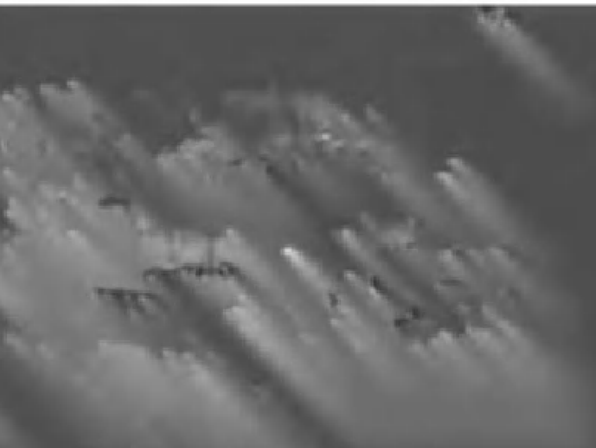
No cases of malaria or filariasis were recorded in the surveys of fishermen. However, blood samples are examined for detection of active malaria in laborers of the Aswan and High Dam area. Passive case detection is conducted by the health department of the Aswan governorate, mainly from fever cases. These measures are viewed as adequate protection against infiltration of malaria carriers from the Sudan. Only one out of 217 persons was suffering from the cyst stage of *Endamoeba histolytica* infection.

Several of the fishermen surveyed were suffering from nutritional disorders and anemia. A high frequency of avitaminosis was observed among fishermen. The most common communicable diseases in the Aswan governorate are typhoid, infective hepatitis, dysentery of various kinds, and occasionally a few cases of cerebrospinal meningitis. A few suspected cases of cholera were reported, but mass prophylactic measures were immediately adopted. Immunization operations undertaken in Aswan and in the lake region include those for typhoid, diptheria, polio, and cholera.

Blood sample examinations of 17 samples from various areas in and near Aswan by Dr. L. H. Turner (School of Tropical Medicine, London) from the rodent *R. rattus* were negative for the *Leptospirosis* antigen. The search was negative for nodules indicating the presence of river blindness in native fishermen living below Aswan Dam. Although Bancroftian filariasis is found in the native villages of fishermen who had migrated to the lake from the Sohag and Qena governorates, none was detected in the immigrants studied.

Environmental sanitation. A survey of environmental sanitation was carried out at places of tourist interest, at fishing camps, and in Aswan and its suburbs. The important tourist attractions in Aswan and the nearby lake region are the Nile River panorama extending from Aswan Dam to the end of the town, the High Dam, the unfinished obelisk, the botanical garden, Elephantine Island, the Agha Khan mausoleum, the Coptic monasteries, the Tombs of the Nobles, and the Nubian villages on the west bank of the river. Southward along the lake lie the lake temples of Kalabsha, Philae, El Sibu, and Abu Simbel. At Aswan the construction of the splendid Kornish El Nil is nearing completion. Opportunities for further improvement of sanitation and/or environmental quality have been iden-

[illegible]



[illegible]

for fishing ports and their portable refrigerated fish storage equipment.

Tourism

The development possibilities for tourism at Aswan, Lake Nasser, and Abu Simbel were studied by the project. This area has long been attractive to tourists for short stays and visits. Quick and comfortable means of transportation were identified as being essential for future development of tourism at Abu Simbel. It was found to be feasible to introduce air travel between Aswan and Abu Simbel. The regular Cairo-Khartoum and return flight could have a stop at Aswan to favor tourism.

It was foreseen that the hotel zone in Aswan, consisting of the new and old cataract, the Kalabsha, and the Nile City hotels, might offer an opportunity for tourist attractions and amenities by the creation of public gardens and parks, outdoor dining facilities, and a museum and showplace for Nubian culture and customs. Modern means of publicity hold promise for the expansion of the tourist industry. One of the tourist attractions in the vicinity of both the High Dam and Abu Simbel was seen as sport fishing for the Nile perch and other predatory fish of which good populations have been shown to exist in the lake. Additions to comfort, recreational and entertainment facilities, and personal services at the hotels were concluded to be worthy of careful consideration. It was suggested that the development of tourism be carried out in the regional planning of Aswan and that a separate administrative unit be added for this purpose. Such a unit could greatly help to meet emerging interests in water contact and water surface sports.

MANAGEMENT FOR MULTIPLE USE

Theoretical economic analysis of preinvestment for development of resources. With a view to appraise preinvestment results of the UNSF/FAO Lake Nasser Development Center Project in the fields of fisheries, agriculture, public health, afforestation, wildlife conservation, navigation, tourism, animal health, resettlement of fishermen and farmers, hydrogeology, meteorology, and aquatic weeds, benefit-cost ratios and internal rates of return were calculated. This effort was based on certain assumptions of likely returns from preinvestments in the several fields in the project. The benefits of the preinvestment here correspond to the amount of money that one would be willing to pay if he were given the market choice of the purchase of technology to exploit the resources in a planned manner. The three types of benefits recognized are direct benefits, indirect benefits, and intangible benefits.

This analysis showed that the tangible benefits gained by the preinvestments are most likely to accrue in the enterprises of improved methods of fishing, improved fish marketing and processing, fish catch and stock assessment, survey of lands and adoption of cropping patterns, control of bilharzia and anophelines and improved medical facilities, promotion of tourism, control of diseases of animals, and resettlement of fishermen and farmers. Intangible benefits would accrue from preinvestment in navigation, meteorology, hydrogeology, fishery biology and limnology, afforestation, and wildlife conservation. The internal rate of return was estimated at 14%, and the benefit-cost ratio was estimated at about 6.5% of the total preinvestment in the project. Preparation of investment projects in these fields is being planned.

Economic analysis for preinvestment projects. Two preinvestment projects that have been developed are the 'housing project for resettlement of fishermen in the Lake Nasser region' and the 'project for icing, holding, handling and transport of the Lake Nasser commerical fish catch.' Benefit-cost ratios and internal rates of return were calculated for these projects.

For the housing project it is estimated that the orderly setting up of villages and the shifting of households from native villages and setting them in new villages would result in a savings of US$10 per year per household extending over a period of 10 years. On this basis the benefit-cost ratio of 4 on the preinvestment cost of settling 3000 households of fishermen was judged to be quite worthwhile. The internal rate of return was calculated to be >30%.

For the project of collection and transport of fish on the lake a benefit-cost ratio of 0.9 was derived. The internal rate of return, calculated on the basis of 2.5% annual benefit credited for a period of 10 years, on the preinvestment was 12.5%. The benefit-cost ratio indicates fair return, and the internal rate of return on the preinvestment in the project is very good.

Acknowledgments. The author takes this opportunity to record his thanks to the government of Egypt, United Nations Development Program and Special

Fund, and the Food and Agriculture Organization of the United Nations for enabling him to give summaries of the various surveys, investigations, and development studies. He also expresses his gratitude to all of the many national and international staff members who were very kind in providing the required information for the preparation of this manuscript.

Editor's note. This paper was prepared in the very early stages of the Lake Nasser Development Center Project, which is a joint project of the Government of Egypt and the United Nations Development Program, the project being executed by FAO. Although the paper represents fairly the state of knowledge of the reservoir and its development problems and opportunities at the time that it was written, subsequent studies have indicated that much of the early information is now changed under present conditions. As the reservoir has continued to fill, limnological and biological conditions have changed, and social and economic conditions have been affected as a result. It is necessary to emphasize to the reader, therefore, that this paper is a description of Lake Nasser as it was known in 1970 and that conditions in the reservoir make it necessary to consult later publications for a current account.

Effect of the Rybinsk Reservoir on the Surrounding Area

N. V. Butorin, S. L. Vendrov, K. N. Dyakonov,
A. Yu. Reteyum, and V. I. Romanenko
Institute of Inland Waters Biology and Institute of Geography, Academy of Sciences
Moscow, USSR

The Rybinsk Reservoir, created in 1941 on the Upper Volga, is the oldest artificial lake of such dimensions in the USSR; thus it has been quite well studied in all respects. In the present paper an attempt is made to generalize the information accumulated about the reservoir itself and its effect on the environment. The number of problems involved in the survey, or deserving mention, is so great that they can only be compressed with difficulty within the framework of a communication that is, of necessity, a summary.

The huge reservoir is located on an almost unbroken plain covered mainly by forests or farmlands on podsol soils that have evolved on sands and loams. One-tenth of the shore is a reserve. The regime of the reservoir and of certain land ecosystems associated with it is determined by the functioning of the Rybinsk hydrotechnical complex, which, because of the large usable volume of the basin (16.7 km^3, or half the annual flow of the Volga), makes possible all types of regulation of the flow of the river.

The area of the reservoir when it is filled to the designed level is 4550 km^2, and its volume is a little more than 25 km^3, the average depth being 5.6 meters. The main role in the water balance is played by the influx of river water (95% of the inflow) and the outflow through the dam (90% of the expenditure). The level of the reservoir undergoes complex changes; the amplitude of the seasonal variation over many years is between 1.0 and 1.5 meters, the amplitude of the annual variation is between 3 and 5 meters, and, finally, during every hot spell the level may drop by 1 or 2 meters. The level may often be changed by the wind, and distortion of the water surface by 40 or 50 cm has been noted.

The mass of the lake is formed in conditions of slow exchange (water mixes from three main feeders, the Volga, Mologa, and Shexna) and the complex relief of the bottom. A distinctive feature of the distribution of all the characteristics of the water basin is their lack of uniformity and sometimes their sharp differences. The waters of the three rivers feeding the reservoir retain their own features for a long time and differ in the whole set of indices of temperature, transparency, color, conductivity, chemical composition, plankton, and so on. In the central part of the reservoir the transformation is complete, and a water mass is formed there with different special qualities.

The reservoir has its own very complex system of currents. In winter, there is weak movement, traceable only along the flooded riverbeds. In spring, currents also mainly originate from river flows but are faster (upward of 1.0 m/sec, even in the lower reaches). In summer and autumn, drift currents formed by the wind prevail in the whole reservoir except for the part along the dam. With a wind speed of around 5 m/sec the speed of the current is 2% of that of the air; when wind speed is doubled, the ratio falls to 0.01 because of the friction of the bottom.

The ordinary state of the water surface is one of agitation, which is due, in particular, to the fact that the wind speed rises higher on the Rybinsk Reservoir than on deeper reservoirs owing to the raised temperature of the water. With a wind speed of 10 m/sec, waves of 1% frequency have a height of 60–100 cm; with a wind speed of 20 m/sec (seldom encountered), waves of the same frequency rise to between 100 and 200 cm.

The waters of the lake are hydrocarbonate and of low salinity. Their hardness varies from 1–2 to 3–5 mg equivalent per liter and increases from spring to winter. They are strongly colored; their intensity on the Cr-Co scale is as high as 80°–

100°, and the average value is between 30° and 60°. Transparency varies between 0.8 and 2.7 meters, and the characteristic value is 1.0–1.2 meters. Color falls very considerably during movement toward the dam, and transparency increases. A nearly permanent deficiency of oxygen is characteristic of the reservoir.

The solid content of the water, the source for the formation of silt, reaches its maximum in the autumn when its weight is 4–5 mg/l and is sometimes as high as 8–15 mg/l as a result of suspensions from the bottom of shallow areas. In winter the concentration of solids falls to 1–2 mg/l. The average annual accumulation of sediment is estimated at 2.6 million metric tons dry weight. The thickness of deposits (sands and silt) varies over the basin from a few millimeters to 1 meter or more. A large area of the bottom, however, is still almost unsilted.

From the end of October or the beginning of December to the end of April or the beginning of May the lake is covered with a thick layer of ice. In the spring thaw the ice melts very quickly, and by the end of May the heat content of the water has risen to 5.5 cal/cm², and its temperature has risen to 8° or 10°C. During this time, large vertical and horizontal temperature gradients arise and reach 8°–12°C. Heat exchange with the water in May absorbs 60% of the radiation balance; the remainder of the solar energy does not cover the evaporation loss, so part of the heat (0.7 cal/cm²) is taken from the air.

In June the reservoir warms up sufficiently to begin giving up heat. In summer the temperature field of the water is relatively uniform. The average temperature in July and August is 17°–19°C, and the maximum is 21°–27°C. In the autumn the homothermal regime is disrupted. In the summer and autumn months, evaporation is the main item on the expenditure side of the heat balance; the ratio of expenditure of energy on evaporation to the total of absorbed radiation rises from 0.4 to 0.8 or 0.9 from June to October, whereas the ratio to the total net radiation rises from 0.5 to 4 or 5. In all, 60 cal/cm² are expended on the various processes in the reservoir itself and in the surface layer of air during the hot season of the year. About 45% of this amount goes for evaporation, and around 37% goes for irradiation of the water.

The primary production of organic matter of autochthonous origin in the Rybinsk Reservoir comes from the activity of phytoplankton. Higher aquatic vegetation, because of the unfavorable conditions, occupies only around 1% of the area of the water basin and on the whole plays a small role in the biotic balance.

Numerically, blue green algae predominate (primarily, *Aphanizo* and *Microcystis*, which account for 70–90% of the total of phytoplankton), but they are outweighted in the biomass by diatoms (*Melosira, Asterionella,* and so on). The development of algae and the gradual increase in primary production of organic matter begin after the breaking up of the ice at the end of April and beginning of May, reach a maximum between the end of June and the beginning of August, and coincide with the intense development of blue green algae. The number and composition of algae vary essentially from place to place, but vertically the distribution of algae is nearly uniform because of the almost constant mixing of the water by the wind.

The thickness of the photosynthesizing layer in the lake is between 1 and 2 meters. From observations over many years, gross production of primary products during the vegetation period has been determined at 325,000 metric tons of carbon (or 76 g/m² of water). In separate years the quantity of matter (in terms of carbon) rises to 100–110 g/m². In unfavorable conditions it may be several times less. Phytoplankton use only 0.1% of the solar energy available.

The destruction of organic matter takes place more rapidly than its formation. Equilibrium between the rates of the two processes is achieved in summer at 1.5–2.0 meters below the surface. The total quantity of matter annually undergoing decay is 50–100% more than the production of photosynthesis. Thus there is a considerable inflow of organic matter into the lake in a suspended and dissolved state.

Bacterial plankton, which have an important function in the ecosystem, have an average concentration in the hot season of 1.4 million cells per cubic milliliter and produce 20–30 g C/m². The total number of bacteria in the various sectors of the reservoir is characteristically uniform, whereas that of saprophytes (on a meat-peptone agar medium) is uneven. In the central, cleanest parts of the reservoir, the number of saprophytes does not exceed 200 cells per milliliter and is usually less. At the mouths of rivers, their number is several hundred times higher, and, in places where sewage enters, it is 10,000 or 100,000 times as high. *B. coli* average 10–20 per milliliter in the center of the reservoir and often as few as 1-5. According to the aggregate of its microbiological indices the Rybinsk Reservoir is a clean one; pollution is only local.

The bacterial population of the soil plays a nearly equal role with bacterioplankton in the breakdown of organic matter. The products of the chemosynthesizing microorganisms in the silt are around one-hundredth of those of algae.

The zooplankton of the Rybinsk Reservoir vary sharply in time and space. The number of organisms in a unit volume varies in different months and in different parts of the water basin by a factor of tenths. In the hot season, Cladocera (*Daphnia* and *Bosmina*) predominate; in cold weather, as a rule, Copepoda predominate. In the annual dynamics of the biomass of zooplankton, two maxima (in June and August–September) and two minima (in winter and in the middle of summer) are noted. At times of maximum development the weight of organisms per liter may reach 1 or 2 mg. The richest population is that feeding on macrophytes in bays and at the mouths of rivers.

The community of bottom organisms has not yet been completely formed. The continuing changes in the soils give rise to a succession in the animal population. The biomass of benthos is very differentiated. In the open parts of the reservoir it is measured in hundredths and tenths of a gram per square meter; at the same time it may be 10–20 g/m^2 and even as high as 40 g/m^2 on flooded water meadows and in the silt of sheltered shallows. Species of Chironomidae and Oligochaeta predominate in the bottom fauna.

Nekton are represented by 30 or so species of fish. The lack of food and irregular level of the reservoir and the worsening conditions for reproduction have reduced the numbers of most fish species and slowed their development. The total productivity of the reservoir does not exceed 7–9 kg/ha (varying in sectors from 2–3 to 34–45 kg/ha). The most important commercial fish are bream, *Abramis brama* (nearly 30% of the total catch), followed by roach, pike perch, *A. ballerus*, and pike. The annual catch per square meter of the reservoir is around 0.5 cal, which is only 0.06% of the primary products. In fact the coefficient of use of the activity of the ecosystem is even lower, since a considerable number of allochtonic organic substances enter into the food chain.

Not only is the reservoir affected by the environment, but also it exerts an active reciprocal effect both directly through the movements of the water mass and indirectly through the air and groundwaters. An important factor in the dynamics of the banks is temporary flooding. The great amplitude of variation of water level from year to year, and within the year, in the conditions of a shallow lake makes for wide distribution of extremely unstable ecosystems. The area of sectors annually under water during the vegetation period alone is measured in hundreds of square kilometers. In zones of temporary flooding the stands of trees have almost completely perished; only single specimens of young pines survive. The grass cover is very patchy; the communities are marked by strongly altered structure and productivity and as such are not found in natural conditions; and the species growing together are differentiated according to their ecological requirements into mesophytes, hygrophytes, and hydrophytes. These ecosystems occupy most of the shore zone. The fauna of temporarily flooded sectors also depends on the variation of level. The regime of the level determines the community of invertebrates and to a great extent the numbers of small mammals and ducks and the distribution of larger mammals.

Abrasion has not widely affected the Rybinsk Reservoir. The length of banks subject to erosion is around 150 km (<10% of the shoreline). The undermining of banks usually occurs in years of full water. The variation in level causes an increase in the volume of rock eroded by waves and significantly protracts the period of reaching dynamic equilibrium. The tempo of abrasion is quite high; generally, the beach shelves are stepped back for 30–50 meters and on capes for >150 meters. No marked reduction of the rate of blending of the shoreline has occurred in recent years. The beaches, spits, and sandbanks are almost deprived of life.

In exchanging masses of air with the surrounding land, the reservoir has affected the climate. The basic cause of this effect is the special character of the radiation and heat balance of the reservoir. The properties of the local climate of the shore are basically directly determined by the sign and value of heat exchange between the water surface and the atmosphere.

The proximity of an extensive water basin is naturally reflected in the wind regime of the districts around it. There is a clearly expressed seasonal and daily disparity in wind speeds near the reservoir and away from it (Δv). In spring the cold reservoir has a weak effect on wind speed along the shore: by day, Δv is usually close to 0, and at night it is 0.1–0.4 m/sec. (The facts given here and below relate to the kilometer strip nearest to the water. Further away, the change falls proportionally with the logarithm of the distance. The outer boundary of the zone in which the effect of the reservoir is felt extends from 2 or 4 km to 10 or 15 km.)

In summer and autumn the wind from the lake is stronger, especially at night (the monthly average for Δv is as high as 1–3 m/sec). As a result the daily difference in wind speed is smoothed out. The winds along the shore undergo periodic change of direction, as shown by the development of breezes. The direction of moderate and strong winds around the reservoir is also variable depending on the local barometric gradient, the swirling of the wind over the water mirror, and the tendency of air masses to move along the shore.

In accordance with the rate of turbulent heat exchange between the water surface and atmosphere, there is an alternation of the cooling effect of the reservoir on the layer of air over the land along the shore as a whole during the day in August and September, during the night in May, and at midday in June. In definite sectors the thermal influence of the reservoir has certain features caused by the orientation of the shore. In spring the lake most strongly lowers air temperatures over shores open to southerly winds and in autumn raises them over shores facing north winds. The temperature difference between the affected zones and the surrounding land may be 2°–3.5°C (from the monthly average). The heat regime of the shore, especially in the south, has several positive features: the total of active temperatures is raised by 4–7%, and frosts end 2–10 days earlier on the average in spring and begin 4–15 days later in the affected zones than in the surrounding area.

Evaporation from the reservoir increases the pressure of the water vapor over the adjacent land by a quantity usually measured in tenths of a millibar; but in the middle of summer this quantity can be measured by 1 or 2 mb. Relative humidity is low at night but high in the daytime (as a rule the difference does not exceed 5%).

The effect of the water surface on the speed of horizontal and vertical movements of the air and on its humidity and temperature is reflected in cloudiness. There is a well-expressed clearing of low clouds in the daytime, the reduction being most marked in the first half of the hot season and varying from 0.5 to 3 or 4. At night, there is a small change; in autumn, cloudiness may increase. In summer and autumn, there is growth and formation of cloud types Cu and Cb at a certain distance from the shoreline, owing to rising currents in the moving air.

As a result of the altered cloudiness in the district of the Rybınsk Reservoir the shores have a special regime of atmospheric humidity. In May and June, after air masses have passed over the water, total precipitation on the exposed shore falls by 15–30% (50 in the daytime); in July and August a slight increase is noted (10–20%), whereas, in September and October, precipitation is sharply activated and rises by 89–120%. The climate around the lake is favorable on the whole for plants, animals, and humans; its negative effect is mainly connected with the strong winds.

Since the creation of the reservoir, there has been a rise in the water table in the surrounding territory, and in parts of the shore a belt of 1 or 2 km wide has been altered by marshes.

The regime of groundwaters on the shore depends on the level of the lake. With the spring rise in level, filtration occurs up to a distance of 200 or 300 meters from the water's edge. The variation in the water table because of the filling and emptying of the lake basin is noticeable in a belt from several hundred meters to 1 or 2 km wide. With this variation, there is an attendant transformation of the chemical composition of the water, in particular its oxygen content, which varies inversely with the level of the water table (and sometimes is reduced to 0).

The disturbance of the natural regime of the groundwaters when the water table falls below 2.5 meters from the land surface causes a transformation on the top soil. In not very wet sectors the change consists of the formation of gley soil in the lower horizons. Moderate wetness is reflected in increased thickness of the accumulated horizon, accumulation of humus, considerable formation of gley soil, and, naturally, an increase in dampness. In very wet sectors, <70 cm above the maximum average level of the reservoir, marshy soils are formed.

The course of soil formation on the shores depends to a considerable extent on the year to year and seasonal variation of the water table. Negative phenomena are much more clearly marked when the water table is high. The alternation of wet and dry years reduces the tempo of marsh formation. The processes of forming a top soil corresponding to the new conditions are still not yet completed.

The changes in groundwaters and soil have affected the succession of plant communities. The formation of marshy soils on low-lying sectors has caused withering of fir trees, has reduced growth by 10–25% in the pines that are the most common forest trees here, and has changed the composition of the soil cover (which is now dominated by mesophytes, hydrophytes, and fen dwellers) and raised its productivity. On more raised sectors, lying at a height of 3.0–3.5 meters above the lake level, the growth of trees has been improved in spite of the development of restorative processes in the soil. The increase in the growth of wood since the creation of the reservoir compared with the preceding period is usually 10–20%; more rarely, where plants had previously suffered considerably from lack of moisture, the increase is 30–50%. In the ecosystems bordering on high bogs (pine woods with sphagnum and hair moss), rise of the water table has sharply activated the bog-forming process, which is expressed in a spread of moss and a reduction of current tree growth by 15–50%. The total area of forest affected by the reservoir is of the order of tens of thousands of hectares.

The variation of the level of the reservoir, reflected in the water table and through it in the soil, affects the vegetation, especially woody plants. A quite close connection exists between annual tree growth and the degree of filling of the reservoir basin during the vegetation period; the connection varies in character in very wet and not so wet localities. In addition, the rate of wear of the runoff prism plays a definite role; in years of rapid fall of the water table the tree rings of pines growing in coastal swamp soil are 10–20% thicker than in years of constant level. Grass communities react to the soil changes by a quantitative rise in the mass of organic matter formed by them, but the quality generally falls in consequence of the changes in the composition of the flora and a growing predominance of perennial grasses.

The changes in habitat are reflected in the fauna. On the marshy sectors of the shore, which provide a good habitat, there is a rise in the population density of terrestrial invertebrates, small mammals, and nesting birds. A radical reconstruction of the soil population occurs. The higher water content of the soil and of the soil air brings about a definite rise in the number of invertebrates. Conditions are particularly favorable in those sectors where the water table is only 1.5 meters below the surface. The number of small animals of these classes (e.g., Nematoda, Oribatei, and Collembola) in the upper horizons of the soil has become higher than before. The total biomass of invertebrates has increased several times over, mainly because of the rise in the number of earthworms and larvae of Diptera. The soil population of boggy areas is poorer than that of the marshy sectors.

The present data available on the processes taking place in the Rybinsk Reservoir and its sphere of influence can serve only as material for future work on drawing up a scheme for optimal regulation of the water flow in the interests of maximum use of natural resources. The choice of one regime of regulation or another must come from a detailed comparison of the scale of the positive and negative phenomena that will occur not only in the reservoir itself and the surrounding area but also in the areas of the other hydrotechnical complexes of the Volga catchment.

The TVA Experience: 1933–1971

REED A. ELLIOT

Water Control Planning, Tennessee Valley Authority
Knoxville, Tennessee 37902

PLANNING THE WATER CONTROL SYSTEM

The Tennessee Valley Authority (TVA) was created as a corporate agency of the federal government by an act of the Congress of the United States nearly 38 years ago. An independent agency, responsible directly to the President, TVA operates with much of the autonomy and flexibility of a private corporation. All powers of the corporation are vested in its three-member board of directors.

The TVA Act passed by Congress clearly defined TVA's responsibility. In the words of the presidential message submitting legislation to establish TVA, this new agency was

> . . . charged with the broadest duty of planning for the proper use, conservation, and development of the natural resources of the Tennessee River drainage basin and its adjoining territory. . . .

The TVA Act directed the agency to provide in this drainage basin the maximum amount of flood control, the maximum development of the Tennessee River for navigation purposes, and the maximum generation of electric power consistent with flood control and navigation.

With the beginning of planning for the development of the water resources of the Tennessee River basin, a new concept of water control was applied: multiple-purpose development for an entire river system. Dams and reservoirs were planned and built not only for the purpose of regulating floodwaters but also to put the river to work to provide navigable waters for modern barges and hydroelectric power. The mountain valleys of the basin's eastern tributaries provide excellent sites for man-made storage reservoirs. Also, the yearly runoff cycle is favorable for combining these several functions. These influences combined to make possible a multiple-purpose development on a scale never previously attempted.

THE VALLEY

The Tennessee Valley and its environs comprise an area of about 208,000 km^2 (80,000 mi^2), roughly the size of England and Scotland together. About half of this area constitutes the watershed of the 1050-km-long (650-mile-long) Tennessee River, one of the major waterways in the United States. Portions of seven states (Virginia, North Carolina, Georgia, Tennessee, Alabama, Mississippi, and Kentucky) lie within the boundaries of the Tennessee River's drainage basin. This basin is a watershed of contrasts. Rugged mountains and green forests dominate the eastern portion of the valley. Rolling hills, open fields, and woodlands lie to the west.

The land resource was underdeveloped and neglected when TVA was founded. Conservation farming was virtually unknown, and the heavy rainfall took a great yearly toll from the eroding soil. Forests had been cut over and burned over, and these activities bared the mountainsides and speeded storm runoff. This combination of resource neglect had contributed materially to widespread poverty in the region, particularly in the rural areas.

Basically, the environment task facing TVA at its inception was to reestablish a shattered and decaying resource base so that it could serve the desperate human needs of those times. The agency has succeeded in large measure. The resource base of the region is largely restored. In this sense the Tennessee Valley is no longer an underdeveloped region of the United States. And on this resource base a vigorous industrial and commercial growth has taken root.

OBJECTIVES AND DECISIONS

Many decisions confronted the TVA board immediately on taking over its responsibilities in

1933. High on the list was the choice of a plan and a method for mobilizing an organization and second was the selection of an engineering plan for an early start on the construction of dams on the Tennessee River.

In beginning its work to rebuild the river, TVA had wide latitude for important decisions; however, it was guided by two instructions in the law. First, a 2.75-meter (9-foot) draft navigable channel had to be provided for the 1050 km (650 miles) from the mouth of the river to Knoxville, the head of navigation. Second, all planning and operation had to give priority to navigation and flood control over all other purposes, including power production.

With the emphasis on navigation a fundamental choice had to be made between a system of numerous, low, single-purpose navigation dams and a smaller number of higher, multiple-purpose dams. Low dams would provide only navigation. Detailed studies of costs and benefits for several variations of low-dam and high-dam schemes revealed that a system of high, multiple-use projects on the main stream offered the most economical solution and much superior facilities for water control. The decision in favor of this type of development of the main stream made possible a fully effective system of projects for flood regulation on the Tennessee River together with material contributions to reduction of flood stages on the lower Ohio and Mississippi rivers.

WATER CONTROL SYSTEM

On the major tributary rivers, storage reservoirs provide seasonal streamflow regulation for flood control and power generation. The Norris project was the first completed some 35 years ago. Other major tributary storage reservoirs include the Cherokee on the Holston River, the Douglas on the French Broad, the Fontana on the Little Tennessee, and the Hiwassee project on the tributary by that name. The Fontana project has the highest dam, reaching about 146 meters (480 feet) above foundation levels. Other lesser tributary projects supplement the control exercised by these reservoirs.

Along the main stem of the Tennessee River, nine dams form the 1050-km (650-mile) water stairway extending from the mouth of the Tennessee to Knoxville. The Fort Loudoun project forms the uppermost step of the stairway bringing navigation to the Knoxville waterfront. Moving downstream, we come to Watts Bar, one of the more scenic reservoirs, and then to Chickamauga near the midpoint of the valley. Below the city of Chattanooga the channel is created by Nickajack, Guntersville, Wheeler, Wilson, Pickwick, and Kentucky dams. Kentucky Lake extends some 293 km (182 miles) across most of the states of Tennessee and Kentucky and provides a total useful storage of about 5×10^9 m^3 (4×10^6 acre-feet). These mainstream reservoirs are created by dams varying in height from the 30.5-meter (100-foot) lift at Wilson to the 12-meter (40-foot) lift at Guntersville. Typically, the structures consist of a spillway flanked by a powerhouse and a navigation lock. With the exception of Kentucky Lake, each reservoir provides only a modest amount of storage capacity equivalent to about 50.8 mm (2 inches) of runoff from the uncontrolled portion of the upstream drainage area.

SYSTEM OPERATION

In accordance with the TVA Act the system is operated '. . . to regulate the streamflow primarily for the purpose of promoting navigation and controlling floods . . . and for power generation . . . so far as may be consistent with such purposes.' The plan of operation, making joint use of storage capacity, is possible because of the nature of the annual rainfall-runoff cycle as revealed by nearly a century of records at some points in the valley. Because major valley-wide flood-producing storms occur between late December and early April, nearly 14.8×10^9 m^3 (12×10^6 acre-feet) of storage space is reserved at the beginning of each year for the regulation of floods, and 11.1×10^9 m^3 (9×10^6 acre-feet) is reserved on April 1. The operating pattern for tributary reservoirs and that for mainstream reservoirs follow the same general scheme. Filling is restricted during the winter and spring months, and then reservoirs are permitted to reach fullest levels during the early summer. Drawdown for power generation and restoration of flood control capability takes place during the summer, fall, and early winter months.

When a reservoir or system is built to serve more than one purpose, the stage is set for possible future conflicts. Operations for power and flood control that require reservoir drawdown usually are incompatible to some degree with recreation. Reservoir fluctuations for mosquito control can be worked into the use of storage for power-peaking operations, but a perfect fit is not to be expected under all circumstances. Since conflicts of use can be expected, it is essential that a sound basis for resolving differences be available.

One obvious basis is the establishment and maintenance of priorities in the plan of system management. This setting of priorities will be necessary in many cases to assure the dependability of the functions provided by the system and the associated economic growth and development. For example, a navigation development must offer long-range dependability if it is to attract shippers and the growth of terminals along the length of its waterways. It must be dependable in terms of depth and fluctuation of water levels. Also, it must be reasonably free of wide variations in streamflow and the corresponding velocity changes. If this dependability is not apparent, growth of the system use cannot take place.

Flood control operation must be dependable for similar reasons. Flood control, often considered important only for the prevention of damage to existing structures, actually is vitally important to future growth. Lands protected from floods, where industries can count on a substantial degree of protection in the long run, can attract much industrial and commercial investment and thus contribute materially to economic development in an underdeveloped area. Essentially, the same need for priorities can be said for other functions built into a water control system. Arrangement must be made therefore to protect system operation against the possibility of whimsical changes that would undercut the primary beneficial results of development.

One universal conflict involves the use of impounded water for flood control and power generation on the one hand and water-based recreation on the other. Recreational interests can tolerate fluctuating water levels if those fluctuations are modest. The larger changes necessary to impound and release water for seasonal regulation are considered incompatible with most recreational uses. In recently conceived multiple-use projects, recreation has been considered in initial planning and the establishment of operating plans. Earlier TVA projects were planned with recreational use strictly as a bonus by-product. Evaluation of future needs will have to recognize all possible uses of existing and future impounded waters and of natural streams.

ENVIRONMENTAL, SOCIAL, AND ECONOMIC CONSIDERATIONS

When a river is turned into a lake, ripples of change spread among living and growing things. To deal with these changes, TVA maintains a staff of ecological scientists at Muscle Shoals, Alabama. They are supported by an environmental research laboratory, where experiments and studies related to water and air quality are carried out.

One of the first environmental challenges that faced TVA involved malaria, the mosquito-borne disease that affected a third of the population near some of the swampy areas along the original Tennessee River. At the time TVA began building dams on the Tennessee, it was known that some earlier man-made lakes had created new mosquito-breeding habitats and had increased the malaria problem, so there was concern that all possible steps be taken to prevent or minimize such a problem.

The program that evolved is based on control of the mosquito vector. Emphasis is placed on providing an ecological environment unsuitable for its propagation. Mosquito control also is integrated with other program needs and is virtually built into the design and operation of the dams and reservoirs.

Prior to impoundage, reservoir basins were cleared of all debris. Drainage ditches were constructed so that no water would be left stranded in pools along the reservoir margin when lakes were drawn down. In instances involving shallow flats where plant life, and hence mosquito production, would be difficult to control, the mosquito-breeding problem was 'built out' by deepening and filling or by diking and dewatering.

The most important postimpoundage measure for the continuing control of mosquitoes on TVA reservoirs is water level management. This control is accomplished at most main river projects by a weekly fluctuation of reservoir levels during the breeding season within a zone of about 0.3 meter (1 foot) and a gradual recession later in the year. Control measures employed by TVA to supplement water level management include drainage maintenance, plant growth control, and larviciding. Collectively, these measures have just about eliminated malaria in the Tennessee Valley.

Another problem area that probably will become more acute is that of low levels of dissolved oxygen in the releases from deep reservoirs. Many deep impoundments, including those of the TVA system, were built without providing ways to withdraw water selectively from the reservoir strata having the higher dissolved oxygen content. The benefits of providing such facilities at a later date will have to be substantial to justify the cost. Other methods (such as upstream dams or barriers of some kind or the introduction of air or oxygen into the reservoir) also would be costly. Eventually, however, the demands may be such as to require that the most feasible methods available be applied in some instances.

One of the major concerns for water quality confronting TVA today is the matter of eutrophication, nutrient enrichment of the water and the bottom of lakes. Although eutrophication as a natural process has been going on for millions of years, the question now is whether man is speeding this process and in so doing speeding the growth of nuisance weeds. TVA is actively pursuing its investigation into the unknowns of nutrient pollution. Watersheds in North Carolina and Georgia are being carefully examined for the runoff of chemical fertilizers to the streams through both groundwater and silt carried off by rainwater.

The greatest weed nuisance in TVA lakes is Eurasian water milfoil, a lacy water plant sometimes used to adorn fishbowls or aquariums. It grows so dense that it clogs coves and blocks boating and swimming. It chokes water intakes and creates an ideal breeding place for mosquitoes. In the Tennessee Valley, water milfoil first became established on one of TVA's mainstream lakes in the late 1950's (perhaps dumped from a fishbowl). For several years we have been battling milfoil with chemicals as well as reservoir manipulations. We can check it and kill it almost to the vanishing point, but we have not yet succeeded in eradicating it completely.

Warmwater discharges from thermal electric generating plants introduce another major potential for change in water quality. So-called 'thermal pollution' did not pose a serious problem at early TVA steam plants, which were built on rivers large enough to dissipate the heat readily. In fact, the most obvious effect has been the popular winter fishing at steam plant discharge basins, where the warm water attracts fish. But as growing power demands require ever larger plants across the United States, both nuclear and conventionally fueled, there is increasing concern about what effects these heated water discharges may have on fish and other aquatic life.

At the site of TVA's Browns Ferry nuclear plant in northern Alabama, large underwater pipes will carry the heated water from the condensers out across the main river channel and release it through thousands of small holes to mix with the streamflow. Mechanical draft cooling towers are being designed to provide additional cooling capacity. Thus the temperature rise of the river water will be minimized. At the site of TVA's Cumberland plant, now under construction, the temperature rise will be held down by large, uniquely designed condensers and by regulation of flows past the facility.

To learn more about the effects of heated water on fish and other aquatic life, TVA and the Environmental Protection Agency are planning a special research facility to be built and operated by TVA at Browns Ferry. A series of man-made channels, simulating natural streams, will be stocked with various species of fish and supplied with water flowing at different temperatures. This model will allow biologists to study long-term effects of heated water on fish life, reproduction, and food supplies under scientifically controlled conditions.

Currently, the detection of mercury in streams and coastal waters is at or near the top of water quality concerns. The discovery of mercury pollution in TVA lakes in 1970 led to a ban on commercial fishing in Pickwick Lake on the lower Tennessee River and a continuing surveillance of all reservoirs in the TVA system for mercury contamination. Mercury's toxicity has been known for centuries. But only recently did we realize in this country that fish are capable of concentrating mercury in their flesh and organs until it builds up to a level many times greater than that in the surrounding water.

Using the highly sophisticated equipment now available, TVA is moving to obtain a complete profile on the mercury conditions in all reservoirs. We also are working with state and federal agencies to control and hopefully eliminate this new pollution threat. Keeping significant mercury discharges out of streams in the future probably will not be too difficult and will be accomplished. But it is not clear how long it will take to clean the mercury out of the bottom sediments of those streams that have received excessive amounts over long periods of time.

TVA's efforts in water quality have expanded over the years. Steps have been taken, for example, to rid the valley's streams and reservoirs of industrial and municipal pollution. Before issuing permits for construction of water-using facilities along the reservoirs, TVA requires assurance that waste treatment plans meet the requirements of the state pollution control agency. In addition, TVA has the option to examine plans for plants proposed along the shorelines to determine whether they will be equipped to handle waste disposal adequately.

We do not have regulatory control over the entire valley. However, through landrights along the shorelines and through research and development efforts, we can assist the builder of new industrial and commercial developments in the installation of adequate waste treatment facilities.

BENEFITS TO REGION AND NATION

The results and benefits to the region and nation from TVA projects have been many, particularly in the areas of navigation, flood control, power, and development of shoreline lands. River traffic on the Tennessee has climbed steadily since the waterway was completed in 1945. The waterway is connected with the inland system of the United States based on the Mississippi River and its major tributaries. In calender year 1970, barge freight on the Tennessee River waterway totaled $>22.5 \times 10^6$ metric tons (25×10^6 tons), a new record for the ninth consecutive year. Shippers using the waterway saved a record $51.4 million during the year; thus the accumulated savings resulting from the improved waterway approached the $550 million mark, more than twice the amount of the net navigation investment.

At the end of fiscal year 1970, cumulative flood damages averted by the TVA system in the Tennessee and lower Ohio and Mississippi basins exceeded $392 million. The bulk of the savings was mostly in the vicinity of Chattanooga, the most vulnerable locality in the watershed. Additional flood control benefits included $150 million in increased values on 2.43×10^6 ha (6×10^6 acres) of productive land along the lower Ohio and Mississippi. In contrast to the total of more than $542 million of total flood control benefits, the investment in flood control has reached about $190 million.

Total generated and purchased power on the system in fiscal 1970 passed 100 billion kw hours for the first time and reached 101.3 billion kw hours. Hydro generation totaled 16.5 billion kw hours, and steam generation was 76.1 billion kw hours. TVA received over 8.6 billion kw hours from other systems.

Industrial growth along the shorelines of the waterway also has risen sharply. Private investment in new and expanded plants on the waterfront since 1945 now amounts to nearly $2 billion. Shoreline development now also offers a variety of recreational activities: picnicking, boating, swimming, camping, and hiking.

IMPLICATIONS FOR THE FUTURE

Experience in multiple-use river development and operation in the Tennessee Valley has attracted the interest of individuals and nations on a worldwide basis. Although this experience cannot be used as a model to be transferred intact to any location, it can be drawn on as we attempt to find adequate methods of approach to problems of making full and balanced use of our natural resources. Trends in water control and water use problems show that only the fullest research and development will meet future needs.

Special tools and new methods are needed as we seek refinement of our planning techniques and our methods of operation. A study in this direction is in the planning stage at TVA. It would be aimed at developing a comprehensive TVA water resource management program. The methods to be developed would consist of several mathematical component models that would interrelate all factors affecting our water resource management. An optimization procedure would also be devised to determine the system design or operations required for best use of the region's water resources.

Development of scientific techniques in the last few years has reached a point that should soon permit us to make simultaneous appraisal of the whole array of management alternatives in a manner that will reflect all elements of costs and values. How we do that could be another chapter in the story of the TVA experience.

Summary: Hydrology and Man-Made Lakes

K. SZESZTAY

Water Resources Section, Resources and Transportation Division
United Nations, New York, New York

From a hydrologic point of view, lakes are storage elements of a local or regional hydrologic system. They alter the quantity and quality regime of the water flowing through this system. The evaluation of the actual or potential effects of a man-made lake on its physical and biological environment should usually start with the identification of the changes in the hydrologic regime as a first step and basis for further studies.

The basic role of hydrologic considerations in the topics of this volume is well reflected by the great number of papers devoted to these questions. The papers on the hydrologic aspects of the subject are discussed in this summary and then are presented as separate papers.

The title of the volume implies two criteria with regard to waters belonging to the subject: they should be 'man-made,' and they should be 'lakes.' Both terms may raise some concern if precise definitions are to be made.

Beyond the really man-made lakes (for which nature supplies only the principal element, water), there are a great number of lakes created by natural processes but altered and controlled more or less by man (artificial decrease or increase of the average water level and surface area, regulation of the shoreline, control of the inflow and outflow, introduction of heat and chemicals by waste disposals, and so on). The identification and agreed application of some indices expressing the relative significance of human influences would probably be of help if distinctions are to be made between natural and man-made lakes. It also seems to be rather difficult to specify accurate dimensions beyond which water bodies are large enough to be called lakes.

Most of the papers belonging to this subject area interpreted the above criteria in a broad sense and discussed generally the problems of storage reservoirs with some emphasis on larger ones. Many of their considerations and findings may be equally applied to problems of natural lakes.

MAN-MADE LAKES AS ELEMENTS OF WATER RESOURCE SYSTEMS

Each natural or artificial water resource system includes two kinds of components: fluxes (inflows and outflows) and storages. The greater the total capacity represented by the storage elements, the more the supply from the system can follow time variations of the water uses served by the system. Man-made lakes are important tools for increasing the total storage capacity of the water resource systems. Estimations on a global scale indicate that the total amount of water supplied for various purposes from the world's storage reservoirs is on the order of 4000 km^3/yr, and it is expected that this value will be roundly tripled until the year 2000 [*Lvovich*, 1969].

To build or not to build man-made lakes in the future is certainly not the right formulation of the question. A more proper formulation, perhaps, is where, when and how to build, and what supplementary studies and actions to undertake to achieve the intended benefits without unwanted damage.

River basins as storage reservoirs. Man-made lakes represent additional storage capacity of hydrologic systems. There always exists an initial (natural) storage capacity of the river basin itself that transforms the rainfall and snowmelt regime into the streamflow regime of the river. The streamflow-regulating effect of this basin storage usually considerably surpasses that of the storage reservoirs. On a global scale the total amount of the streamflow regulated by the natural subsurface storages into base flow (dry weather flow) is estimated to be on the order of 12,000 km^3, i.e., about one-third of the total runoff from land areas [*Lvovich*, 1969; *Szesztay*, 1970]. Changes in land use or in soil cultivation practices may result in increased basin-regulated flow and may serve in some cases as a partial or alternative solution for constructing storage reservoirs. In other cases, these changes may decrease basin regulation and may raise or increase problems of floods and erosion.

Man-made lakes and water balance of the river basins. Natural or artificial changes in storage capacities of a river basin generally alter not only the streamflow regime but also the water balance. These effects may be of particular significance in arid and semiarid regions. Comparative studies have shown that the construction of several small-size and medium-size storage reservoirs (with a total capacity of about 200×10^6 m^3) has reduced the annual flow by 10% in average years and by 25% during dry years in a 2000 km^2 semiarid river basin of northeast Brazil [*Dubreuil and Girard,* this volume].

This 'hydrologic side effect' should not be overlooked in planning storage reservoirs and comparing them with other alternative solutions of water supply. In arid and semiarid regions, by increased storage reservoir development, a point may be reached beyond which the reduction of total water yield by increased evaporation losses surpasses the possibilities of increasing low flow discharges from reservoir storage [*Langbein,* 1959].

Alternatives in planning of man-made lakes. The basic reason for constructing reservoirs and man-made lakes is usually the increased need for domestic, agricultural, or industrial water supply. When water demands of the region are specified, a careful study of all possible alternatives should follow, perhaps including the following principal types of solutions: (1) construction of storage reservoirs, (2) artificial recharge of groundwaters, (3) extension of groundwater explorations, (4) diversion of water from neighboring regions, (5) increase of the streamflow by watershed management, and (6) decrease of the specific water requirements by technological changes.

Within each type of solution, usually several alternatives may be found. In case 1, for example, the same increase in water supply may be assured by one big reservoir or several small reservoirs or by combining this solution with any of the others. Some of the alternatives or combinations may be sorted out rather easily, but others may require intensive studies before a selection can be made [*National Academy of Sciences,* 1968].

One of the important issues concerns the involvement of studies of environmental effects of man-made lakes into the very beginning phase of formulating and evaluating alternatives. Theory and techniques of modeling and simulating large complex systems consisting of a hierarchy of models or submodels are rapidly developing, and it may be expected that alternative problems of man-made lakes will soon be studied by this method with due regard to all their hydrologic, environmental, economic, and social aspects.

Classification of lakes: a tool for integrating experiences. Positive and negative experiences of existing reservoirs and man-made lakes are important sources of improved planning and management in the future. For example, the valuable documentation and studies of the *Food and Agriculture Organization* [1970; *Lagler,* 1969] can be mentioned. One of the difficulties in evaluating and interpreting experiences is the large variety of problems and reasonable methods of solution according to local conditions. A problem-oriented classification of lakes and reservoirs based on the primary hydrologic and environmental factors predetermining or influencing their physical, chemical, biological, and radiological regime could be one of the tools for overcoming or decreasing this difficulty.

With regard to the selection of the basic factors of the classification, a reasonable compromise should be found between requirements of completeness and representativeness on the one side and those of an easy interpretation and availability in the planning stage on the other. As a very tentative list the following groups of factors may serve as a basis for further consideration: (1) size and geometry of the lake or reservoir, (2) water balance conditions, (3) climate, (4) soil and vegetation at the site of the reservoir before its construction, (5) soil, vegetation, and morphology of the drainage area, (6) age of the lake or reservoir, and (7) influence of men on the natural conditions.

Within each of the above groups a few parameters should be specified. In the case of group 2, for example, the following three indices may identify the principal features of the water balance conditions [*Szesztay,* 1967]:

1. The first is the average volume of water in the lake related to the average annual flux. The latter is the sum of input (precipitation + inflow) or output (evaporation + outflow) components of the water balance. This ratio characterizes the renewal process of water in the lake.

2. The second is the ratio of average annual precipitation on the lake surface to the average annual flux.

3. The third is the ratio of average annual evaporation to the average annual flux.

After having specified each of the appropriate classification indices for a sufficiently large number of existing lakes and reservoirs in different parts of the world, we can make a statistical evaluation. The aim of this evaluation is to derive correlation relationships between classification indices and the principal parameters characterizing the physical, chemical, biological, and radiological conditions of the lakes and their environmental effects. These relationships and the classified data bank are of great help in estimating expectable conditions or selecting analog cases for detailed studies during the first phases of the planning process.

FLOW REGIME AND STRATIFICATION IN MAN-MADE LAKES

Water is certainly the medium for which man-made lakes are created. But not all kinds of water may satisfy human needs. Its quality has to correspond to certain criteria depending on the purposes for which the water in the lake or supplied from the lake is used. The planning of a man-made lake requires predictions not only on quantities of water filling the bed of the lake and causing fluctuations of its level, but also on the quality regime of the water that will be stored in or supplied from the lake.

The physical, chemical, biological, and radiological properties of the water in the lake or leaving the lake can considerably differ from the properties of the waters entering the lake. It is not possible to understand, predict, or control this change without knowing the flow regime and the stratification processes within the lake.

Basic considerations. First, the existence or the possibility of a density stratification is the first question to be clarified if the flow regime of a lake or reservoir is to be investigated. Seasonal temperature fluctuations are the most common causes of a density stratification, but other agents such as dissolved or suspended solids could also be factors. Beyond differences in densities (temperature) in different depths the rate of flow through the given cross section is the principal factor determining the possibility of the formation of a stagnant layer. A critical value of the densimetric Froude number (comparing the rate of flow to the density gradient) has been derived theoretically for specifying conditions of the formation of a stagnant layer, but laboratory and field data indicate that differences in geometries and flow characteristics can cause significant deviations from this theoretical value [*Elder and Wunderlich*, this volume]. In the temperate zone reservoirs with little inflow and outflow, expressed stratification may be observed even in cases of small depth (10-12 meters), whereas strongly flushed reservoirs may be homogeneous down to several times those depths.

Second, in case of density stratification the inflow waters may move and be stored at the surface (overflow), at the bottom (underflow), or at an intermediate depth (interflow) according to how the conditions of their temperature (density) fit into the temperature profile of the reservoir [*Slotta*, this volume]. For similar reasons, flows caused by natural outflows or withdrawals are also developing in specific layers of limited thickness. As a result, several distinct and independent currents may simultaneously exist within a lake or reservoir with density stratification.

Third, wind drift is a major factor of the flow regime in shallow waters and in the surface layers of deep lakes [*Filatova and Kalejarv*, this volume]. The geometry of the shoreline and the lake basin plays an important role in the formation and development of the flow pattern corresponding to a wind of given direction, velocity, and duration. Because of the changes in wind regime and the secondary flows generated by wind that cause changes in the water surface, the actual flow pattern reflects the residual effect of several preceding winds.

Methodology of investigations. Hydromechanical analysis of the basic processes, field surveys, and physical or conceptual models are equally important and mutually interrelated tools in investigating flow regime of lakes and reservoirs. The determination of the thickness of the withdrawal flow layers in the case of selective withdrawals is a good example for the combined application of hydromechanical analysis and field research [*Wunderlich and Elder*, this volume]. As a result, two formulas have been derived for such problems: one for the cases of surface and bottom withdrawals and another for intermediate withdrawals.

Hydraulic models and laboratory tests are widely used tools in studying basic and applied problems of flow regime and stratification. Transient flow problems (including dilution of waste waters and identification of the effect of the geometric configurations on flow patterns) can be analyzed with satisfactory results also by models with geometric distortion on the basis of specifically adopted conditions of kinematic similarity. In the case of wind-caused currents, quantitative results can be expected only by models having the same horizontal and vertical scales.

Hydraulic models have been successfully applied also to studies concerning the influence of entering streamflow on currents of density stratified reservoirs [*Slotta,* this volume]. Laboratory results were compared also with data of an interesting field measurement traced by dye concentrations at one of the Tennessee Valley Authority (TVA) reservoirs.

Applications. The identification of stratification and flow regime is the basis of the solution to many practical problems concerning movement of heat and dissolved or suspended materials in lakes or reservoirs. In the man-made lakes of the TVA system, the power-peaking operations of the hydropower plants are the dominating factors determining flow regime [*Granju et al.,* this volume]. For maintaining the required water quality conditions, it is important that waste discharges to the system be released in a prescribed proportion to the instantaneous flow passing the point of release. A good example of the applicable methods for solving such problems is reported by *Granju et al.* [this volume] for Kentucky Lake. The flow regime of this reservoir is determined by the intermittent operations of the upstream and downstream hydropower plants as well as by an uncontrolled navigation canal connecting Kentucky Lake with the upstream reservoir. The solution was based on a mathematical routing model and supplied predicted flows and stages for 21 cross sections at 1-hour intervals for a 42-hour forecast period in $<$ 1 min of computer time on an IBM 360/50 system. The forecasts are based on the expected power production of the two plants that is revised day by day.

Heated waters are frequently released into the lakes and reservoirs by steam electricity generating plants. A comprehensive evaluation of the applicability of the results of theoretical investigations under the conditions of the TVA reservoirs led to the following principal conclusions [*Benedict et al.,* this volume]:

1. For the conditions of stratified flows the observed wedge lengths of the heated waters agreed closely with those computed on the basis of the theoretical solution proposed by G. L. Bata.
2. For the case of no heat loss, which prevails close to the discharge point, the surface area within a specified temperature rise and the distance to complete mixing can be computed with reasonable accuracy on the basis of several proposed diffusion models.
3. Surface cooling usually has little effect in the initial regions, but it may become a significant factor if the influenced area increases.

A comprehensive model is under development at the University of Texas for simulating long-term water quality changes [*Fruh and Clay,* this volume]. In its present phase the model is composed of four principal components: inflow thermal and chemical routing, atmospheric and radiation sources and sinks of heat, vertical diffusion of heat and chemical concentrations, and outflow routing (selective withdrawal). In the course of further development it is intended to include components such as chemical-biological changes of nonconservative chemicals within the impoundment and accounting for continuous changes in the water, heat, and chemical budgets of the impoundment.

Present investigations are focused on heat balance and temperature regime. In the computations concerning stratification conditions and flow regime, the Koh and the Bohan-Grace solutions have been tested, and the latter has been applied. Heat balance components related to the water surface and those determined by the inflow and outflow were assessed separately but were combined in later phases of the procedure. Temperature profiles, total heat content, and outflow temperatures have been selected as criteria in comparing computed and observed values of Lake Travis (south central Texas) for a 2-year period.

REFERENCES

Benedict, B. A., E. M. Polk, Jr., F. L. Parker, L. H. Motz, and J. E. Edinger, Movement of heated water discharges from power plants in man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Dubreuil, P., and G. Girard, Influence of a very large number of small reservoirs on the annual flow regime of a tropical stream, in *Man-Made Lakes: Their*

Problems and Environmental Effects, Geophys. Monogr. Ser., vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Filatova, T. N., and T. O. Kalejarv, Some results of 20-year network observations on currents in Tchudsko-Pskovskoe Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Food and Agriculture Organization, A partial annotated bibliography on water level fluctuations and minimum pools in reservoirs for fish and other aquatic resources, *EIFAC 70/SC 111-5,* 68 pp., Jablonna, Poland, 1970.

Fruh, E. G., and H. M. Clay, Jr., Selective withdrawal as a water quality management tool for southwestern impoundments, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Granju, J.-P., J. Garrison, and J. Price, Hydraulic transients in man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Lagler, K. F. (Ed.), *Man-Made Lakes: Planning and Development,* 71 pp., Food and Agriculture Organization, Rome, 1969.

Langbein, W. B., Water yield and reservoir storage in the United States, *U.S. Geol. Surv. Circ., 409,* 1959.

Lvovich, M. I., *Water Resources of the Future* (in Russian), 175 pp., Praswestenie, Moscow, 1969.

National Academy of Sciences, *Water and Choice in the Colorado Basin: An Example of Alternatives in Water Management, Publ. 1689,* Washington, D. C., 1968.

Slotta, L. S., Stratified reservoir density flows influenced by entering streamflows, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Szesztay, K., Some problems of lake hydrology, *Publ. 3,* Res. Inst. for Water Resour. Develop., Budapest, 1967.

Szesztay, K., The hydrosphere and the human environment, paper presented at IASH-Unesco Symposium on Hydrological Experimental and Representative Basins, Int. Ass. of Sci. Hydrol., Wellington, New Zealand, 1970.

Wunderlich, W. O., and R. E. Elder, Mechanics of flow through man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Experience on Hydrologic Substantiation of Projected Reservoirs

A. A. SOKOLOV

State Hydrological Institute, Leningrad, USSR

The control of river discharge by means of reservoirs, some of which are nearly as large as the greatest lakes of the world, has caused a need to develop methods for forecasting (computing) the hydrologic regime of these reservoirs and predicting the environmental changes that they cause. As a result of theoretical, field, and experimental studies carried out in the USSR, United States, England, France, Italy, and other countries, a number of practical recommendations have been made recently on the computation of water, heat, and salt balances; dynamics of the water masses; transformation of shores and bottom; and silting of the projected reservoirs.

At first these recommendations were mainly based on the results of investigations of lakes that had been considered natural analogs of man-made reservoirs. Later, permanent hydrometeorological observatories were established at a number of reservoirs to check the methods of hydrologic computation used for projecting and to supply hydrometeorological information and forecasts for reservoir operation. Such observatories have been established, for example, on all the reservoirs of hydrologic power plants on the Volga, Don, Dnieper, Angara, and other large rivers of the USSR.

The International Symposium on Hydrology of Lakes and Reservoirs at Garda in 1966, organized by the International Association of Scientific Hydrology (IASH) in cooperation with the United Nations Educational, Scientific and Cultural Organization (Unesco), and the Symposium on the World Water Balance at Reading in 1970, organized by Unesco and the World Meteorological Organization (WMO) with the support of IASH, were of great importance for the generalization of methods for computing the hydrologic regime of the projected reservoirs.

Scientific papers presented at these symposiums showed that, though considerable progress has been achieved in the branch of hydrology under study, there are still many gaps in the complicated problem of hydrologic substantiation of newly made reservoirs and more detailed study is required for more accurate computation (forecasts) of the elements of the hydrologic regime. Our knowledge of the problem in question is of special importance for the developing countries that do not have sufficient experience in designing and establishing reservoirs.

WATER BALANCE OF RESERVOIRS

Computation of water balance is one of the major tasks of hydrologic and economic substantiation of projected reservoirs. Computation of water balance for short periods of time (months) is usually made by the following equation:

$$Q_{in} + Q_p - Q_d - Q_e \pm Q_s \pm Q_{ic} = A \qquad (1)$$

where Q_{in} is the surface inflow, Q_p is precipitation on the water surface of the reservoir, Q_d is the discharge through the hydroelectric power plant or the discharge of the river flowing out of the lake, Q_e is evaporation from the water surface and from the surface of the temporarily drained shore zone, Q_s is temporal loss of water due to saturation of the shores, Q_{ic} is temporal loss of water due to ice left on the shores during the decline of the reservoir level, and A is the accumulation in the reservoir.

The reliability and validity of the projected water balance computations depend on the knowledge of the hydrology of the water body and on the development of hydrologic science. If the hydrology of the water body and of the whole country is sufficiently studied, the computation of water balance components of the projected reservoir is not difficult. The methods used for determination of the balance components are shown by a number of authors, such as Z. A. Vikulina (USSR), D. R. Dawdy (United States), H. S. Riggs (United States), J. A. Cole (United Kingdom), Z. Kos and V. Souček (Czechoslovakia), M. Melentijevich (Yugoslavia), S. Dyck and M. Schramm (German Democratic Republic), and others. When the data are insufficient or absent, the computation is very complicated, though appropriate methods are available.

From the great number of problems concerning the computation of water balance of reservoirs, we shall discuss the most important from our point of view. When we compute the water balance of reservoirs and determine their guaranteed water yield during dry periods, it is important to determine long-range variations of water inflow, particularly in arid regions where the variations are great and rather extensive observations are required for reliable evaluation of statistical parameters of variable discharge and inflow. Evaluation of possible grouping of wet and dry years is of great interest. Along with common statistical methods, numerical models of long-term observation series composed by the Monte Carlo method are widely used in computations of water and water economy balances of reservoirs.

One of the important problems is the computation of runoff losses by evaporation from reservoirs. If sufficiently substantiated formulas for the computation of evaporation and field observational data are available, the value of evaporation from the water surface can be estimated with rather high accuracy, provided initial values of vapor pressure differences and meteorological characteristics above the evaporating surface are reliable. On the basis of generalization of the long-term experience obtained in the USSR, standard guidance materials for computing evaporation from a water surface have been developed. Studies on the radiation balance of reservoirs are being carried out to check these guides by the heat balance method. Similar methods for computing evaporation are used in other countries where comprehensive studies on evaporation are also being carried out.

A measuring system for computing evaporation from a water surface for short periods of time is being established. For this purpose, evaporation from Godivelle Lake computed by the method of water and heat balances is being compared with direct measurements (J. Jaquet and L. Mandelbrot, France).

When he was evaluating the accuracy of evaporation computations on the basis of reliable data on all the components of water balance of a reservoir with a capacity of 2 million m^3, P. Dubreuil (France) showed that even under the most favorable conditions, evaporation could be rather accurately estimated for time intervals no shorter than 5 days (in rain periods the interval for reliable estimation increases up to 15 days). A close relationship has been found between direct measurements of evaporation (by level variations of several reservoirs, provided there is no inflow, outflow, and precipitation) and data obtained by floating evaporimeters (G. Girard, France).

The analysis of variability of annual evaporation and influencing factors (G. E. Harbeck, United States) has confirmed previous conclusions and studies made in the USSR; i.e., obtaining valid average annual evaporation values requires a much shorter series of observations than obtaining the same characteristics of precipitation and runoff.

Studies on evaporation by different methods were made on a small lake in the United States (J. Ficke); these methods included accurate records of water balance components and estimation of energy (heat) balance and mass transfer (method of turbulent diffusion). These studies showed that water and heat balances ensure the best results for a considerable period of averaging and for great intensity of evaporation whereas methods based on mass transfer equations are preferable for evaluating evaporation for short periods (and for periods with comparatively small evaporation).

However, computing the water balance of a projected reservoir requires not only the value of evaporation from the water surface of the reservoir but also the runoff losses that are computed by the difference of evaporation from the water surface Z_b and the evaporation from the land area occupied by the reservoir Z_c. An approximate method for computing such losses was presented by the author at the International Symposium on Hydrology of Lakes and Reservoirs at Garda in 1966.

Unfortunately, evaporation from certain types of land areas is not yet sufficiently studied. The present methods give only average values for large territories with various features.

Therefore one of the most important tasks connected with the increase of accuracy in computing the water balance of reservoirs is the improvement of methods for computing evaporation from different types of land areas, particularly from floodplains as well as from reservoirs partly covered by aquatic plants and from parts of the shore periodically drained during the fall of the water stage. In this respect the study of the effect of the aquatic vegetation on evaporation is of interest (V. S. Eisenlohr, United States).

The estimation of underground inflow to a reservoir, as well as filtration and bank storage, is rather complicated; these elements are not sufficiently studied and therefore are often not taken into account in water balance computation. At any rate, underground inflow to reservoirs on the plains, as shown by special studies, is not great, i.e., not more than 1-3% of the surface inflow. Temporary losses by soil saturation in the shore zone are usually computed by the backwater curves and by the difference between water content and porosity of the shore rocks. Their role in the water balance depends on the size of the periodically drained area and the water capacity of the rocks forming the reservoir.

Z. A. Vikulina has shown that subsequent checking and computing of so-called current water balances of existing reservoirs during their operation allowed the conclusion that discrepancies in the monthly balances are, on the average, ±5% and those in the annual balances are 1-3%. In a number of reservoirs for which the components of water balance are computed without sufficient accuracy the discrepancies may be very great, and they may equal ±15-20% in some months and ±5-10% for the year.

Accurate determinations of the mean water level of the reservoir and its morphologically homogeneous parts are of great importance for the increase of accuracy in water balance computations during reservoir planning and are more important during reservoir operation. Accuracy is particularly important if we consider water balance for short periods of time (10 days or 1 day). Computation of water balance with allowable accuracy for diurnal time intervals is a very difficult task at the present level of accuracy of computing water balance components.

COMPUTATION OF WATER AND SALT BALANCE OF RESERVOIRS

The hydrochemical regime of reservoirs is due to annual variability of the volume and chemical composition of inflow (river discharge and local runoff), the volume of precipitation on the water surface, outflow, water use, infiltration, evaporation, and processes of ice formation and ice melting. The following factors have practically no influence on the salt balance of a reservoir: sedimentation and solution of salts as a result of physical, chemical, and biological processes and reactions of exchange and adsorption; salt transfer by wind; and salt losses or gains with changes of the flood zone boundaries.

Practical requirements concerning the salt content in water and the composition of dissolved salts for projected man-made lakes can be met with computations made by the water and salt balance method. Studies on the problem of water and salt balance forecasting for planned reservoirs were made by N. M. Bochkov and P. P. Voronkov (USSR), K. W. Prophet (United States), and others. The estimation of the average mineralization of the reservoir M_a for the definite period n could be made by

$$M_a = M_{e(n-1)} + M_{en}/2 \tag{2}$$

In (2) the average weighted mineralization of water for the end of the estimated period M_e is determined by the following ratio, in which the main components of the water and salt balance for separate periods are presented:

$$M_e = \frac{M_b V_b + M_{if} V_{if} + M_{ic} V_{icm} - M_{ic} V_{icf} - 0.5 M_b V_{of}}{V_b + V_{if} + V_p + V_{icm} - V_{ev} - V_{icf} - 0.5 V_{of}} \tag{3}$$

where M_b and V_b are the mineralization and the volume of water in the reservoir at the beginning of the design period, M_{if} and V_{if} are the average weighted mineralization of the inflow and the volume of inflow, M_{ic} and V_{icf} are the average mineralization of ice and the volume of water lost by ice formation, V_{icm} is the volume of water resulting from melting of ice, V_p is the volume of precipitation on the water surface, V_{of} is the volume of outflow, and V_{ev} is the volume of evaporation. This method produces satisfactory results when the hydrodynamic conditions of the reservoir provide sufficient mixing within the total water mass.

Formula 3 computes the ultimate mineralization of water in the reservoir for a design period M_u, and then formula 2 computes the mean mineralization for any given time interval M_m.

For small reservoirs in which alimentation is contributed by local runoff the duration of design periods (duration of the predominance of interflow, subsurface flow, and groundwater flow in the channels) and the volume of the flow under question are estimated by a hydrograph. The latter is plotted for river reaches located upstream from the backwater zone. The hydrograph separation is made according to a scheme based on the peculiarities of formation of the flow in the basin. Since an intensive interflow coming into the channel results in a sudden rise in the water level, groundwater inflow into the channel practically ceases. Therefore, if the lag time of the interflow for a given basin is known, it is possible to make a graphic estimation of the period of its predominance in the channel and of its volume, respectively. The same method may be used to estimate the volume of subsurface and groundwater flow.

Since it is necessary to take into account the drainage area when man-made lakes are projected, the necessity may arise to establish such lakes without considering some salinization of the water. In such cases the water and salt balance method can be used to estimate the possible increase in mineralization of the projected reservoir and to envisage the removal of highly mineralized water from the reservoir prior to the spring flood if necessary.

If no water removal occurs, the mean weighted mineralization of a man-made lake at the end of the spring flood M_{ls} (mineralization late in spring) should be estimated by the following equation:

$$M_{ls} = \frac{M_b V_b + M_{ss} V_{ss} + M_{ic} V_{icm}}{V_b + V_{ss} + V_{icm}} \qquad (4)$$

where M_{ss} and V_{ss} are mean weighted mineralization and the volume of water in the soil and surface water (genetic category), respectively; these serve as the main source of alimentation of lakes and reservoirs during the spring flood. According to (3), mean weighted mineralization of water in a lake or reservoir for subsequent periods (i.e., late in summer and late in winter) may be computed in a similar way by the use of appropriate (for the given period) components of the water and salt balance.

If some portion of spring floodwater is removed from the reservoir, the computation for the end of the total period of filling of the reservoir should be made in two steps. Moreover, it is necessary to take into account only the important components of water and salt balance for a specific time interval. The computation may be made more strictly when the change of water mineralization is taken into account by the exponential curve.

If the spring period results in the water removal of more than twice the reservoir volume late in winter, the reservoir will be 'washed' in such a way (if mixing of different water layers is sufficient) that it will be possible to accept the mineralization of the reservoir at the end of the spring flood as being equal to the mineralization of inflow.

DYNAMIC PHENOMENA

The development of research on waves, currents, and water level fluctuations due to wind effect, as well as the improvement of methods for their computation, has been demanded by a constant increase in the requirements of hydraulic engineering, river transport, flotage, and so on. As a result of the study of wind waves on inland lakes and reservoirs a theoretical background has been developed for the computation of wind waves on the basis of the equation of wave energy balance.

For the substantiation and development of practical methods of computing the wave regime on lakes and reservoirs, field observational data on waves have been collected. The measuring technique has been modified, and methods of observation and data processing have been improved. By citing this improvement, we refer to the creation of mechanical and electrical wave-recording gages, the development of methods for wave stereophotography, and the application of methods of mathematical statistics for data processing.

Summarization of observational data on lakes and reservoirs made it possible for A. P. Braslavskii to develop a method for the computation of wind waves on the basis of data on wind velocity, the length of wave fetch, and the depth of the reservoir. By this method it is possible to compute wave elements all over the water area of the lake or reservoir and to obtain charts (collation maps) of waves for different directions and velocities of wind. The charts, prepared prior to the establishment of reservoirs, are used in operational practice for navigation and flotage.

The most significant difficulties in the research on the mechanism of waves are connected with the lack of reliable methods to fix the processes characterizing this phenomenon. Wave-recording gages used at present make it possible to obtain the characteristics of water level fluctuations at particular points in the lake, and this capability makes possible the calculation of the height and the period of waves of a given frequency after an appropriate processing. But it is impossible to judge the space and time variability of wave distribution.

Until recently, the study of currents in the open part of inland lakes and reservoirs has been usually confined to the evaluation of the general circulation on the basis of indirect indications and sporadic measurements of currents from ships. Such information has been obtained only for a few reservoirs and does not give a complete notion of the character and peculiarities of currents on reservoirs.

More comprehensive information from field observations has been obtained for coastal areas of some reservoirs in connection with the study of sediment transport and shore transformation; but even in this case the amount of information is rather limited. As for the indirect methods of current determination, it is reasonable to mention the dynamic method for the computation of density circulation in deep lakes, which may be considered a modification of the widespread dynamic method relative to seas. This method has been applied for the computation of currents of some large lakes, e.g., Baikal and Ladoga.

Recently, investigations of currents in lakes and reservoirs have been intensively developed for the study of water pollution. Long-term observations of currents in the open parts of lakes and reservoirs by autonomous instruments are being organized, and use of aerial photography for the simultaneous study of currents over a large water area is being enlarged. Observations of currents in the coastal area are being increased as well.

Direct methods of measurement of currents include (1) measurements of direction and velocity of a current at a point from a ship or on an autonomous device by current meters of different types and (2) observations of the trajectory of objects in suspension (floats) over a certain part of the water area. According to which method is used, the observations may embrace more or less of the water area. The lack of an automatic instrument for reliable recording of slow currents is the most substantial hindrance to the development of observations of low-velocity currents that are characteristic of numerous inland reservoirs.

The collection of a great amount of observational data has led to the improvement of methods of data processing. During the last few years, statistical methods of data processing have made it possible to obtain numerical characteristics of prevailing currents in some areas of particular reservoirs, and some attempts have been made to evaluate quantitatively the contribution of individual factors in the total transfer of water masses.

The existing computation methods give only the idea of individual current types, which usually are not observed in a pure form. Such computations for lakes and reservoirs, however, have not yet been widely accepted.

The study of wind effect on water level fluctuations in reservoirs is of particular interest. A. V. Karaushev has developed a method of computation according to wind velocity, direction, and duration.

PROBLEMS OF ICE REGIME OF RESERVOIRS

Theoretical investigations and analysis of observational data on reservoirs located in different climatic zones have been made to obtain quantitative characteristics and to establish general regularities of freezing processes, formation, and breakup of ice cover on the reservoirs, as well as to evaluate the character of ice regime variations on river reaches after the construction of hydraulic structures that cause a backwater effect.

The variety of ice phenomena, dates and duration of freezing, ice cover, and ice breakup are determined by the combination of meteorological and hydrologic conditions, morphometric peculiarities, and the operational regime of the reservoir.

Investigations of freezing processes based on the study of heat balance and water mixing conditions, as well as on the analysis of data on the characteristics, dates, and duration of the freezing period, showed three types of freezing typical of reservoirs. They differ by the intensity and the location of ice formation (on the surface or at a depth), type of ice (surface ice or frazil ice), and the duration of the freezing period (1–3 or 10–15 days).

Methods of computing freezing of reservoirs developed by V. V. Piotrovich, K. I. Rossinski, L. G. Shuliakovski, B. V. Proskuriakov, and R. V. Donchenko (USSR) and Z. Litynska (Poland) make it possible to solve the practical problem of the expected character and duration of freezing by means of a consecutive computation of principal characteristics of freeze-up processes and use of their interrelations.

After the freeze-up a new phase in the regime of a reservoir begins. In this period the ice cover is subject to further development due to the increase of ice thickness caused by crystallization of water at the lower surface of the ice pack, freezing of frazil ice under the ice cover, and congealing of snow saturated with water covering the ice. The intensity of the increase of ice thickness in winter is determined by the changes of heat balance and heat conductivity of the ice cover. On the basis of observational data, characteristics of the intensity of increase of ice thickness in winter have been obtained.

The destruction of ice cover on reservoirs occurs under the influence of heat and dynamic factors. The processes of ice destruction are described in detail by V. V. Piotrovich and B. M. Ginzburg, who have suggested a method for the computation of ice breakup on reservoirs.

The operational regime of a reservoir has a great influence on the formation and breakup of the ice cover. When the reservoir is freezing, increased discharges of hydroelectric power plants demand the acceleration of water mixing and consequently contribute to the increase of the freezing period. The operational regime of hydroelectric power plants located upstream determines the duration and dates of freezing in upstream reaches of corresponding reservoirs.

Because of a considerable lowering of water level in the reservoir, the ice cover is broken, and much of it remains on the shores, islands, and shoals (about 40%). These complex problems have not been properly investigated.

The existing methods of computation of ice regime elements of reservoirs are mainly based on the heat balance method and do not solve the problems of dynamics of ice cover on reservoirs. Special investigations on reservoirs are needed to study ice drift, ice cover deformation, formation of ice jams and ice dams in the backwater zone and in lower pools of hydroelectric power plants, change of radiation, and characteristics of ice during the melting period.

The study of these important problems of ice regime of reservoirs is essential to solve problems on the increase of the navigation period, evaluation of ice load on hydraulic structures, and water intake arrangements.

FORMATION OF SHORES AND BOTTOMS OF RESERVOIRS

The problem of formation of shores and bottoms of man-made lakes has become greatly important from a practical viewpoint during the last 2 decades, particularly in connection with the establishment of large reservoirs on great lowland rivers of the USSR and some other countries. Up to 2 decades ago the process of shoreline formation of man-made lakes had not been observed, and in fact there was no process in nature that could be treated as an analog. Thus there were great difficulties in estimating and forecasting shoreline deformations, which turned out to be many times greater than was expected. Further field observations on a number of reservoirs showed that the shifting of a shoreline consisting of soft ground is very intensive and sometimes may reach 50–100 m/yr. In some cases it may become necessary to move large populated areas and other costly objects situated on the shores of new reservoirs.

A method of estimating (forecasting) shoreline deformation in reservoirs was developed in the USSR and published in 1953. This method avoids large errors that may have serious aftereffects. At first the method was used only for estimating the final stage of shoreline deformation, but later improvement made it possible to estimate shoreline deformation for any time interval.

Laboratory studies of wave transformation in shallow water gave a qualitative scheme of bottom velocities. On the basis of the analysis of this material a theoretical scheme of energy losses in shallow water and the formula of extreme stability of bed sediments were developed. Thus, in particular, it was proved theoretically and confirmed by experiments that energy losses of the wave are caused by bottom filtration capacity rather than by bottom roughness. Using this theoretical basis, N. E. Kondratiev deducted the formula of the profile of a stable shore shoal and the formula for determination of depth near the shoal edge.

The relation between the depth at the outward edge of the shoal H, the wave height h, wavelength index $k = 2\pi/\lambda$, the depth of filtrating layer P, and the size of bed sediment particles d is expressed by the equation

$$h = \frac{2d \sinh kH}{\eta} \left[-\tanh kP \pm \left(\tanh kP + \frac{3.4\eta}{kd \tanh kH} \right)^{1/2} \right] \qquad (5)$$

which can be simplified as follows:

$$H = 0.64h \sinh^{-1} 8.1h \qquad (6)$$

The stable profile (the final stage) is compared with the initial shore profile (nondeformed) by graphic superposition of these profiles, and the balance between the volume of eroded material and accumulated material is taken into account.

The development of the process in time is described theoretically by the assumption that this process fades asymptotically according to the exponential law. Other methods have been suggested that would allow estimating, with different degrees of accuracy, and forecasting possible deformations of reservoir shores. To check and improve the existing methods, special field investigations are being carried out at present on some reservoirs.

RESERVOIR SILTING

One of the most important aspects of the hydrologic regime of large reservoirs is the sediment regime that depends on erosion, sediment transport, and sedimentation. The main source of sediments in a reservoir is the sediment load of inflowing rivers. In some cases a considerable portion of sediments may result from bank collapse, lateral inflow, and transport by wind.

Sedimentation is caused by the decrease of the transport capacity of the stream along the longitudinal axis of the reservoir, which tends toward 0 in the widest part of the reservoir. The transport capacity decreases with an increase in depth and a decrease in stream velocity.

The regularities of sedimentation in reservoirs are reflected by the equation of balance of the transported sediments. This equation takes into account the sediment income through the inlet cross section, sedimentation, and uplifting of particles due to turbulent exchange processes and bottom eddies. On the basis of this equation an exponential expression of the longitudinal distribution of sediment concentration was obtained. It is most expedient to apply this expression to individual sediment fractions. The value of the total sediment concentration and of the total sedimentation of the fractions is estimated by a summation of the individual fractions.

The equation of the distribution of sediment concentration along the longitudinal axis x of the reservoir and the formula of the transport capacity of the stream are the methodological basis for the computation of reservoir silting. Computation shows what part of sediment is deposited in the reservoir and what part is carried away through the outlet. It is also possible to estimate sediment distribution along the reservoir. For this purpose the computation is carried out for the design reaches into which the reservoir is divided.

The change of the partial sediment concentration for the i fraction of sediments on a reach of the reservoir of Δx length is expressed by the equation

$$S_{i_{\text{end}}} = S_{i_{\text{tr}}} + (S_{i_{\text{beg}}} - S_{i_{\text{tr}}}) \cdot \exp \{[-B(u_i + k_i)/Q]\Delta x\} \qquad (7)$$

where u_i is the fall velocity of sediment particles of the i fraction; B is the reservoir width; Q is the discharge; k is the parameter of sediments of the i fraction, the value of u_i and the hydraulic characteristics of the stream being taken into account; $S_{i_{\text{beg}}}$ and $S_{i_{\text{end}}}$ refer to the sediment concentration at the beginning and at the end of the reach, respectively; and $S_{i_{\text{tr}}}$ is the partial transport capacity of the stream for the i fraction on the Δx reach.

Detailed estimates of reservoir silting are supplemented by hydraulic computations that account for morphometric changes of the reservoir bed due to silting. Hydraulic computations are based on plotting the curves of the free surface of the reservoir.

Approximate estimates of reservoir silting, as well as practical methods of estimating pond silting, are based on the estimation of the relative capacity of a reservoir expressed by the ratio of reservoir capacity to the volume of annual streamflow. For these methods only the data on long-term average annual sediment discharge are used. The above methods also include extrapolations that allow estimates of reservoir silting by the end of any future year on the basis of the data on reservoir silting by the end of the first year of reservoir operation by means of the exponential equation. The problems of sedimentation and the technique for computation of reservoir silting are described in a number of articles and monographs. One of the first monographs on reservoir silting, published in 1939, was written by G. I. Shamov, who suggested an interesting extrapolation method for the estimation of reservoir silting. Various points related to the same problem are described in the works by S. T. Altunin (1952), V. S. Lapshenkov (1961), I. A. Shneer (1964), and K. I. Rossinski and I. A. Kusmin (1964, USSR); C. W. Farnham, C. E. Beer, H. G. Heinemann, J. W. Roehl, and M. Elliott (1966, United States); J. P. Carbonnel (1966, France); L. Cyberski (1966, Poland); and B. Djordjevic (1966, Yugoslavia). The works by A. V. Karaushev present theoretical methods for the estimation of silting of large (1965) and small (1966) reservoirs based on a general scheme.

The data on sedimentation in a number of reservoirs in India, the United States, and some other countries are given in a 1960 paper by D. V. Goglekar. This work also contains some empirical relations for the estimation of reservoir silting. A guide for the computation of the silting of large and small reservoirs that describes both well-known and new methods has been published in the USSR. The available observational data, though scarce, show the sufficient reliability of the existing computation methods and indicate certain drawbacks at the same time.

In future, various aspects of the problem of reservoir silting should be studied. It is most important to collect field data not only on the total volume of sedimentation but also on sediment distribution over a reservoir as well. It is quite obvious that it is impossible to estimate sediment distribution and the ways of sediment transportation without adequate information and a study of currents. Special attention should be paid to field observations of alongshore sediment transportation during wind waves.

Theoretical work should be aimed at the improvement of the methods for computation of the transport capacity of streams and at the development of the theory of sediment movement under complex conditions of currents. It is very important also to carry out experimental investigations of the parameters of sediments (fall velocity, volumetric weight of sediments, and so on).

The use of electronic computers for the estimation of reservoir silting is very promising. Unfortunately there are several difficulties in this respect, particularly due to multistage schemes of detailed computations of silting.

Acknowledgments. This report has been prepared in cooperation with Z. A. Vikulina, A. V. Karaushev, N. E. Kondratiev, P. P. Voronkov, M. M. Einbund, and R. V. Donchenko.

Hydrometeorological Studies of Lakes Victoria, Kyoga, and Albert

K. V. KRISHNAMURTHY AND A. M. IBRAHIM
UNDP/WMO Hydrometeorological Survey, Entebbe, Uganda

With a surface area of about 69,000 km², Lake Victoria is the second largest freshwater lake in the world (next only to Lake Superior), lying astride the equator within the countries of Uganda, Kenya, and Tanzania. Lakes Kyoga and Albert downstream have areas of 6300 and 5500 km², respectively. The area of the catchment as a whole is approximately 378,000 km², of which about 325,000 km² is in Uganda, Kenya, and Tanzania and about 53,000 km² is in Twanda, Burundi, and the Congo. The White Nile, fed and regulated by these lakes, flows out of Uganda, into the Sudan, and thence, after being joined by the Blue Nile, into the United Arab Republic (UAR). The drainage area of the Upper Nile and Lake Victoria contains the third highest peak in Africa, Mount Rwenzori (5120 meters), next only to Mount Kilimanjaro (5895 meters) and Mount Kenya (5199 meters) in height.

BRIEF DESCRIPTION OF THE THREE LAKES

Lake Victoria. Lake Victoria is the second largest freshwater lake in the world, and the Nile River, which flows out of it, is the longest river in the world at a length of about 6500 km.

The general shape of Victoria is an open trough running from north to south. The hills to the north and south are quite low, and the watersheds are ill defined; to the east and the west the land rises to mountainous heights along the edges of the two rift valley systems.

During the period 1896–1934 the extreme range between the maximum and the minimum lake levels was 1.74 meters, but, on the basis of subsequent data, this range was estimated at 2.0 meters. With the high lake levels of May 1964, this range is now reckoned at 3.1 meters.

An examination of 10-day mean gage readings discloses a maximum monthly variation of 33 cm and a yearly variation of 71 cm. The maximum lake level generally occurs in the months of May–June and in October, and sometimes a small secondary peak is observed in December.

The falling stage during a year is usually between 20 and 40 cm and is never more than 70 cm. The rising stage can be somewhat larger, and for the period 1899–1960 the maximum was 90 cm (in 1946–1947). During the 3-month period from October to December 1961, this stage rose 105 cm, and there was a further rise of 61 cm by June 1962. From April to July the west, north, and northeast parts of the lake rise more rapidly in level than the south part. The northern part of the lake rises about 45 cm more than the southern part.

Lake Kyoga. Lake Kyoga basin lies between latitudes 0°30′N and 3°30′N and longitudes 31°30′E and 34°50′E. Its drainage area of 75,000 km² includes most of Karamoja, the western half of Mount Elgon, Debasin Mountain, and most of the land between Lake Kyoga and Lake Victoria. The area is characterized by a series of low hills and flat valleys with impeded drainage.

Lake Kyoga proper extends from 1°00′N to 2°00′N and from 32°10′E to 34°20′E. The arms of the lake are enclosed by high land. From the latest areal photographs the lake area including the fringe swamps is estimated to be about 6300 km² at a contour of 1020 meters. The lake is generally shallow, the maximum recorded depth being about 7 meters.

The lake is mainly fed by the Victoria Nile, which runs in a well-defined channel for approximately 70 km from its exit at Jinja and which is interrupted by a series of rapids before it enters the lake some distance downstream of Namasagali. The outlet of the lake is at Masindi Port, after which the Kyoga Nile runs as a sluggish swampy river before being interrupted by another series of rapids. Then this section of the Nile passes over the Murchison Falls and broadens until it ends in a swampy delta at the Lake Albert exit. Most of the rivers draining into Lake Kyoga are swampy and lose considerable parts of their flows before entering the lake. The annual range of the lake level is 40 cm, and its all-time range is 3.81 meters. Its main supply comes from the Victoria Nile, which has an average flow of about 23 billion m^3.

Lake Albert. Lake Albert lies between 1°N and 2°20′N and 30°20′E and 31°30′E. It has a surface area of about 5500 km^2. The lake is 175 km long and 40 km wide and lies at an altitude of 620 meters above sea level. It is a part of the Great Rift Valley, which includes Lakes Tanganyika, Kivu, Edward, and George. Lake Albert has a recorded maximum depth of about 50 meters (168 feet) and a salinity of 480 ppm in comparison with 600 ppm for Lake Edward, 200 ppm for Lake Kyoga, 100 ppm for Lake George, and 65 ppm for Lake Victoria. The lake is mainly fed by the Kyoga Nile, which flows into its northern part. Semliki flows into its southern end, and small streams like the Muzizi, Nkussi, Wambabya, and Waki flow across the eastern escarpment. Its outlet is at Pakwach, after which the Albert Nile flows sluggishly in a swampy plain with a slope of 2.2. cm/km.

The normal range of Lake Albert is 45 cm, and its maximum range up to 1961 was 4.61 meters. In later years the level rose still further, and the all-time range is now reckoned at 5.3 meters. Tables 1*a–c*, 2, and 3 show the areas involved in the three basins of Lakes Victoria, Kyoga, and Albert.

VARIETY IN PHYSICAL AND HYDROLOGIC CONDITIONS

Mean annual precipitation is extremely varied over the project area. Rainfall over Lake Victoria varies from >2000 mm along the western edge to <700 mm near the eastern shore. Generally speaking, precipitation decreases with distance from the lake, and this tendency is particularly true on the western side. As the high elevations in Kenya are approached to the east, precipitation increases again to as much as 2000 mm. Tentative estimates put the average annual rainfall over the lake at 1400 mm, over the land catchment at 1000 mm, and over the catchment in east Africa as a whole at about 1200 mm. Rainfall in Karamoja and the southern shore of Lake Victoria is much less.

TABLE 1*a*. Areas in the Lake Victoria Basin: Total Land and Water Distribution

	Area, km^2	Area, %
Lake Victoria (less islands)	67,800	25.6
Islands	1,500	0.6
Mainland	193,900	73.8
Total	263,200	100.0

TABLE 1*b*. Areas in the Lake Victoria Basin: Land and Water Distribution by Countries in Square Kilometers

	Lake	Island	Land	Total
Kenya	3,900	...	44,000	47,900
Tanganyika	34,700	1000	84,200	119,900
Uganda	29,200	500	32,100	61,800
Ruanda-Urundi	...	...	33,600	33,600
Total	67,800	1500	193,900	263,200

These variations in topographic and meteorological conditions produce corresponding variations in the hydrologic characteristics. The Kagera on the west in Tanzania and the Nyando in the east in Kenya are perennial rivers; however, the streams along the semiarid lakeshore in Sukumaland in Tanzania are seasonal and flashy, and the northern lakeshore and the Katonga basin in Uganda are swampy. Mean annual runoff varies from about 500–600 m^3/sec for the Victoria Nile to as little as a few hundred liters per second for some of the smaller rivers. Swift and steep rivers in the vicinity of Mount Elgon in Kenya are in sharp contrast to the sinuous meanders in the lower reaches and extensive swamps in the lacustrine ends of tributary streams.

IMPORTANCE OF THE LAKE SYSTEM TO THE RIPARIAN COUNTRIES

The data to be collected and studies to be undertaken by the project are of significance from

TABLE 1*c*. Areas in the Lake Victoria Basin: Land and Water Distribution in Percent

	Lake	Land	Total
Kenya	5.8	22.7	18.2
Tanganyika	51.2	44.5	45.5
Uganda	43.0	16.5	23.5
Ruanda-Urundi	...	17.3	12.8
Total	100.0	100.0	100.0

TABLE 2. Areas in the Lake Kyoga Basin

Catchment	Area, km^2
Kafue River	16,700
Lake Salisbury	24,000
Malawa River	14,100
Victoria Nile below Jinja	3,500
Omunyal	4,200
Sezibwa	800
Other areas including Lake Kyoga	12,200
Total	75,500

the viewpoint of economic development to all the riparian countries; the fields of hydropower generation; irrigation; flood control; inland navigation; swamp reclamation; urban, rural, and industrial water supplies; fisheries; recreation facilities; and tourism are particularly important.

As far as power is concerned, the most important plant at present is the one at Owen Falls Dam near Jinja with an installed capacity of 150,000 kw. The station is presently working on the 'run of the river' principle and as such does not represent any consumptive use of water. There are other minor power installations like the Kikagati plant on the Kagera near the Uganda-Tanzania border and the artificial reservoir upstream of the Mcalder mines in the Gucha Migori basin in Kenya. There are several other projects for power in various stages of consideration and action by the governments. These hydropower schemes require a knowledge of the quantum of continuous flow that can be expected in the rivers and the periods in which the flows above and below the normal would occur in order to evolve suitable patterns of power generation.

In the field of irrigated agriculture the sugar cane estates near Bukoba in Tanzania and Kakira in Uganda may be mentioned as examples of the existing irrigation facilities in the Lake Victoria basin besides the small schemes for some plantations in Kenya. Possibilities of extending irrigation facilities in the tributary basins and from the lakes are also being considered by the participating governments. Schemes for the use of water for irrigation would need data on the variations in river runoff from season to season within a year and from year to year over a succession of years.

Flood control structures or the inclusion of the element of flood control in multipurpose water resource development requires a study of the behavior and pattern of floods and the storms that produce such floods. For this purpose and for spillway design it is necessary to undertake detailed studies of the behavior of storms, their depths, durations, and frequencies over the catchment areas upstream as well as to develop estimates of maximum possible precipitation.

Lake Victoria is practically an inland sea on which navigation is of major economic importance. From a number of ports on the lakeshore, East African Railways and Harbors corporations annually transport >500,000 passengers and 500,000 tons of goods. The big ships that operate on Lake Victoria range from 1000 to 1500 metric tons. With wagon ferry terminals at selected port installations, Lake Victoria is a link between the northern and southern railway networks and also the eastern and western networks extending from Mombasa to Kasese and as far west as the Kivu province of the Congo. The EAR&H corporations are interested in the variations in the levels of the lakes from the viewpoint of the effect on navigation facilities.

There has been no detailed survey and mapping of swamp areas, which are extensive in the catchments of the lakes. On the basis of tentative studies conducted in the past the extent of the swamp areas may be around 10,000 km^2. Their reclamation is of interest not only from the viewpoint of agricultural development at these locations but also from the viewpoint of the overall effect of such reclamation on the hydrology of the lakes and the flows in the concerned tributaries.

The river basins and the lakes in the project

TABLE 3. Areas in the Lake Albert Basin in Square Kilometers

	Land	Lake	Total
	Lake Albert		
Uganda	13,504	3187	16,691
Congo	2,816	2278	5,094
Total	16,320	5465	21,785
	Semliki		
Uganda	2,610		
Congo	7,027		
Total	9,638		
	Lake Edward and Lake George		
Uganda	18,790	1062	19,852
Congo	6,976	1600	8,576
Total	25,766	2662	28,428

area constitute important sources for urban, rural, and industrial water supplies. In addition to major schemes of water supplies for towns and villages and stock ponds, important industries like breweries, cement factories, sugar mills, and mines also use water.

Fishing is an important traditional activity on the lake system. The total value of the catch in Lake Victoria is estimated at more than £5 million, and efforts are being made to improve the catch and its value. The interrelationship between hydrometeorology of the lake and fish biology is an area in which much information is yet to be known. The temperature and wind effects are factors that need further study. There are important game parks, places of tourist interest, and recreation facilities within the project area for which the use of water assumes significance.

More than eight million people live in the catchment of Lake Victoria alone. This total corresponds to a density of 50 inhabitants per square kilometer, which is above the average for Africa. However, much higher concentrations occur in large parts of the area. At the same time, large parts of the area are scarcely populated because of the presence of game reserves or marshes or for other reasons. In other places, densities higher than 80 inhabitants per square kilometer are frequent, such as in Entebbe, Kampala, the Jinja region in Uganda, the Kano plains in Kenya, and the Mwanza and Bukoba areas in Tanzania.

In such conditions, advanced forms of economic development such as intensive agriculture and industries are of great importance. The development of water resources constitutes an important infrastructure to both forms of economic development.

INTERNATIONAL ASPECTS OF THE NILE WATERS

The development of water resources of Lakes Victoria, Kyoga, and Albert is important not only to the countries of Uganda, Kenya, and Tanzania (besides other riparian countries in the Upper Nile like Rwanda, Burundi, and the Congo) but also to the Sudan and the UAR, which receive waters from the Upper Nile basin (besides the Blue Nile from Ethiopia). There were international agreements between Egypt and Uganda as early as 1929. Similarly, there were agreements between Egypt and Sudan; the latest one was in 1959, and it provided for arrangements for the technical cooperation between the two countries in regard to the Nile waters.

In the case of Lake Victoria the outflow is controlled by the Owen Falls Dam at Jinja, which is presently operated in such a manner that natural flow is maintained downstream. At the same time, there have been proposals under consideration from time to time for fuller use of the potential storage behind the dam by adopting commonly acceptable regulation procedures. Further, several control structures in the Upper Nile basin to control the releases from the three lakes for the common benefit of the concerned countries have been under consideration.

A scientific consideration of these various proposals for the regulation of the lake system and the possible future negotiations on allocation of waters among the riparian states would need a comprehensive determination of the water balance of the system of the lakes and hydrometeorological analyses of several involved parameters like rainfall, evaporation, inflow, and outflow on a commonly acceptable basis.

Although the data for such a scientific determination are adequate in some parts of the Upper Nile, the data are notably inadequate in some other locations. The objective of the present project is to fill the gaps and to provide the data that are necessary and important to facilitate international collaboration in the development of the water resources in an integrated manner, the entire river being taken as one basic unit.

OBJECTIVES

Therefore the major objectives of the project undertaken by the governments of Kenya, Sudan, Tanzania, UAR, and Uganda with the assistance of the United Nations Development Program (UNDP) and the World Meteorological Organization (WMO) are 'the collection and analysis of hydrometeorological data of the catchments' of the lakes

> . . . in order to study the water balance of the Upper Nile. The data collection and the study are expected to assist the countries in the planning of the water conservation and development and to provide the ground work for inter-governmental co-operation in the storage, regulation and use of the Nile.

The specific tasks assigned to the project are: (1) setting up additional data-collecting stations

(24 hydrometeorological, 156 rainfall, 67 hydrologic, and 14 lake level recording stations) and upgrading some of the existing stations to complete an adequate network from which basic hydrometeorological data can be collected and analyzed; (2) establishing seven small index catchments for intensive studies of rainfall-runoff relationships for application to other parts of the catchment area; (3) aerial photography and ground survey of those sections of the lakeshore areas that are flat and that will be most subject to change with variations in the levels of the lakes as well as a hydrographic survey of Lake Kyoga; (4) analysis and interpretation of data collected; and (5) training the staff of the participating governments in hydrometeorological work.

TECHNICAL PROBLEMS

The principal technical problems involved and the methods adopted toward their solution with special reference to Lake Victoria are described here. The general equation for the water balance of a lake can be written as inflow = outflow ± change in storage, or

$$I_r + P_L + I_G = O_R + E \pm S \pm O_G \quad (1)$$

where

I_r, inflow into the lake through the land catchment;
P_L, direct precipitation over the lake;
I_G, inflow from groundwater;
O_R, outflow through rivers;
E, evaporation loss;
S, change in storage;
O_G, outflow through groundwater.

In the case of Lake Victoria the groundwater factor both in inflow and outflow is considered insignificant, so (1) is generally written as

$$I_r + P_L = O_R + E \pm S \quad (2)$$

Then again, change in storage over a long period of time is assumed as being nil, so (2) for a long-term mean year becomes

$$I_r + P_L = O_R + E \quad (3)$$

or

$$I_r - O_R + P_L - E = 0 \quad (4)$$

The problems involved in the accurate determination of each of the above parameters may now be considered.

Inflow into the lake from the land catchment. In previous studies on water balance, estimates of mean annual inflow from the land catchment into Lake Victoria varied from 15 to 18 billion m³. Prior to the project, flow from 35% of the area (58% of the total flow) was measured, and flow from ungaged areas was estimated on the basis of rainfall, characteristics of the catchment, and similarity with other rivers. The augmentation of the hydrologic network by the project brought the gaged area to 80% and measured flow to about 90%. For estimation of flow from ungaged or difficult areas, seven small index catchments have been selected for dense instrumentation and intensive studies on rainfall-runoff relationships for application to other parts of the basin (four index catchments are situated within the Lake Victoria basin). As a result, it will now be possible to measure the inflow into the lake from the land catchment with much greater accuracy than before.

Outflow from Lake Victoria. Owing to the existence in the past of Ripon Falls and at present of the Owen Falls Dam near Jinja, the outflow from the lake has been measured with the greatest degree of accuracy of all the parameters in the water balance equation, because all the outflow from the lake is channeled through Jinja. The mean annual outflow is about 23.4 billion m³.

Direct rainfall over the lake. The determination of the value of the mean annual rainfall directly falling on the lake has always been a difficult problem because of the inadequate network covering such a vast area of the lake (69,300 km², including 1500 km² of islands within the lake), and there have been widely varying estimates, such as 1420 mm. Prior to the project (i.e., in 1967), there were nine rain gage stations on the islands and 24 stations on the lakeshore (a total of 33 stations) that could be used for working out direct rainfall over the lake. Based on this meager network, mean annual rainfall by the isohyetal method is estimated to be 1420 mm or about 100 billion m³.

The project has since added 20 stations on other islands and nine on the shore; these stations make up a total addition of 29 stations and bring the strength of the existing network to 62 to cover the lake. This network is expected to improve the degree of accuracy of the estimation of rainfall over the lake to about 13%. This degree of accuracy cannot be further improved on by conventional methods of increasing the network density because of the vastness of open water in the lake. Proposals were considered from time to time of the feasibility of determining aerial rainfall over the lake by methods of radar surveillance but were given up because of high costs, initial as well as recurring, and other difficulties. However, rainfall over the lake remains one of the sensitive parameters in the water balance equation.

Evaporation from the lake. Estimates of evaporation from the lake have previously been made on the basis of the water budget method by deducting outflow from estimates of inflow into the lake and rainfall over the lake. Recently, the project has set up five evaporation pans on five lake islands, as well as nine pans on the shore at some of the first-order meteorological stations. Thus data would be available from 14 evaporation pans on and around the lake for the direct estimation of lake evaporation. Besides the standard class A pans a Russian evaporation pan (20 m^2) has also been set up to help in the determination of evaporation by the pan method. Besides pan data, it is proposed that data be collected for the determination of evaporation by mass transfer and energy budget techniques.

The results obtained from the various methods will help an intercomparison and will help to formulate final estimates of evaporation in water balance studies. However, it is not possible to predict with precision the degree of accuracy of the estimates of evaporation over such a vast lake area. It will be realistic to consider that the degree of accuracy of the evaporation estimate will be less than that of the rainfall estimate.

Change in storage. It will be seen that in the above water balance equations the parameter relating to change of storage has been omitted from consideration because it is negligible when long periods of time are considered. But this negligibility will not be the case when water balance estimates are to be made for periods of a single year or a month. In this case, change of storage will be a significant factor to reckon with. In the previous estimates of water balance for Lake Victoria, this factor has been worked out on the assumption that, in view of the large size of the lake, surface area remains the same for different water levels in the lake. Although this assumption may be true for Lake Victoria as a whole, it will not be the case for critical flat lakeshore areas in select reaches. Therefore additional topographic surveys are under way in selected areas for refining estimates of changes in storage and for providing additional data for land use planning of such areas. In the case of Lake Kyoga a complete hydrographic survey of the lake is under way.

TABLE 4. Assumptions Made in Calculating Total Error in Water Balance Equation

Parameter	Value, 10^9 m^3	Error Assumed, %	Error, 10^9 m^3
Inflow from land catchment	18	5	0.9
Outflow	23.4	5	1.2
Rainfall over the lake	100.0	10	10.0
Evaporation from the lake	100.0	10	10.0

LIMITATIONS

To combine the total error in the water balance equation from the individual errors in the estimations of individual parameters involved, let us make the assumptions shown in Table 4. Then the error in the global water balance equation will be $(10^2 + 10^2 + 1.2^2 + 0.9^2)^{1/2} = 14$ billion m^3 (approximately). This amount is a considerable quantity of water in comparison with the order of inflows into and outflows from the lake. Moreover, the possible degrees of error in the estimations of the parameters of rainfall over and evaporation from the lake are so decisive in comparison to the other two elements because of the vastness of the lake that the importance of as accurate a determination of these two parameters as possible can hardly be over emphasized.

CONCLUSION

The objective of the hydrometeorological survey of the catchments of Lakes Victoria, Kyoga, and Albert being the determination of the water balance of the lake system, the approach and the assignment of the project have been to collect data to enable the determination in as accurate a manner as possible of the values of each one of the parameters involved in the water balance equation, namely, rainfall over lake and land areas, evaporation, inflows, outflows, and changes of storage. In view of the large size of Lake Victoria the water balance equation is highly sensitive to the values of direct rainfall over and evaporation from the lake and the differential between the two parameters.

Retardation of Evaporation from Open Water Storages

Es. P. Kumaraswamy
Irrigation Research Station, Poondi Public Works Department, Madras, India

In the present context of overall development and scientific advancement the demand for water has increased considerably as a result of the increase in population and industrial activity. But the available resources of water, particularly in the arid and semiarid regions, are limited. Any development of water resources should therefore ensure efficient control, conservation, and use of available water. This goal would mean the restriction of all avoidable losses, such as evaporation losses and seepage losses. Whereas seepage loss in watercourses and fields returns to streams and aquifers for reuse, evaporation loss signifies water that is finally lost from the available supply. Hence there is need for more emphasis on minimizing, if not preventing, the vast losses due to evaporation. In Australia, the United States, and other countries, research carried out during the past decade indicated that straight chain and fatty alcohols possessed the capacity to spread and thus to give cover on the water surface and suppress evaporation. Cetyl or stearyl alcohol or a combination of both was found to be specially adaptable. Experiments were taken up in arid zones of India to assess the efficacy of these alcohols under Indian conditions.

This report deals with such an experiment conducted at Buderi, where, in addition to efficacy, practical feasibility was also studied. The various methods of application of the compounds on the water surface and the techniques of testing and assessing the results of the field tests are discussed.

Engineers and hydrologists engaged in the design and operation of storage reservoirs particularly in the arid and semiarid regions are well aware of the enormous loss of water by evaporation. For the Indian subcontinent, this loss generally varies from 1.9 to 2.2 meters (6 to 7 feet) of storage of water per year. It is a universally acknowledged fact that lack of water more than anything else hampers and restricts the development of certain areas on both the agricultural and the industrial fronts. In the dry regions, particularly, a rapidly increasing population tends to accentuate the critical water supply position. In irrigation, depths of water evaporated from the surfaces of ponds, lakes, reservoirs, seepage areas, rivers, canals, and open conduits constitute a loss of water that otherwise could be delivered to the fields.

Storage reservoirs are a major source of loss of water since they expose vast surfaces to evaporation. In the case of small reservoirs and tanks, which are usually shallow, the loss by evaporation may frequently be more than the amount actually used. In such cases, evaporation control will increase the quantity of water available for beneficial use and will improve the quality of water, since evaporation removes only pure water.

Methods of evaporation control should aim at exposing the least possible extent of water surface. Control methods include impounding water in narrow, deep reservoirs and covering water with a fixed or floating roof. If the water surface could be kept covered, the evaporation losses would be minimized to a very great extent. But this method is impractical, and the cost is prohibitive even for very small areas. So recourse was taken to the use of a monomolecular film to provide a floating cover. Alcohols having long chain structures (such as cetyl alcohol and cetyl stearyl alcohol) form a monomolecular film on contact with water; this film is sufficiently enduring under field conditions. The field tests show that a monomolecular film of cetyl and cetyl stearyl alcohols can reduce evaporation losses significantly. In this report, studies conducted relating to the use of monomolecular film and the measurement of actual evaporation losses and seepage losses in the field are dealt with.

EXPERIMENTAL SETUP

Experiments were carried out in Buderi tank near Poondi in Madras state. This tank is situated just 3.2 km (2 miles) southwest of the irrigation research station at Poondi and is adjacent to the Poondi Reservoir on the western side. The tank has a water spread of about 11.2 ha (28 acres) at full-tank level and a maximum depth of 3.7 meters (12 feet). It was ideal for conducting studies because the water was not used for irrigation or any other purpose and the inflow was limited to monsoon periods only.

The land pans and the meteorological instruments were located on the periphery of Buderi Lake. The meteorological instruments were (1) a maximum-minimum thermometer for recording temperature, (2) a wet and dry thermograph for automatic continuous record of the wet and dry bulb readings, (3) a recording type of rain gage, (4) a hair hygrograph for automatic continuous record of relative humidity, (5) two anemometers (one at 1.9 meters and the other at 4.3 meters of elevation from the ground level) to record the wind velocities, and (6) a wind vane for recording the direction of the wind.

Of the above instruments the maximum-minimum thermometer, wet and dry thermograph, and hair hygrograph were mounted on standard Stevenson's screens under conditions stipulated by the Indian Meteorological Department. All the automatic recording gages were devised on a clockwork mechanism. The readings of the maximum-minimum thermometer and anemometers as well as the direction of wind (indicated by the wind vane) were observed at 8 A.M., 12 noon, and 4 P.M. every day. The standard charts for the automatic continuous recording instruments were changed at 8 A.M. every day. Apart from these, separate sensitive thermometers were used for measuring the temperature of the air, the water in the pans, and the water of the tank. The levels in the various pan and floating evaporimeters were noted daily.

METHOD OF DISPENSATION

There are various forms of applying the chemical cetyl stearyl alcohol onto the water surface; some of them are solutions, emulsion, powder, and pellet. The first three of these forms were used in the experiment.

Solution. Before starting the field experiments at Poondi, preliminary experiments were conducted in the Concrete and Soil Research Laboratory at Madras to arrive at a suitable solvent for the chemical. Of the several solvents tried, mineral turpentine was the least volatile, and, although it was a bit low, its solvent power for cetyl alcohol was sufficient. Hence this solvent was used in the field experiments conducted.

For application in the field, about 448 grams (1 lb) of cetyl alcohol dissolved in 7.6 liters (2 gal.) of mineral turpentine was found to be a good solvent at almost saturation limit for dispensing in solution form. The mineral turpentine helps in no way to reduce evaporation, but it helps the chemical to spread and cover the whole water surface quickly. The mineral turpentine, being volatile, evaporates and leaves the cetyl alcohol on the water surface.

The solution prepared was applied to the water surface by traversing the lake on boats as well as from the shore. Sprayers were used to spray the solution. Cylindrical dispensing units with conical bottoms were also set up on shore all along the periphery of the lake. The chemical dripped slowly and constantly from these units. Those units situated on the windward side were operated with consideration of the direction of the wind. This method proved to be advantageous on windy days.

Emulsion. Since the use of the solvent mineral turpentine was found to be costly, dispensing the chemical in emulsion form was tried. The emulsion was prepared in the following manner. The prescribed quantity of cetyl alcohol was powdered and placed in a drum with a little soap powder; 3.8 liters (1 gal.) of water was added to it. The mixture was then heated to 80°C, at which point the cetyl alcohol was completely dissolved. This mixture was then churned well for an hour until it turned into a paste. The requisite quantity of water heated to 80°C was added to this paste, and the mixture was again churned well for 1 or 2 hours. The churning could be done by either an electrically driven churner or a manually operated churner. In the former case the mechanism consisted of an electrically driven motor with a long spindle attached to its armature carrying a paddle with vanes on the other end. The emulsion could also be prepared to the same consistency with a manually operated churner; the two methods were equally good. To keep the mixture in emulsion form for a long time, an emulsifier called 'cheekol' was used. A mixture of 3.8 liters (10 gal.) of water poured into

448 grams (1 lb) of cetyl alcohol and melted and kept in a liquid form was used, and a few drops of cheekol were added to the mixture. The liquid was churned for 30 min, and the emulsion full of foam was prepared. The emulsion was transported to the place of injection and dispensed on the water surface.

To dispense this emulsion, a funnel with a regulating valve was employed. The dripping of the emulsion was regulated by the valve. The emulsion was dispensed throughout the water surface, and the film strength was tested. For preparing emulsion, quantities of cetyl alcohol varying from 0.9 to 1.35 kg (2 to 3 lb) were used daily.

Powder. Another form for application of the chemical is the powder form. The alcohol, which is supplied in the form of big lumps, had to be pulverized and made into a fine powder before it could be applied to the water surface. For this purpose a ball mill of 285-liter (75-gal.) capacity was installed. The ball mill is a cylindrical drum rotated at a constant speed by an electric motor through suitable reductions. A suitable quantity of small bits of steel called cylpebs is placed inside the cylinder; these cylpebs act as pulverizers. It takes about an hour to get a powder of uniform fineness. The powder thus obtained was applied to the water surface as a fine spray by the use of hand rotary dusters, which were operated manually by rotating a handle. The spray issuing from the nozzle can be adjusted by means of a lever. The dusters are portable and handy for operation, and the spraying can be done from shore as well as from a boat.

CHARACTERISTICS OF MONOLAYER

Experiments have shown that a method of detecting the presence of a monolayer and determining the degree of compression is required in evaluating the effectiveness of the monolayer as an evaporation retardant. Indicator oils of standard strengths were employed for this purpose. However, it has been found that the location of the monolayer on a large surface can be observed visually and also can be photographed easily from vantage points above the water surface. During periods of calm wind conditions the whole lake surface took on a glossy appearance, characteristic only of the areas covered by the monolayer. A compressed monomolecular film was remarkable for its ability to quiet ripples on the water surface. However, during rough conditions of weather it was impossible to spot the covered regions except in small streaks.

Dosage. Several factors affected the rate at which the alcohol was applied to the reservoir, the most important being previous film coverage, wind, and the operational procedure used. For Buderi Lake it has been observed that the rate of application varied from 46 to 225 grams (0.1 to 0.5 lb) for the first two methods and was about 360 grams (0.8 lb) for the powder method. Applications were made during the daylight hours for short periods ranging from 7 to 10 days. The film losses by wind action, attrition, and so on were made up by fresh dosage.

Pressure and durability of monolayer. Film pressure was tested by indicator oils of standard strength. If the film does not exert sufficient pressure, a drop of indicator oil will disperse. If the pressure is higher than that of the indicator oil, the oil will stand as a discreet drop. The use of such indicator oils of different strengths made it possible to assess fairly accurately the presence of a monolayer and its surface pressure within a range. The following indicator oils were used: Shell high-speed diesel oil, 13 dynes/cm; Shell vitriol 13, 16 dynes/cm; Shell vitriol 21, 24 dynes/cm; and Shell Ensisfluid, 40 dynes/cm.

It was concluded after experiments in other parts of the globe that for a film pressure of <5 dynes/cm, the retardation of evaporation was little; however, between 5 and 40 dynes/cm, retardation increased steadily to its maximum. Also, 40 dynes/cm was the equilibrium value at which the film was found to offer maximum resistance to the escape of water molecules.

The factors that adversely affect the maintenance of the monolayer are strong winds and the bacterial and protein content of water. But wind may be considered as being the most important. At wind speeds of 2.2–4.4 m/sec (5–10 mph), with variable directions, extensive areas can be covered with relative ease; with a speed of <2.2 m/sec (<5 mph), practically the whole lake can be covered with the monolayer. However, at wind speeds of 9 m/sec (20 mph) it is impossible to maintain the film on the water surface.

ASSESSMENT OF EVAPORATION

The total loss from the lake is constituted by the losses due to seepage from the lake and losses due to evaporation. The seepage loss from any lake or reservoir is governed by the characteristics of the soil forming the bed and banks and by the depth of the water column.

The lake level fluctuations during an untreated period and the loss from the untreated floating pan evaporimeter for the same period were determined. To allow for the vast surface of the lake, a coefficient of 0.8 was used with the loss from the untreated floating pan to obtain the natural evaporation from the lake. The natural evaporation loss thus obtained was subtracted from total loss from the tank to give the seepage loss, which was assumed to be the same for the next treated period, the consecutive periods being made so short that the lake level did not fall by more than 15 cm during the test periods.

The total loss from the lake was determined by the fall in water level. By subtracting the seepage loss from the total loss, the evaporation loss could be arrived at. The evaporation losses from the tank were arrived at from the floating pan evaporimeter, the pan coefficient used being 0.8. The value of evaporation loss obtained during untreated periods was taken to be the evaporation loss during treated periods. To make this method applicable, experiments were carried out with alternate treated and untreated periods (7-10 days each).

COMPARATIVE STUDY OF THE THREE METHODS OF DISPENSATION

Though all three methods basically give rise to the same effect (i.e., the formation of a monomolecular film on the water surface), each method has its own merits and demerits from the points of view of application, economy, ease of operation, effectiveness, and so on. All three methods are applicable to field conditions, and, for large reservoirs, boats are used for carrying out spraying operations.

For preparing the solution, large quantities of mineral turpentine are required, and this necessity increases the cost. Only water and a very small quantity of cheekol or some emulsifier like soap are required for emulsion. So far as the powder form is concerned, larger quantities of powder have to be sprayed to obtain good results. The following statement gives a quantitative idea of the savings that have been achieved under the various methods:

Form of Application	Liters Saved per Rupee Spent
Solution	5130
Emulsion	10,830
Powder	low and highly inconsistent

Cost of operations and quantities of water saved are given in Appendices 1 and 2.

For preparing and dispensing the emulsion or solution, no power-driven equipment is required, but for preparing the powder form a ball mill is required. When sprayed through hand rotary dusters, the powder at times chokes the nozzle; it also forms into lumps if stored for long periods. From economic considerations and facility of operation, the emulsion method appears to be the best under local conditions. But if we consider the fact that the alcohol is an imported commodity in comparison with mineral turpentine, which is manufactured indigenously, the solution method may compare favorably with the emulsion method.

DISCUSSION AND CONCLUSIONS

The aim of the study was to assess the efficacy of the straight chain alcohols in reducing evaporation under Indian conditions and recommend a suitable method of dispensing the chemical. The experiments at Buderi were done during a period extending over 6 years. Three methods of dispensation were tested, namely, solution, emulsion, and powder form. Initially, the solution method with the alcohol dissolved in mineral turpentine was adopted. This method was amenable to easy dispensing, and spreading was very effective. The cost of the turpentine storage and the transportation charges were the disadvantages. Next, the emulsion method was attempted. This method has been almost condemned in the western countries. Initially, emulsion was prepared with the help of an emulsifier, but, later, manually prepared emulsion was seen to be as good. The cost of preparation was thus very low in comparison with the solution method. The spreading was quite good under moderate wind. This method does not require power or an auxiliary chemical and appears ideal for Indian conditions. As a third method, the powder form was tried. This method required equipment such as a ball mill, dusters, sprayers, and so on. The ball mill required a power supply, and the application of the powder required petrol and oils. Moreover, the powder could only be stored for about a week, after which it had a tendency to clot together to form small lumps. During dusting or spraying a part of the powder was carried away by the wind and lost, so the alcohol required was roughly double that needed for the solution method.

The efficacy of spraying alcohol was found to decrease with an increase in temperature. It is clearly observed that percentage savings for the tropical climate of this country are about 20% as against 50–60% in the United States, Australia, and other places where the climate is temperate. It is also to be mentioned that alcohols have to be imported, and an attempt at mass production of an indigenous equivalent has not yet succeeded. Study with a small sample, however, indicated that an indigenous equivalent will be even slightly better than the imported alcohol, but the problem of mass production does not appear to have been taken up.

APPENDIX 1: SOLUTION METHOD

Treatment period: February 1 to February 9, 1960 (8 days)

Evaporation loss from untreated floating pan: 17.5 mm

Natural evaporation loss: 17.5 mm × 0.8 = 14 mm

Total loss from the tank during the same period: 31 mm

Seepage loss for 8 days: 2.5 mm × 8 = 20 mm

Restricted evaporation loss: 31 mm − 20 mm = 11 mm

Savings due to treatment: 14 mm − 11 mm = 3 mm

Percentage savings: (3/14) × 100 = 21.4%

APPENDIX 2: EMULSION METHOD: COST OF OPERATIONS AND QUANTITY OF WATER SAVED

Method of Calculation

To work out the cost of operations, the following rates were adopted: 448 grams of cetyl alcohol, Rs1.50; three mazdoors for spraying and rowing the boat per day, Rs4.50; and petty expenses per day (such as firewood and soap powder for making the emulsion), Rs0.50. The quantity of water that would have been lost if the film had not been applied is determined from the water level capacity curve.

Sample Calculation

Duration of test period: 10 days.

Water level in the tank at the start of the experiments: 3.7 meters.

Depth of water that would have been lost owing to natural evaporation of lake if not treated: loss from untreated floating pan times 0.8, i.e., 51.55 × 0.8 = 41.24 mm.

Quantity of water for the loss of 49.5 meters of head: 1200 m^3.

Percentage savings due to treatment: 20%.

Quantity of water saved by treatment: 6000(20/100) = 1200 m^3.

Total cost of operation: cetyl alcohol cost 30 × 1.5 = Rs45.00; labor charges were 4.5 × 10 = Rs45.00; petty expenditures toward firewood, soap powder, and so on amounted to 0.50 × 10 = Rs5.00; the total was Rs95.00.

Quantity of water saved per rupee: 1200/95.00 = 12.6 m^3, and 12.6 m^3 × 995 liters = 12,500 liters.

Accuracy for the Computation of Water Balance of a Large Reservoir of the USSR

Z. A. VIKULINA AND T. D. KASHINOVA
State Hydrological Institute, Leningrad, USSR

The study of water balance of large reservoirs of the USSR starts immediately when the reservoirs are filled; for this purpose a network of stations and gages is established on reservoirs and their tributaries to provide observational data essential for the preparation of monthly and yearly balances. For water balance computation the following equation is used:

$$Q_m + Q_l + Q_g + Q_p + Q_i$$
$$- (Q_{\text{dis}} + Q_{\text{in}} + Q_e + Q_f + Q_i) = A_y + A_u + H$$

where Q_m is the inflow into the reservoir from main streams; Q_l is the lateral inflow and inflow from small watercourses from the drainage area directly to the reservoir; Q_g is the groundwater inflow directly to the reservoir through its bottom; Q_p is precipitation (liquid and solid) on the surface of the reservoir; Q_i is the water content in ice and snowpack on the reservoir and on the banks accumulated in winter during the fall in water level and drifting in spring during the water level rise Q_i'; Q_{dis} is the discharge through hydraulic structures at the outlet; Q_{in} is the water intake for irrigation, water supply, and other needs; Q_e is the evaporation from the free water surface; Q_f is the filtration from the reservoir through its sides and bottom; A_y is accumulation (rise and fall of water level) in the reservoir; A_u is underground accumulation in rocks composing the shores of the reservoir; and H is the discrepancy of the balance.

All the water balance components except groundwater inflow Q_g, filtration Q_f, and accumulation in rocks A_u are determined by observational data from the station network established at the reservoir. Groundwater components Q_g, Q_f, and A_u are estimated only for selected reservoirs where special hydrogeologic investigations have been undertaken.

Methods for the study and computation of water balance of the reservoirs of the USSR have been described elsewhere; in the present paper an attempt has been made to determine the role of the least-studied water balance components and to evaluate the accuracy of the computation of the principal water balance components.

Water balance computations, the reliability of which is evaluated by the dimensions of discrepancy, are made with the accuracy sufficient for practice. The discrepancies are usually within the limits of mean square error estimated on the basis of random errors of the principal water balance components, i.e., surface inflow, discharge through hydraulic structures, and accumulation in the reservoir. Errors beyond the permissible limits are not numerous and account for 10–12% of the total number of cases. However, small discrepancies characterizing a sufficient accuracy of computation of the water balance on the whole are not representative for the evaluation of the accuracy of computation of individual water balance components. Therefore it is very important to determine the individual effect and reliability of the determination of all the water balance components, including those that are not estimated by the observational data from the station network. As has been mentioned already, the groundwater components fall into this category of water balance elements. Very often the underestimation of these elements is considered an important disadvantage of the methods of water balance computation of reservoirs; moreover, it is supposed that a proper evaluation of the groundwater component would make it possible to increase the accuracy of the water balance computation considerably. However, available information on water balance computation, as well as the results of special hydrogeologic investigations, indicate that the groundwater components in the water balance of reservoirs are rather insignificant; therefore even a very careful evaluation of these components cannot cause a considerable increase in the accuracy of water balance computation.

On the basis of special hydrogeologic investigations to characterize the depth of rocks drained by the reservoir, their physical properties, and the slope of the depression surface of groundwater for individual reservoirs (e.g., Rybinsk and Kuibyshev reservoirs), it was possible to determine the amount of groundwater inflow. The annual volume of groundwater inflow is 1.1 km^3 into the Kuibyshev Reservoir and is 0.3 km^3 into the Rybinsk Reservoir. These volumes are equal to 0.4 and 1%, respectively, of the surface inflow, since the mean annual surface inflow is 240 km^3 for Kuibyshev Reservoir and is 32 km^3 for Rybinsk Reservoir. Thus the groundwater inflow is very small, and its value is within the limits of accuracy of determination of the most important income component of the balance, i.e., surface inflow.

Losses by filtration occur very seldomly, since the location of reservoirs in large river valleys, which are mighty drains for the environment, usually eliminates the possibility of losses. On one of the large reservoirs, however, an intensive filtration into shores has been discovered. This filtration is due to karst limestones distributed over a certain area of the basin. Hydrogeologic conditions of this reservoir have been investigated very carefully, and a reliable evaluation of losses by filtration was made; the annual loss equals about 0.3% of the annual discharge through the hydraulic structures at the outlet of the reservoir. Thus losses by infiltration even under the most favorable conditions are quite small in the balance of large reservoirs.

Besides a direct flow of groundwater, some portion of the water temporarily accumulated in banks of the reservoir A_u contributes to the water balance of reservoirs. During seasonal water level fluctuations of the reservoir the stationary position of the groundwater table may be located only at the lowest water level of the reservoir. Above this level, there is a zone of variable backwater with the unsteady groundwater regime. In spring, when the reservoir is filled with snowmelt, bank filtration begins the groundwater level rise, and groundwater storage tends to increase. This process is terminated when the water level in the reservoir begins to fall, and then starts the depletion of temporarily accumulated groundwater that returns to the reservoir. This regularity was found during observations on a number of reservoirs and was proved correct on Rybinsk and Novosibirsk reservoirs where detailed hydrogeologic observations had been undertaken in the coastal zone for several years. On the basis of these observations it was possible to estimate the width of the zone of the backwater distribution in rocks, to define physical properties of rocks, and to determine groundwater level fluctuations at different distances from the edge of the water. On the basis of these data it was possible to determine the volume of water temporarily accumulated in the shores during different years. For Rybinsk Reservoir, this volume varies from 0.1 to 0.3 km^3; for Novosibirsk Reservoir it varies from 0.2 to 0.5 km^3, since its shores are composed of coarser and consequently more permeable rocks.

At a small absolute value of the mentioned water balance component, its relative value may be considerable with respect to the total volume of water accumulated in the reservoir A_y. For example, for Novosibirsk Reservoir, where the accumulation in the reservoir varies from 0.05 to 2 km^3, the amount of water lost in the ground (up to 0.5 km^3) may be comparable to A_r, and in this case it is desirable to take into account the groundwater component.

Precipitation and evaporation from water surfaces are more ponderable, though they are also secondary water balance components. In the yearly balance of reservoirs on rivers the portion of evaporation is 1–3%, but it becomes greater in summer, i.e., 10% and even 20% of the total discharge from the reservoir. In such cases it is very important to estimate the error of evaporation value and to consider such errors at the determination of mean square error of the water balance computation.

It is impossible to make a quantitative evaluation of evaporation from the surface of large reservoirs on the basis of direct measurements; therefore evaporation is estimated by formulas, and observations on water temperature and meteorological conditions above the water surface are used as basic data. Until recently, this method for the computation of evaporation was the only method used for operational needs. In the last few years the research results of the Main Geophysical Observatory, the State Hydrological Institute (GGI), and a number of hydrometeorological observatories on reservoirs made it possible to improve methods for the study and computation of the radiation balance, heat storage, and temperature of water on the surface of reservoirs. These improvements provided a wider application of the heat balance method in design practice to determine evaporation for particular years and months. Experimental computations, accompanied by the estimation of evaporation by the formula of the State Hydrological Institute, have been made for several reservoirs, but detailed computations have been performed for the reservoirs listed in Table 1. The values of total evaporation, estimated by two independent ways, are very close; the average discrepancy between monthly evaporation is ±15%, which may be considered a standard error of estimation of evaporation from the free water surface.

Inflow due to precipitation on the reservoir surface in the balance of reservoirs on rivers is insignificant, i.e., about 1-5% of the monthly and annual balances. Therefore even a greater accuracy of precipitation data may not considerably affect the computation results. Experience on water balance investigations shows that mean error for precipitation measurements may be assumed to be equal to ±20% approximately.

Errors in the determination of water accumulation in the reservoir A_y are considerable; moreover, they are very difficult to eliminate. The error for mean water level determination is, on the average, ±1 cm; this parameter serves as the base characteristic for the estimation of the accumulation by the stage-volume curve. For a large reservoir created on a river, if its area reaches thousands of square kilometers, the error for the accumulation may be several dozen million cubic meters; i.e., the error becomes comparable with the surface inflow during low water in summer and in winter and with the amount of accumulation during these periods.

The reliability of surface inflow estimation, as well as that of discharge through hydraulic structures, is of the utmost importance for the accuracy of water balance computations, since these elements comprise >90% of the water balance of the reservoir. According to the estimation accepted for hydrologic practice the accuracy of hydrometric discharge measurements is ±5% on the average, though it may vary considerably under unfavorable conditions. The analysis of data on the inflow to the reservoirs on the Dnieper River, made by R. A. Shostakova, testifies to the decrease of accuracy in the determination of inflow in spring and in late autumn, when the error of monthly inflow determination is about 15-18% and even 20-25%. In other months, if discharge measurements are taken when the river is free from ice and runs within its channel, the error of monthly inflow determination does not exceed ±5%.

It is supposed that discharge through hydraulic structures, the most important expenditure component of the balance, is estimated with greater accuracy than hydrometric streamflow measurements are. However, the detailed analysis of flow measurements on several hydroelectric power plants of the USSR revealed greater errors in the estimation of this component. These errors have numerous causes, e.g., application of approximate data on mean daily capacity and mean head of turbines. As a rule, mean daily capacity is determined from the total operation of all the turbines (in hours) without subdivision into individual units; mean head is determined by a restricted number of measurements insufficient to fix head variations at the maximum consumption of electric energy. Because of this averaging a certain underestimation of discharge takes place, and the errors of flow estimation are 8-10%. In some periods, especially during spring snowmelt floods, the errors of measurement of discharge through hydraulic structures may be 12-15%.

TABLE 1. Evaporation Computations

Method for Estimating Evaporation	Reservoir	Year or Period	Evaporation from Free Water Surface, mm							
			May	June	July	Aug.	Sept.	Oct.	Nov.	Total
GGI formula	Rybinsk	1962	21	94	73	80	45	32		345
Heat balance method	Rybinsk	1962	23	94	73	83	46	23		342
GGI formula	Kuibyshev	1957 to 1966	76	121	143	133	102	75		650
Heat balance method	Kuibyshev	1957 to 1966	52	106	153	164	126	86		687
GGI formula	Tsymliansk	1966	93	103	162	204	167	79	44	852
Heat balance method	Tsymliansk	1966	62	129	138	220	125	106	48	828

Thus actual errors in the individual determinations of components of water balance considerably exceed their mean values; therefore a sufficient closing of the balance (when discrepancies are rather small) is the result of a mutual compensation of errors with different signs. Meanwhile, at present, the problem of daily inflow estimation becomes very acute, and it becomes necessary to estimate the accuracy of the most important water balance components for daily intervals and to solve the problem of the reasonable use of the water balance method for daily inflow computation. The latter problem has been already considered by some scientists; recently, the authors have estimated the daily inflow for several reservoirs by two methods: from hydrometric measurements Q_h and as the residual term of water balance Q_b. Principal conclusions obtained from the preliminary analysis are as follows:

1. Close values of Q_h and Q_b have been obtained only for periods characterized by an abundant volume of water (in spring), when the errors of determination of accumulation are not great in comparison with the inflow into the reservoir and discharge through the hydroelectric power plant. In this case, daily inflow may be determined with the average error of ±20% when either of the two methods mentioned above is used.
2. At the initial period of reservoir filling (when the accuracy of discharge measurements tends to decrease and great errors occur at discharge measurements through spillways) as well as during summer and winter low-flow periods due to accumulation errors (comparable to the value of the decreased inflow), the application of the water balance method is not reasonable for determining daily inflow into the reservoir. The discrepancy between Q_h and Q_b is equal to tens and even hundreds of percent under such conditions.
3. During periods mentioned in point 2, daily inflow should be determined by hydrometric measurements, and their accuracy should be estimated for different conditions. The estimation of accuracy should be made for periods with different rates of flow, and the available hydrometric data on surface inflow and the regulation of tributaries should be taken into account.

These problems, aimed at the improvement of methods for the study and computation of daily inflow into reservoirs, are of the first priority in the development of water balance investigations on the reservoirs of the USSR during the next few years.

Seepage Losses from Lake Nasser

TAHER ABU WAFA AND AZIZ HANNA LABIB
High Dam Authority, Cairo, Arab Republic of Egypt

The Aswan High Dam, a bold structure, which may be considered among the most significant works in the engineering field, is a productive and protective plan of the first order. Water conservation, flood protection, and storage are the primary purposes of the High Dam and of Lake Nasser, which the dam impounds. Lake Nasser is the second largest man-made lake in the world, and it gives agriculture a net yield of 74,000 million m^3 of water annually.

Work on the project started in 1960 and was completed in 1970. The rising water behind the dam is now creating the big lake. Its gross water content at the maximum storage level of 18,300 meters will be 164,000 million m^3, a little less than the lake capacity of Bratsk Dam in the USSR. The capacity of the lake of Bratsk Dam is 175,000 million m^3, and this lake is at present the world's largest man-made lake. The large capacity of Lake Nasser can guarantee, in all years, the irrigation requirements for 3,130,000 ha in Egypt for the production of cash crops and can generate 2.1 million kw to provide annually an electric energy of 10,000 million kw hr to be used in industrial fields.

In places the lake has a width of up to 25 kilometers, but it is considerably narrower at the south end. At full storage it covers an area of 5900 km^2. Before construction of the dam the losses from the new reservoir were estimated at about 10,000 million m^3 annually, of which 9000 million m^3 were losses due to evaporation from the surface. The average seepage losses were rationally estimated at 1000 million m^3/yr.

SEEPAGE INVESTIGATIONS IN THE EARLY STAGES OF DESIGN

The region of the new reservoir of the High Dam covers the reach of the old Aswan Dam Reservoir up to Wadi Halfa, a distance of about 350 km, and extends farther southward into the Sudan for a distance of about 150 km. Along the first 50 km from the dam and along the last 150 km in the Sudan territory the banks of the river containing the lake are of granite basement outcrops that are practically impermeable. Along the remaining 300 km the river cuts the sedimentary Nubian formation of sandstone, the permeability of which is known to be very low.

All hydrologists who studied the problem of seepage in the reservoir in the early stages of the project were of the opinion that the places where crystalline basement forms the reservoir basin would be impermeable in general. A higher permeability would be possible in the Nubian formation of sandstone, but it must be taken into consideration that this formation contains repeated clayey fine-grained sandstone layers that can be considered to have almost no permeability.

They estimated the rate of seepage into the Nubian sandstone to be 2000 million m^3/yr at a lake level of 180 meters and 600 million m^3/yr at a level of about 150 meters. At the very high levels of the new lake, losses may be excessive, but in this case the losses would be advantageous as they would help in getting rid of the excessive floodwaters that do not contain silt and that, if left to escape downstream of the dam, would cause damage to the riverbed by scour. Other geologists even expected that the fine-grained clay materials that remain suspended for a long time in the stored waters would ultimately seal any porous rock and reduce greatly the seepage losses from the storage.

Helstrom, the Swedish consulting engineer who has several published studies on the underground water in the Libyan plateau, was able to estimate the velocity of water through the Nubian sandstones under a gradient of 1 : 2000 at about 15 m/yr. This very small velocity of percolation was calculated for an estimated coefficient of permeability in the Nubian sandstone at Dakhla Oasis of the order of 2.3 ×

10^{-3} to 8.4×10^{-2} cm/sec. In 1960, during the investigation of the salvage of Abu Simbel temple in Nubia, permeability tests in Nubian sandstone within the lake limits showed an overall permeability of even less than 4×10^{-5} cm/sec.

Dr. Hurst, hydrologic consultant to the Egyptian Ministry of Irrigation in Cairo, when asked in 1961 to express his opinion on the problem of seepage losses from the reservoir, mentioned that

> The water table under the Western Desert has been mapped (Ball, Murray, Helstrom) from levels in wells and shows a gradient from the mountains of Tebesti north-northwestward toward the Nile. The flow of the water through the sandstone, owing to low permeability, is extremely slow, and Helstrom gives a velocity of 15 meters a year. The rain which produced the water now in Egypt fell 100,000 years ago, so that the water has been called 'fossil' water. This water which is the source of water in the oasis does not come from the Nile.

He added that

> Helstrom gave the permeability of sandstone from experiments on samples and on wells in Dakhla Oasis and also quoted measurements from America, Sweden, and the great artesian area of the Australian desert. They were very similar (most of them are of the order of 10^{-4} or less).

At this stage of design work on the project it was believed that, if any definite faults would increase possible seepage losses from the new lake, these would become evident and it would be possible to deal with them. Moreover, there was no evidence of such faults, or the old Aswan Dam Reservoir would have shown larger losses than it did.

CHARACTERISTICS OF THE RESERVOIR AREA

The reservoir area lies in the Nubia plain where vegetation is very scarce and poor. The desert conditions are extremely rigid. The area is practically rainless, arid, and lifeless, and no surface water resources are known.

Most of the area that is to be flooded by the new lake is covered by Nubian sandstones consisting of variegated sandstones and clays (shales) overlying the basement. Sandstones are stratified, and their bedding is horizontal or slightly inclined. Variegated shales of the Upper Cretaceous period overlie the Nubian sandstones. They are normally developed on altitudes that will not be flooded. Older gravel terraces and recent dune sand formations are found in Wadis.

Two main directions of technical lines are developed in the region. One is east-west, prevails in the southern part of the area, and is most noticeable in the Wadi Kalabsha faulted complex; the second is north-south and prevails north of Wadi Kalabsha.

From observation in the field the faults are nearly vertical and filled either by siliceous cement or iron oxide cement. This cementing material is more resistant to weathering than the Nubian sandstones. Thus filled and sealed faults represent now conspicuous ridges on the surface that can be seen and followed for many kilometers. On the east bank of the river, such detailed data about tectonics are not known.

HYDROLOGIC INVESTIGATIONS IN THE CONSTRUCTION STAGES

During the first stages of work on the High Dam it was found to be essential to collect information about the underground water table in the layers of the Nubian sandstone on the banks of the river and to detect how this water table is affected by the rise and fall of water in the lake of the old Aswan Dam. For this purpose, eight bore holes were drilled in 1962 on a section across the Nile at Garf Hussein (100 km upstream of the dam). Geologic examination of the extracted core samples from the bore holes revealed that the sandstone prevailing in the area is of different grain sizes and colors. The local cracks noticed at the surface are usually vertical and parallel to the course of the river. They were found to be filled and cemented by iron carbonates and limonites and are more or less sealed.

Down to a depth of 20 meters, which is well below the permanently saturated rock, the coefficient of permeability was found to be between 2×10^{-3} and 2×10^{-4}. A study of the water levels inside the bore holes revealed that the very small velocity of percolation caused by filling and emptying of the old reservoir falls off in amplitude very rapidly, so that the distance over which it has any practical effect was a matter of hundreds of meters rather than kilometers. The level of the underground water beyond this distance is not affected by the water level in the reservoir; this finding proved that the expected seepage losses from the new lake of the High Dam were reasonably estimated.

In 1964 the first-stage works on the High Dam were completed, and partial filling of the new lake was started. A new program of work was planned and executed to supplement the seepage investigations that were performed in 1962. The new investigations were carried out to cover the area of the new lake, from the High Dam southward to Wadi Halfa. The purpose of the new investigations was to obtain reliable data on the surface geologic and lithologic characteristics, permeability, and groundwater relations of the sedimentary rocks forming the bottom and banks of the lake in this area. Thus, on the basis of the collected data, controversial opinions on the seepage losses would be corrected, and an approach for more realistic estimation of these losses could be achieved.

The new investigations included drilling more bore holes and permeability tests at three cross sections across the Nile at Garf Hussein, Toshka, and Adindan (100, 240, and 311 km, respectively, upstream of the High Dam). The bore holes were drilled down to about 10 meters below the riverbed level. Other deep bore holes were also drilled at these cross sections down through the layers of sedimentary rocks to hit the basement igneous rocks.

In total, 29 shallow bore holes and five deep research bore holes hitting the basement complex have been completed. Twenty-three of the shallow bore holes and all the deep bore holes were completed as piezometers and were equipped with automatic water level recorders. The total length of all bore holes reached 4617 meters, of which 1747 meters were tested for permeability.

A study of the extracted core samples and permeability tests inside the bore holes and of the water levels inside the piezometers revealed the following:

1. The total area within the limit of the new lake in the river valley up to Wadi Halfa is covered by Nubian sandstones. The Nubian sandstones are underlain by granite basement. Overall thickness of the sandstones is about 400 meters; this thickness decreases gradually toward the east, west, and south. The sandstones are prevalently in a horizontal position and are interbedded with clay. False bedding in sandstones is common. They are consistent, medium hard, abrasive, fine to coarse grained, and cemented by clayey and siliceous cement. They do not contain limey grains or cement. Mica particles are rare, but carbonized plant pieces are common in deeper sections.

2. Concerning tectonics, two directions of faulting predominate. One is north-south and prevails north of Wadi Kalabsha, and another is east-west and prevails in the Wadi Kalabsha faulted complex. The Kalabsha zone is the most disturbed zone and consists of fine-grained well-cemented hard and compacted sandstones. Faults and fissures are sealed by siliceous and iron oxide materials that have been injected in past geologic periods by ascending solutions.

3. The coefficient of permeability of the Nubian sandstones parallel to bedding was found to be in the area of 3×10^{-4} cm/sec, and that perpendicular to bedding overall is of the order of 5×10^{-5} cm/sec. The overall porosity is in the area of 25%.

4. On the basis of the recorded water levels in the piezometers of the deep and shallow bore holes it appears that at present there are at least two groundwater aquifers in the Nubian sandstones separated by a layer of variegated impervious clays: the upper unconfined aquifer that is completely penetrated by the riverbed at Garf Hussein and the deep aquifer that is confined and is at present not affected by the water of the river. The deep confined aquifer is recharged mostly from the Eastern Desert as well as from the southwest.

5. On the basis of the same piezometric levels and the prepared water table maps it was possible to conclude that before the erection of the old Aswan Dam the groundwater was seeping from both banks into the river. A proof of this conclusion was Dr. Ball's observation in the year 1898 at Dakka, a site about 100 km upstream of the dam, of warm water seeping into the Nile at the 100-meter level on both banks. He later inferred from this observation that the Nile here had cut into the same water-bearing beds that supplied the oasis of the Western Desert. However, after the filling of the old and then the new lake at Aswan, seeping conditions were changed, and the reservoir is now losing water along its banks.

ABSORPTION LOSSES

The rise of water level in the new lake is now forming a so-called bank storage. The dry rock below the flood surface every year is saturated with water; this saturation is manifested in the total balance of the reservoir as a new loss. Once the reservoir is filled to its maximum level and the whole volume of the flooded rock is fully saturated, no more water will be lost from the lake for bank storage.

On the basis of a dry rock porosity of 25%, losses due to saturation of rock at the different accumulation levels of the lake were estimated (Table 1). According to Table 1 the total volume of water required for rock saturation vertically below the surface of accumulation is about 48,000 million m^3, which will be lost in a number of years until the reservoir fills to its maximum level. Once the lake reaches its maximum level and all flooded rocks are entirely saturated, no more water from the new reservoir will be lost vertically.

SEEPAGE LOSSES

The lateral seepage flow from the lake depends on two factors: the coefficient of rock permeability and the hydraulic gradient of the groundwater. The average coefficients of permeability obtained from permeability tests at the three sites of investigations were as follows: at Garf Hussein, 4.1 × 10^{-4} cm/sec (east) and 8.2 × 10^{-4} cm/sec (west); at Toshka, 1.0 × 10^{-4} cm/sec (east) and 1.92 × 10^{-4} cm/sec (west); and at Adindan, 2.0 × 10^{-4} cm/sec (east) and 1.0 × 10^{-4} cm/sec (west).

Behind the bank storage zone the water table gradients perpendicular to the river in all sites of investigation were nearly constant. The gradients established in 1970, after the water level in the new lake had reached about 41 meters above that of the old Aswan Dam, were found to be of the order of 1.2 × 10^{-4} to 2.3 × 10^{-3} cm/sec.

On the basis of the calculated coefficients of permeability, hydraulic gradients, and the thickness of the permeable strata affected by seepage on both banks of the river represented by the three cross sections at Garf Hussein, Toshka, and Adindan, the total seepage losses from Lake Nasser at its maximum level were found to be equal to 0.206 m^3/sec. This finding means that the worst possible case of seepage that could happen from the new lake would be 6.45 million m^3/yr.

TABLE 1. Losses Due to Saturation of Rock

Level, meters	Flooded Area, 10^3 m^2	Pore Volume, 10^3 m^3
120 to 130	339,000	847,500
130 to 140	465,000	2,325,000
140 to 150	623,000	4,672,500
150 to 160	838,000	8,380,000
160 to 170	1,160,000	14,500,000
170 to 180	1,154,000	17,310,000
Total	4,579,000	48,035,000

The main factor causing such negligible seepage is the low permeability of the rock. By increasing the permeability to the range of 10^{-3} cm/sec, which is exaggerated for the Nubian sandstones, the total seepage might be increased 10 times. Another factor is the water table gradient, which in the present stage of accumulation has reached a value of 1.2 × 10^{-4} to 2.3 × 10^{-3} cm/sec. However, the gradients established in future may increase when the rise of water level in the lake reaches a maximum of 60 meters. On the assumption that this head of water will fall off within a distance of about 2 km from the shore, the water table gradients may attain a value of $60/2000 = 3 \times 10^{-2}$, or about 15 times the gradients of the present state of accumulation.

From this consideration the worst possible case of seepage losses that could happen would be $6.45 \times 10 \times 15 = 967.5$ million m^3/yr, which is still less than those estimates introduced into the early hydrologic studies of the project where the losses were rationally estimated at 1000 million m^3/yr.

Readings of piezometers will be carefully continued, and eventual corrections of the values of underground water gradients might be introduced. Should any abnormal behavior be noticed at any place, it might be recommended to drill more bore holes and to conduct further studies on the seepage losses.

At the present stage of water accumulation, there is no indication of any exceptionally weak areas where seepage might be dangerous. The faulted zones in the lake are sealed in clayey facies and are less permeable than the normally developed clean Nubian sandstones.

CALCULATION OF SEEPAGE LOSSES BY COMPARING THE ANNUAL FLOW AT THE INLET AND OUTLET

Another method for calculating the losses of water from the lake was by comparing the annual flows at its head and tail. Since the time when regulation on the High Dam started (1964), the water flow at the inlet and outlet of the lake has been measured annually. The differences between the inflows and outflows represent the actual seepage losses from the reservoir every year.

TABLE 2. High Dam Reservoir Losses

	Maximum Reservoir Level, meters	Inflow, 10^9 m^3	Outflow Plus Water Accumulation in Reservoir, 10^9 m^3	Actual Reservoir Losses,* 10^9 m^3	Theoretically Calculated Losses, 10^9 m^3		
					Absorption	Evaporation	Total†
1964 to 1965	127.60	119.430	119.082	0.348	0.091	0.942	1.033
1965 to 1966	132.70	79.550	78.497	1.053	0.295	1.552	1.847
1966 to 1967	142.45	69.120	67.760	1.360	1.190	2.679	3.869
1967 to 1968	151.25	92.370	87.290	5.080	2.427	4.485	6.912
1968 to 1969	156.55	71.102	62.740	8.362	4.034	5.773	9.807
1969 to 1970	161.30	69.539	61.263	8.276	2.719	6.975	9.694
1970 to 1971	164.88	81.790	70.373	11.417	3.593	8.177	11.770
Total	...	582.901	547.005	35.896	14.349	30.583	44.932

Before the High Dam the maximum reservoir level was 120 meters.

*These losses were obtained by subtracting outflow plus water accumulation in the reservoir (column 4) from inflow (column 3).

†The total losses were obtained by adding absorption (column 6) and evaporation (column 7).

Lateral seepage losses were then deduced by deducting from the actual losses the theoretically calculated absorption and evaporation losses from the lake.

Calculations in Table 2 show that, during the first 6 years of accumulation in Lake Nasser, where the total rise of water reached 41 meters, there was no evidence of any lateral seepage losses and that, until the present time, actual losses from the reservoir are even less than the theoretically calculated absorption losses (bank storage) and evaporation losses.

However, by the repetition of the calculation of losses by this method for more years to come, any probable errors in the inflow and outflow measurements and the differences between them will be reduced. The real trend of the seepage losses could then be more accurately detected.

Fall and Rise of Lago del Oro

REMY L. A. DE JONG[1]
Department of Civil Engineering, University of Tennessee
Knoxville, Tennessee 37916

A recent market survey of the Tucson, Arizona, area conducted by a local bank states the following statistics: present population, 360,000; estimated population in the year 2000, 1.3 million; median age, 24.42 years. Figures like these indicate the dynamic growth of this particular metropolitan area, and they also tend to dispute the widely held belief that Tucson is primarily a retirement community. Actually, only 21% of the area's households are retired, and <9% of the total population is 65 or over. Against such a background the need for more recreational facilities becomes evident.

The project described below is situated on the western slopes of the Santa Catalina Mountains, approximately 30 min north of the city of Tucson, Arizona. The dam and reservoir, owned and operated by the Rail N Ranch Corporation, a private land development company, are expected to become the nucleus of a large land development plan. Construction of the reservoir took place during the latter part of 1963, and initial inflows were collected during the spring of 1964.

DESCRIPTION OF THE PROJECT

Lago del Oro was created by the construction of an earth-filled dam in the stream bed of a desert wash, the Canada del Oro. When it is filled to spillway level the reservoir will have a surface area of approximately 1,133,100 m^2 (280 acres), and a storage volume of >11,070,000 m^3 (>9000 acre-feet). Hydrologic studies indicated that the average annual flow volume would be slightly in excess of 7,380,000 m^3 (6000 acre-feet). Although the primary purpose of the reservoir is recreation, a corollary benefit is the reduction of floods, which can be very extreme under the local climatological conditions. Evaporation losses in southeast Arizona are estimated at approximately 2.44 m/yr (8 ft/yr), which together with the fact that runoff is concentrated in the summer and winter seasons, will lead to annual lake level fluctuations that do not have a negative effect on recreational water usage and lake development.

The earth-filled dam consists of a zoned embankment with granite riprap shells on the upstream and downstream faces and a slightly sloping clay core. The intermediate zones are composed of local granular fill material. The maximum height of the dam above the bottom of the channel is 39.62 meters (130 feet), the upstream slope is 1 to 2½, and the downstream slope is 1 to 2.

PERFORMANCE

The first substantial runoff to provide storage in the reservoir occurred in July 1964, and it raised the reservoir to a maximum depth of 9.14 meters (30 feet). Shortly after this inflow, small amounts of surface water were observed downstream of the dam, but initially this appearance was taken to be collected surface runoff. However, persistent puddle formation long after the storms had ceased indicated that subsurface seepage had to account for the appearance of water downstream from the dam.

The water level in the reservoir continued to decline until December 1965, when substantial rainfall filled the reservoir to approximately 80% of its capacity. Similar, but more pronounced, signs of seepage appeared again in the same places as well as near the downstream slope of the embankment itself.

As soon as evidence became available that the reservoir was not holding water as expected, hydrologic observations were initiated to collect data that would permit quantitative evaluation of the losses. It was found that the seepage losses when the reservoir was filled to an elevation about 4.57 meters (15 feet) below the spillway crest were as high as 0.95 m^3/sec (15,000 gal./min), or in excess

---

[1] Now at Box 125, Miller Star Route, Tucson, Arizona 85726.

of 0.849 m^3/sec (30 ft^3/sec). Since the supply to the reservoir is derived from an ephemeral stream, the excessive seepage losses led to an immediate and rapid drop in the lake level.

INVESTIGATIONS

Safety aspects of the situation were considered, and, although a study showed that failure of the structure was not likely to cause loss of life or extensive damage to property, a relief trench was dug behind the dam to carry away excess surface water collecting there. A series of large relief wells was later added in the same location to permit lowering of the water table below the toe of the dam in case of an emergency.

Review of information on the reservoir site and a close examination of the construction procedures indicated three probable areas where excessive seepage might be occurring:

1. Design of the dam called for a clay core extending through the embankment down to sound bedrock. A section of this core located below ground surface was to have been constructed by excavating down to the bedrock and backfilling with clay. To make the trench walls as steep as possible and thereby to cut down on the amount of excavation, water was allowed to stand in the trench during its construction. Suspicions arose that, in some places, large boulders may have been improperly identified as bedrock because of the presence of the water and that therefore the trench had not been extended deep enough to permit construction of a dependable core.
2. The above-mentioned section of the core was constructed as a slurry trench clay core, and clay with a very high water content was left in place. Above a given elevation, where it was no longer feasible to have water standing in the trench, a much drier clay mix was used to continue construction of the core up to the crest of the dam. Some investigators voiced their doubts that a contact between the upper and lower core sections would provide a dependable seal in view of the widely different shrinkage characteristics of the two types of material and the subsequent 'bridging' of the dry clay over the puddled core.
3. Close scrutiny of the reservoir area revealed that, although one side of the reservoir bottom consisted of sound, clean granite, the other side was composed of a rather tight conglomerate containing several old buried steam channels (identified by coarse sand and gravels) and that some of these channels had occasional outcroppings in the reservoir bottom.

Shortly after it became clear that the project was not performing satisfactorily a team of experts was engaged to carry out the work necessary for identifying the problems with the reservoir and to recommend remedial procedures. The investigative efforts can be grouped under the following headings.

Hydrologic data collection. The purpose of the data collection procedure, which is continuing to date, was to allow close monitoring of all remedial efforts that were subsequently attempted. Instrumentation was installed to obtain a continuous record of inflow, evaporation, and water levels of the reservoir itself as well as of several observation wells in the vicinity of the project.

Site inspections. At intervals of no more than 7 days the project area was visited by one of the investigators in order to provide a visual check on unexpected developments and on proper operation of the instrumentation.

Geologic study. A comprehensive investigation was conducted that included a description of the regional geologic setting and of the geology of the damsite and the reservoir, as well as a review and summary of all the preconstruction investigations that were carried out earlier. A series of test holes was drilled through the embankment; this series led to the confirmation of the existence of openings inside the dam core as well as of a substantial previous zone under this core. Further test-drilling around the damsite located several of the buried sand and gravel channels referred to earlier.

Tracer tests. As part of an effort to locate the outflow channels, tests were run with fluorescent rhodamine B dye. Analysis of those test results indicated conclusively the occurrence of seepage flow through and under the embankment.

Geophysical tests. Seismicity as well as resistivity tests were conducted around the damsite to locate clear discontinuities in the subsurface materials and thereby hopefully to confirm the findings of the tracer tests. Information thus obtained turned out to be very helpful in assembling a better picture of variations in permeability values in different areas of the reservoir bottom.

CORRECTIVE MEASURES

In view of financial limitations as well as constraints imposed by legal entanglements during the early part of the investigations, attempts to improve the performance of the reservoir were undertaken in a probing and stagewise fashion. The following listing gives an idea of the range of repair efforts; since both the duration and the timing of the various operations varied widely, no strict chronological sequence is observed in this listing. In all cases the relative effectiveness of the project was tested by evaluation of the water balance of the lake.

Clay slurry. In a very early stage of the project a large amount of clay slurry was pumped into the lake. Although a lack of data prevented before and after comparisons, the losses continued to be unacceptable, and this procedure was not repeated.

Chemical sealants. Application of an enzymatic biochemical sealer was attempted when the reservoir was at a low level but not completely empty. No benefit was indicated, probably because no compaction of the reservoir bottom was possible during this application.

Grouting. A limited program of cement and chemical grouting was carried out. Comparison, by means of properly situated observation wells, between grouted and nongrouted zones of the dam showed that the operation had been locally beneficial. However, projections of the need for additional grouting, both in the embankment and along other parts of the reservoir shoreline, indicated that this approach would not be economically feasible as a final solution to the seepage problem.

Modification of soil distribution in reservoir. As a result of miscellaneous tests and inspections it was decided to mechanically modify sections of the reservoir bottom with the dual purpose (1) of achieving more uniformity in the soil materials and of thus eliminating 'pockets' of highly pervious deposits that might act as concentrated outlets and (2) of preparing the reservoir bottom for access to earth-moving and compaction equipment to be used in future repair efforts.

Clay blanket. In a continuation of the previous phase a 30-cm (12-inch) clay blanket was spread and compacted over part of the reservoir bottom. This blanket created a perched basin that has since shown signs of sharply improved performance. Isolated problems resulting from local scour and variations in blanket thickness still occasionally plague the project, but a continued program of inspections, evaluations, and progressive blanketing is believed to be the most economic and dependable solution to the seepage difficulties.

CONCLUSIONS

Although none of the problems encountered in this project were new and original, the scope of the investigations after construction underscores the need for comprehensive project studies before construction is undertaken. Studies of this nature should include not only the feasibility of one specific structure (such as the dam in this case) but also a prognosis of the performance of the total project (in this case the dam and the reservoir) at least from an engineering viewpoint but preferably also with regard to other environmental factors.

The execution of the various tests and investigations related to this man-made lake clearly indicated the benefits to be derived from an interdisciplinary approach to potentially complicated situations that permits suggestions of a wide range of ideas, some practical, some not, but all open to discussion and evaluation on their merits.

Influence of a Very Large Number of Small Reservoirs on the Annual Flow Regime of a Tropical Stream

PIERRE DUBREUIL

Department of Applied Research, Hydrologic Service
Office de la Recherche Scientifique et Technique Outre-Mer, Paris, France

GEORGES GIRARD

Hydrologic Service, Office de la Recherche Scientifique et Technique Outre-Mer
Paris, France

Northeastern Brazil, an area of 1 million km^2 having 20 million inhabitants, is an extremely dry area because the predominantly crystalline bedrock permits no retention of water and because the rains there are rare and very variable and the climate tends to be arid. An extremely widespread policy of catchment reservoir construction has been put in effect since the beginning of this century. On the occasion of studies undertaken by a French-Brazilian group for the integrated control of the Jaguaribe basin (area of 70,000 km^2 in the state of Ceará), we were able to examine the regional hydrologic regime and the influence that the policy of reservoir construction has had on this regime.

IMPORTANCE OF RESERVOIRS

Just as clearing the land involves people (at present there are 23 inhabitants per square kilometer in the Jaguaribe basin) and a change in the environment, the construction of dams is a human enterprise that has taken place throughout the twentieth century and has resulted in a continually changing landscape in this area. The influence of construction (i.e., the emplacement of increasing storage capacities) on the hydrologic regime is undeniable.

The pattern of construction was estimated from documents (archives, aerial photographs, and maps) and from field surveys; this estimate was limited to the Sitiá basin (1790 km^2), a small portion (3%) of the Jaguaribe basin. The evolution of the storage capacity for the Sitiá basin, as shown in Figure 1, is as follows: 10% of the storage capacity as of 1965 was in place prior to 1920, the first doubling of the capacity from 10 to 20 million m^3 occurred in 1934–1941, and the second important growth period (increase of 85%) was from 1955 to 1964 (evidence of the intense pace of construction from which there seems to be as yet no letup).

In 1965 the estimated constructed storage capacity for Jaguaribe basin was nearly 5 billion m^3 and was composed of the following: (1) several thousand small reservoirs (none surpassing several hundred thousand cubic meters) constructed by landowners and agricultural developers with a total capacity of about 200 million m^3; (2) 300–500 reservoirs of medium capacity (about 500 thousand to 10 million m^3), some of which were constructed by private interests and some of which were constructed by public organizations, with a total capacity on the order of 500 million m^3; (3) 13 large public reservoirs having capacities ranging from 2 to 185 million m^3 with a total capacity of 540 million m^3; and (4) two dams of very large capacity, Orós on the middle Jaguaribe River (2 billion m^3) and Banabuiú on the stream of the same name (1.5 billion m^3). The overall storage in 1965 attained 34,000 m^3/km^2 (or a depth of 34 mm/km^2) for the Sitiá basin and 70,000 m^3/km^2 for the Jaguaribe basin.

REVIEW OF THE CLIMATE AND HYDROLOGIC REGIME

Situated between 4°30′S and 8°S, the Jaguaribe basin opens toward the ocean and would be ex-

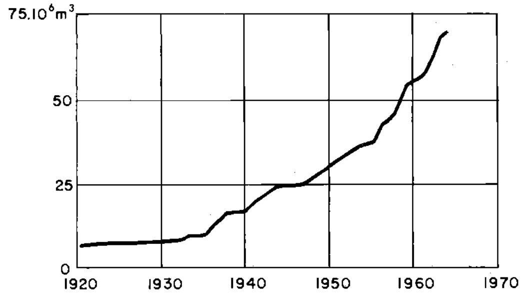


Fig. 1. Evolution of the construction of reservoir storage in the Sitiá basin.

pected to have a climate of equatorial maritime tendencies. However, the very peculiar regime of the air masses over the Brazilian northeast imparts a short tropical cycle on the precipitation. This cycle is subject to large deviations from one year to the next and hence leads to a climate that is semiarid.

The precipitation regime is of a tropical type. The rainy season during the austral summer is concentrated in 6 months, and there is a single maximum in March or April. The monthly distribution of rain is highly variable. The variability of the total annual precipitation (700 mm) from year to year is characterized by a coefficient of variation of 0.37.

The mean monthly air temperatures are between 25° and 28°C throughout the year. The mean minimum monthly temperatures vary from 19° to 24°C, and the corresponding maximum temperatures vary from 29° to 34°C.

The annual evaporation from a free water surface in this climate amounts to about 3 times the annual precipitation. The monthly distributions of evaporation as measured from a U.S. Weather Bureau class A pan, from a floating pan, and from a free water surface are well known; the variability about their mean ranges is from 8% during the dry season to 20% during the rainy season. On an annual scale the variability does not exceed 10%. The mean annual evaporation from a detention reservoir in the Jaguaribe basin has been evaluated to vary from 2100 mm for a maximum water depth of 20 meters to 2600 mm for a maximum water depth of 4 meters. In the dry period from June to December, this evaporation varies from 1350 to 1700 mm according to the maximum depth of the reservoir.

Under such a semiarid and irregular climate with respect to precipitation, the hydrologic regime of the Sitiá basin cannot be but very irregular. In some years, runoff is very abundant with floods and inundations; in others, runoff is limited in time and to a small part of the basin, and sometimes there is no runoff.

The mean runoff observed over the years for this regime (72 mm for the Sitiá) is always more than double the median annual runoff, and the irregularity of the runoff from year to year is very high (coefficient of variation of >1). After ordering the observed annual flows according to Galton's law, one can estimate that the dry decennial runoff would be 1–2 mm whereas the wet decennial runoff would be 200–220 mm.

On the average the monthly distribution of flow is as follows (expressed in percent of annual runoff): January, 5.5; February, 24.5; March, 42.5; April, 22.5; May, 4.5; and June, 0.5. The other months are dry. The interannual variability is still greater than the degree of variability during the year.

ANALYSIS OF THE INFLUENCE OF RESERVOIRS ON RUNOFF

To attempt to delineate the influence on the annual runoff of a mass of reservoirs, sometimes constructed in a cascading chain one after the other along the thalweg, we proceed from the simple to the complex by considering first a single reservoir, then the extreme cases of a reservoir either empty or full at the end of the runoff season, and finally the general influence of the principal reservoirs on the Sitiá basin.

Effect of a Single Reservoir

As long as a reservoir does not overflow, the entering runoff (from the upstream basin) does not participate in the outflow (streamflow as observed downstream). The duration of this absence of participation in the outflow and the importance of the outflow in relation to the entering runoff depend on two criteria: (1) the maximum storage height L_m, obtained by dividing the maximum capacity of the reservoir by the surface area of the basin; and (2) the height compensating for the evaporation E_c, obtained by dividing the maximum surface area of the reservoir by the surface area of the basin.

If one supposes that the losses due to infiltration and human and livestock consumption are negligible in comparison to those due to evaporation, as is the case in the Sitiá basin (or the Jaguaribe basin), the outflow of the reservoir occurs only if the entering runoff is greater than E_c (full reservoir at the end of the preceding water year) or has a value increasing toward L_m (empty reservoir at the end of the preceding water year).

Effect of Several Reservoirs

If these reservoirs are parallel on neighboring thalwegs, their independent effects add up to the final modification of the outflow from the basin. If the reservoirs follow each other on the same watercourse, their various criteria L_m and E_c and the various amounts of precipitation in their respective drainage basins combine in a complex manner to form their total effect.

In the Sitiá basin the areas controlled by one, two, three, and more than three reservoirs in series constitute, respectively, 53, 18, 4.4, and 1.4% of the total area. The maximum storage capacity is 61.5 million m^3. To reconstruct the effect of all these reservoirs, a simplifying assumption was made that the runoff over the entire basin is homogeneous.

Minimal effect. This effect corresponds to the case of the year $n + 1$ succeeding an abundant year during the course of which all reservoirs were overflowing and were full at the beginning of the dry season (between n and $n + 1$). In this case the reservoirs will deduct at the beginning of the year $n + 1$ a volume equivalent to the height in order to compensate for the evaporation E_c for each reservoir. In total, for the Sitiá basin in 1965, the evaporation of 1500 mm from a reservoir surface area of 21.7 km^2 corresponded to a volume of 32.6 × 10^6 m^3 (53% of the total storage capacity of the basin), equivalent to a depth of 18 mm over the entire basin (34 mm over the drainage area controlled by the reservoirs). This depth is deducted when the reservoir having the greatest value of E_c overflows. The deviation between the runoff depth observed L_o downstream from the Sitiá basin and the natural runoff depth L_n varies from 18 to 0 mm in proportion as the fraction controlled by the reservoirs diminishes and as the different reservoirs, with decreasing value of E_c, are susceptible to overflow. In Figure 2 the curve OP expresses L_n as a function of L_o, which increases from point O to point A. At point A, $L_n = L_o + 18$; the curve OP is tangent at O to the line OK, which represents the percentage of the basin not controlled by reservoirs (calculated from the angle between the abscissa and the bisector of the graph).

Maximal effect. This effect corresponds to the case of a year $n + 1$ in which the reservoirs were dry at the end of the preceding dry season. In total, for the entire Sitiá basin in 1965, this evaporation corresponded to 62.5 × 10^6 m^3 of the total storage volume, or 35 mm of runoff depth (66 mm on the area of the basin controlled by reservoirs), a depth equal to the median of the observed runoff. The maximum reduction of 35 mm occurs only when the dam having the greatest storage depth L_m is filled. The reduction diminishes from 35 mm toward 0 if the observed runoff depth diminishes; its value depends on the classification of the reservoirs in decreasing order from L_m. At the extreme the curve OV is also tangent to OK, and, beginning at point B, OV becomes the straight line $L_n = L_o + 35$ mm (Figure 2).

Intermediate effect. Figure 2, showing a relation between observed runoff L_o and natural runoff L_n, can be determined for each limiting curve (minimum effect and maximum effect) point by point after the reservoirs are classed according to decreasing values of E_c and L_m and when the corresponding observed runoff for each reservoir is calculated (equal to the inflow under the assumption of homogeneous runoff over the whole basin).

The natural runoff in an intermediate runoff year $n + 1$ is thus composed of $L_o + \Delta$ and $L_o + \Delta'$ depending on the degree of filling of the reservoirs (assumed to be homogeneous throughout the basin) at the end of year n. This degree of filling (or rather its inverse) is represented on Figure 2 by the segment FE, which separates the curve OV from the line intercept at L_o. The degree of filling is expressed by the relation FE/L_o and varies from 0 (reservoirs full), when L_o is greater than the value corresponding to point B, to 1 (reservoirs empty), when L_o has a minimal value L_{on} (approaching 18 mm) such that FE becomes GZ (where Z is the intercept of the tangent to the curve OV at point B). The curve of the year $n + 1$ (which depends on the degree of filling at the end of the year n) lies between OV and OP and passes through a point H located on the line DC at a distance from D such that $DH/DC = FE/L_o$.

The transition parameters Δ and Δ' between L_o and L_n, varying with L_o, increase from 0 to the maximums equal to 18 and 35 mm, respectively, when L_o exceeds the values of the runoff depth compensating for the maximum evaporation loss E_c (point A on OP) and the runoff depth cor-

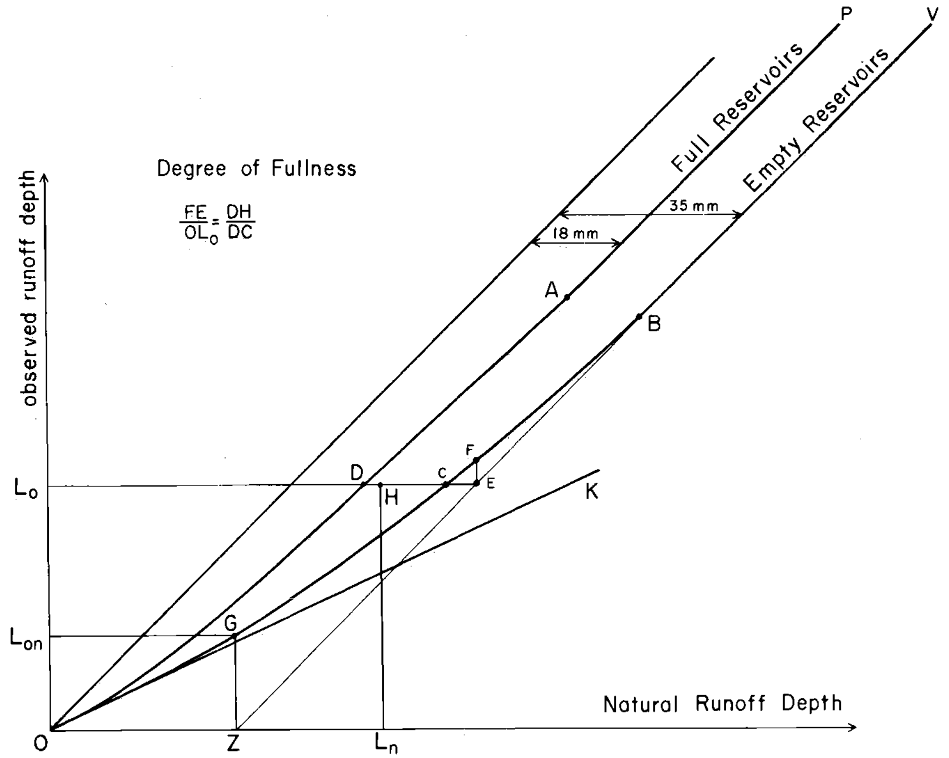


Fig. 2. Influence of the reservoirs on the runoff from the Sitiá basin as of 1965.

responding to the maximum storage L_m (point *B* on *OV*).

COMPARISON OF OBSERVED AND NATURAL RUNOFF OF THE SITIÁ

Figure 2 permits the evaluation of the natural annual runoff on basis of the observed runoff and the state of filling of the reservoirs for the period 1957–1965 during which the total volume of storage remained relatively stable. The annual runoff is not the same for earlier years, and we have also drawn a family of curves for the period 1943–1957 by assuming a total volume of storage that is one-half the volume for 1964 and by assuming proportionally greater annual losses because the earlier reservoirs were less deep.

Before 1943 the number of reservoirs and the storage volume were small. The deviation between observed and natural runoff did not exceed 5 mm, and the natural runoffs were inferred directly from the observed runoff. Without being overly rigorous (assuming homogeneous runoff and degree of filling of reservoirs), this method permits the reconstruction for the period 1923–1965 of the natural runoff or the streamflow that would have occurred if there had been no reservoirs in the Sitiá watershed.

The exact influence of the reservoirs cannot be clearly described unless one considers the chronology of construction of the dams. Using only Figure 2 and working backwards for the period prior to 1957, one can then establish the complete and homogeneous series of runoff flows that would have been observed since 1923 if the degree of construction attained in 1965 had existed since that time.

This series of runoffs L_{65} is compared to two other series L_o and L_n by means of characteristic parameters in Table 1. The presence of reservoirs in the Sitiá basin increases the asymmetry of the annual flow, and, through the shift in the evaporation, their presence diminishes the annual flow (more so when the year is dry). The apparent aridity of the hydrologic regime is increased.

This effect, already clear in the chronological display of 1923–1965, is still more pronounced in the situation of 1965, which best represents the future when the pace of construction ceases: (1) the natural median is reduced by 25% (L_o) and by

TABLE 1. Runoff Series 1923 to 1965 (Depth in Millimeters)

	L_0	L_n	L_{65}
Median	35	47	30
Mean	72	81	60
Standard deviation	87	89.4	...
Coefficient of asymmetry	3.65	3.12	...
Quinquennial (wet year)	97	116	96
Quinquennial (dry year)	11	15	8

36% (L_{65}), (2) the natural mean is reduced by 11 and 24%, and (3) the runoff having a 5-year recurrence is diminished by 17% in a wet year but by 27–47% in a dry year.

CONCLUSION

The influence of very numerous small reservoirs on the annual flow of a tropical river has been clearly shown by the example of the Sitiá, in whose basin the reservoirs have a storage capacity corresponding to a depth of 34 mm over the drainage area, or 42% of the mean flow. The simple graphic method has been shown to be satisfactory despite some uncertainties that it allows. To achieve greater precision or to judge the efficacy of these reservoirs realistically, a simulation of the combined management of all the dams in the basin would be required.

Mechanics of Flow through Man-Made Lakes

WALTER O. WUNDERLICH AND REX A. ELDER[1]
Tennessee Valley Authority, Knoxville, Tennessee 37902

Man-made lakes are universally used to impound surface water for a great variety of purposes. In the Tennessee Valley Authority (TVA) region, there are about 30 major reservoirs (most of them created between 1930 and 1970) with a total water surface area of about 2400 km^2, a total water volume of about 27 billion m^3, and depths of up to 137 meters. Water quality changes are known to occur in these water bodies and can be observed in the discharges for varying distances downstream. These changes are the result of complex interactions between many factors, such as geometry and size of the reservoir; storage management over the yearly cycle; outlet geometry and location; amount, distribution, and quality of the inflow; internal mixing processes; optical properties of the water; climate of the environment; biological and chemical processes in the water; and heat and mass transfer processes across the water surface and the ground [*Churchill and Nicholas,* 1967; *Wunderlich and Elder,* 1967].

The essential function of most reservoirs is the regulation of large temporary runoff for flood control and other purposes. The releases from a reservoir can be intermittent or relatively steady; sometimes these releases are rather large in comparison to natural river flows. The associated internal flow patterns can be very complex if density stratification exists. Heat transfer across the water surface and heat advection due to the inflows and outflows can cause a great variety of temperature and density patterns. Reservoirs with little inflow and outflow may maintain a considerable temperature difference between surface and bottom throughout the summer over a depth of only 10 meters, whereas strongly flushed reservoirs with deep intakes may be warm and homogeneous in temperature down to several times that depth [*Wunderlich and Elder,* 1968].

In the presence of a density gradient, water particles become stabilized at the elevation of their density, and sustained forces are needed to dislocate them permanently to other elevations since gravity or buoyancy forces tend to move them back to their original level. For example, the initial turbulence of inflow, no longer sustained by open-channel flow, dies down as the flow enters into the reservoir, and the water becomes quiescent. The reduction of turbulent vertical exchanges enables horizontal movements to persist over considerable distances. For the same reason, outflow is withdrawn from layers of limited thickness around the turbine intakes. Several distinct and independent currents may be simultaneously present within a reservoir, such as inflow currents, withdrawal currents, wind currents, and others [*Wunderlich and Elder,* 1967].

For several years, TVA has been conducting laboratory and field research to investigate the mechanics of flows in density-stratified reservoirs. The measurements of current velocities in reservoirs became possible with the development of a deepwater isotopic current analyzer that is capable of field use. This instrument, briefly called Dwica, has been described in detail elsewhere [*Vigander and Wunderlich,* 1971]. Its unique feature is a measuring range from 0.001 to 0.3 m/sec. The measurements are, however, very laborious and inherently slow, so the progress in data collection has been slow. It is not possible to obtain an instantaneous and complete picture of the velocity distribution in one cross section let alone in several cross sections at the same time. Therefore a considerable amount of speculation is still necessary in data interpretation. The use of dye injection in deep reservoirs has been explored and proved to be a means of identifying water masses, water movements, and, to some extent, dilution. The limited amount of data obtained

---

[1] Now at Bechtel Corporation, San Francisco, California.

so far by these techniques has provided, nevertheless, very valuable information on real prototype flow mechanics. In the following discussions, some of the Dwica and dye injection data are presented. For their interpretation, use is made of theoretical and laboratory test results obtained by others.

FLOW MECHANICS

In flow mechanics studies of stratified reservoirs the cause for density stratification must be known. Temperature differences are the most common cause, but other agents such as dissolved or suspended solids could be factors. In most TVA field tests, direct density measurements were made on water samples by using constant mass hydrometers [*Elder and Wunderlich,* 1968]. Apart from minor differences in absolute density the density gradient was always found to be directly related to temperature. A sample of these test results is shown in Figure 1. In the data analyses, pure water densities computed by the Thiessen-Scheel-Diesselhorst equation [*Tilton and Taylor,* 1937] at in situ temperatures are used.

Inflow. Dependent on the density difference between the incoming water and the reservoir water, overflow, underflow, or interflow may result. These flow patterns are shown schematically in Figure 2. Basically, any inflow seeks its density level and moves along this level into storage position. If this level happens to be the withdrawal zone, the inflow will move directly through the reservoir. In other cases, water may be stored for considerable periods of time.

Typical for all inflow types is the deepening of the inflow depth until a critical depth d_0 is reached. From this section downstream, underflow or overflow results depending on whether the density of the inflow is respectively greater than or less than that of the reservoir water. The depth of this critical section is governed by [*Harleman,* 1961, 1969]

$$F_0 = (Q/A_0)/[g(\Delta\rho/\rho)\, d_0]^{1/2} \qquad (1)$$

where Q is the inflow rate, A_0 is the cross-sectional area, g is the acceleration due to gravity, $\Delta\rho$ is the density difference between inflow and reservoir water, ρ is the density of the moving fluid, and d_0 is the critical depth. The critical section for an inflow of 19 m³/sec at 15°C into water of 28°C is shown in Figure 3. This section occurred between kilometer 4.5 and kilometer 4.4 on the Natahala River. The data yield a Froude number F_0 of about 0.5 at the critical section. Below this point the inflow moved under the warmer reservoir water to become an underflow, which can be followed in Figure 3 as it moved along the reservoir bottom.

If the inflow water is warmer than the reservoir

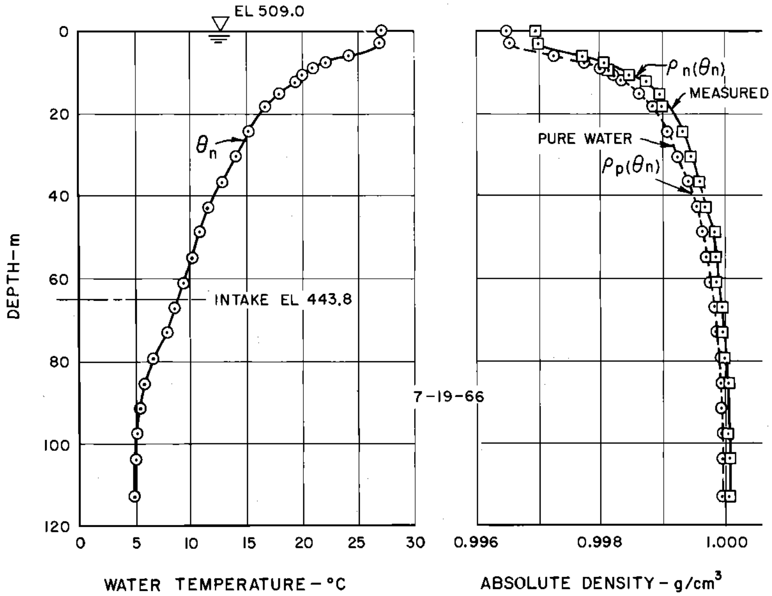
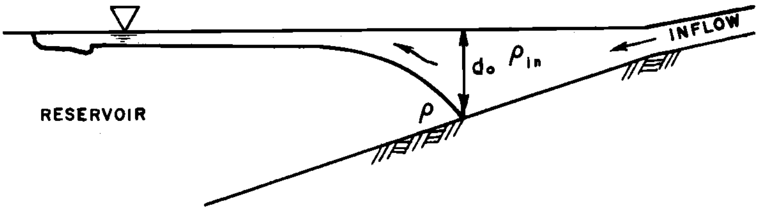
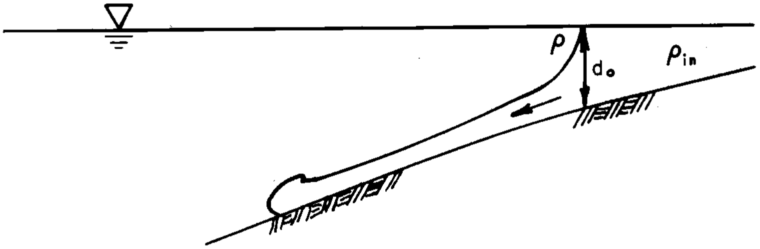


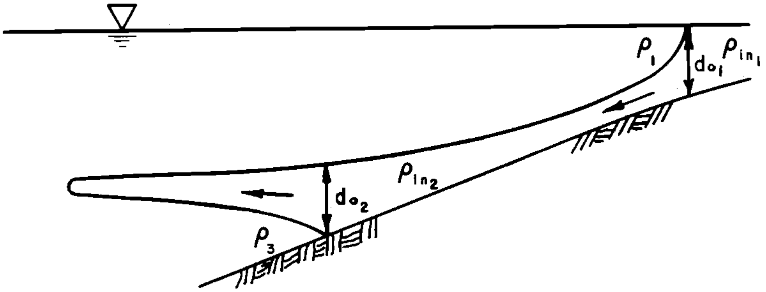
Fig. 1. Measured and pure water densities (Fontana).



(a) OVERFLOW $\rho_{in} < \rho$



(b) UNDERFLOW $\rho_{in} > \rho$



(c) INTERFLOW $\rho_{in_1} > \rho_1$, $\rho_{in_2} < \rho_3$

Fig. 2. Overflow, underflow, and interflow.

water, as is generally the case in spring, the inflow after passing the critical section spreads as a warm surface flow. An example of this type of flow is shown in Figure 4 where 16°C inflow water moved on top of 10°C reservoir water.

In deep reservoirs an underflow is likely to encounter still colder water, the result being that underflow ceases and interflow results. The level where this change occurs depends on the original inflow density and its modification due to mixing at the inflow point and along the underflow interface. At the interflow depth the flow depth increases and builds up the energy head necessary to drive the water along the plane of its density level and into its final storage position (Figure 2). An example of this type of flow is indicated by the dye concentration isopleths of Figure 5. In the upper part of the figure the inflow, originally at a mean temperature of about 14°C, arrives at the lift-off point in the vicinity of kilometer 125 on the Little Tennessee River at about 17°C. There the inflow deepens and feeds into its density layer. The downstream movement of the dye cloud shown in Figure 5 indicates a slow decrease in level elevation due to the withdrawal of water from the reservoir through an intake at an elevation of 444 meters.

Outflow. The location of the principal withdrawal intakes has a dominant influence on the water quality development in most reservoirs [*Wunderlich and Elder,* 1969]. Because of suppression of vertical movements in the presence of density stratification, water is withdrawn from a layer around the intake opening (Figure 6).

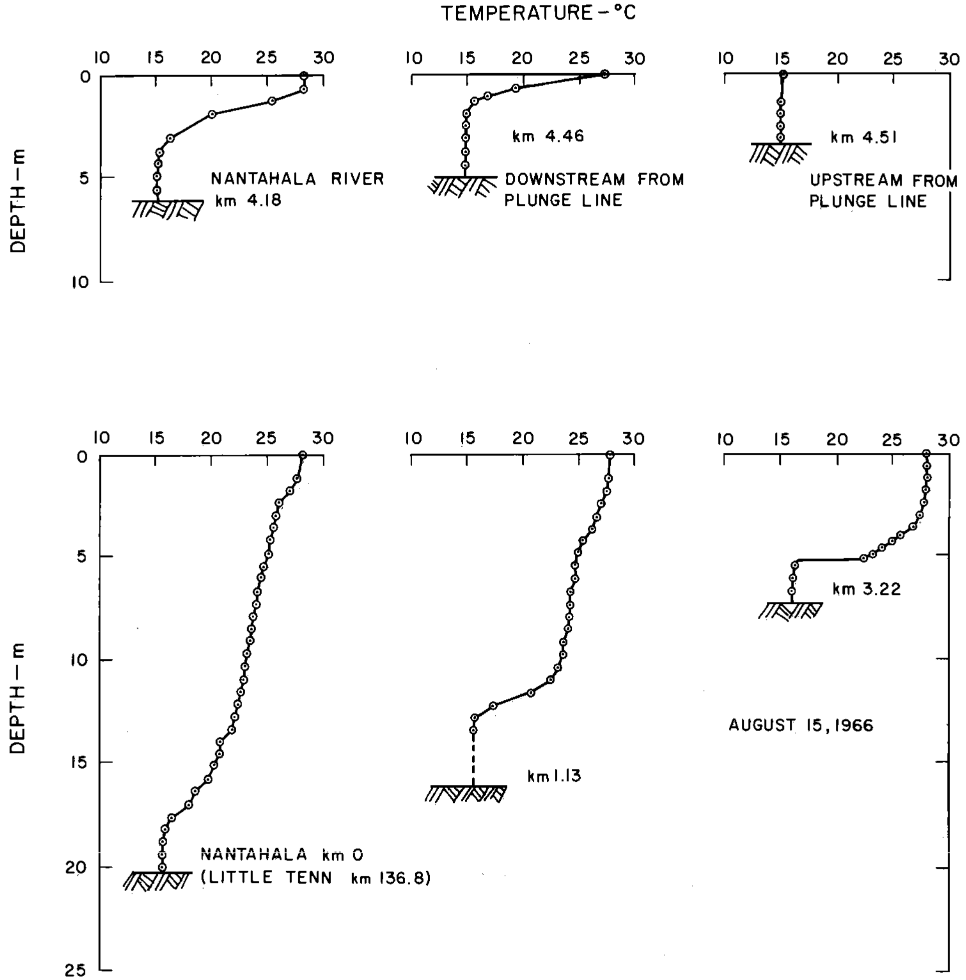


Fig. 3. Inflow. Plunging occurs near kilometer 4.5 (Fontana).

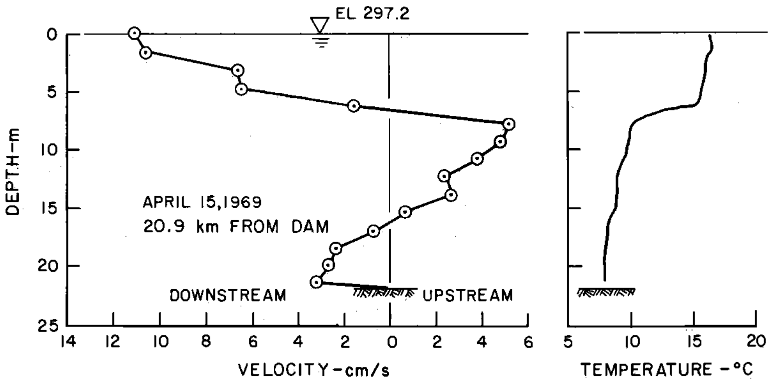


Fig. 4. Overflow of warm inflow (Douglas).

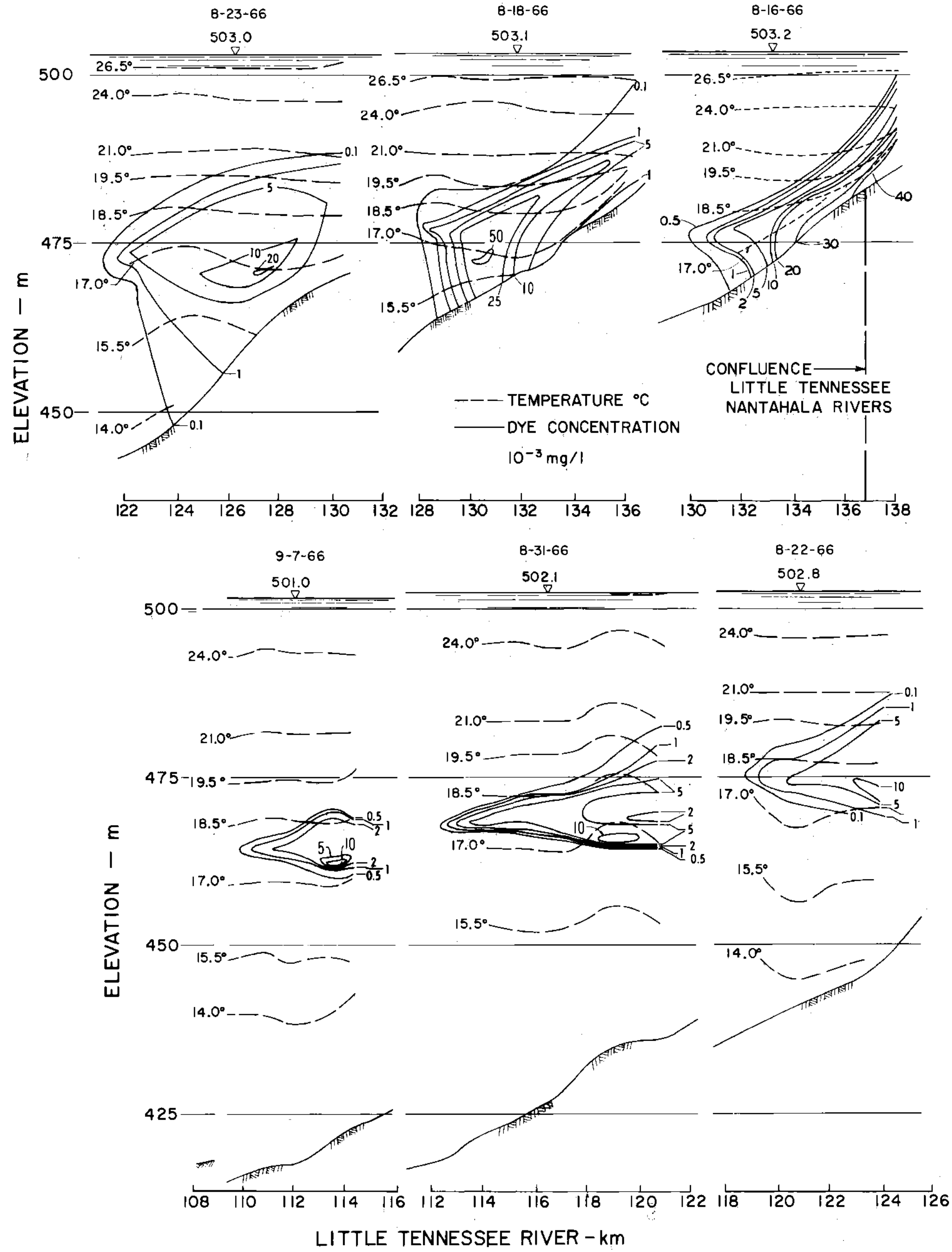
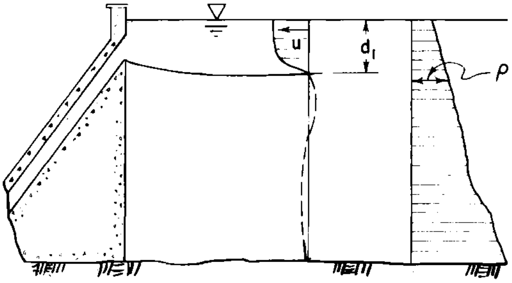


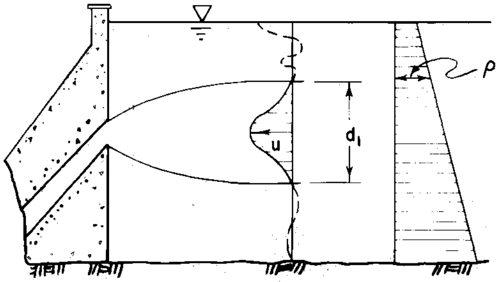
Fig. 5. Underflow and transition into interflow (Fontana).

Dependent on its location an intake may be classified as high, intermediate, or low. The determination of the thickness of the withdrawal layer for various intake configurations has been the subject of studies by several investigators and of field studies on several reservoirs.

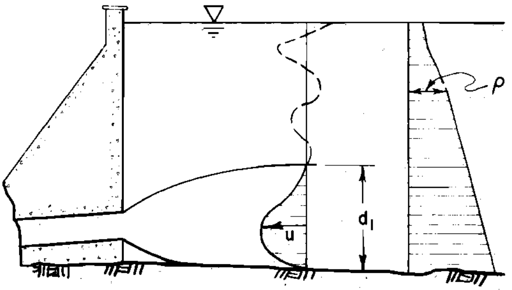
In Figure 7 the flow into a high intake is presented. In this case the cold outflow from an upstream impoundment at about 17°C moves on top of still colder water down the reservoir toward the intake. Solar heating creates a very thin warm layer of about 1 meter in thickness on



(a) HIGH INTAKE



(b) INTERMEDIATE INTAKE



(c) LOW INTAKE

Fig. 6. Selective withdrawal.

top of this flow, but this layer is also drawn into the intake.

In Figure 8 a rather warm summer inflow of 24°C moves toward the turbine intakes beneath a still warmer reservoir surface layer at 29°C. Below this current, cold winter water at 7°C is preserved as a stagnant pool throughout the summer.

A rather large flow into a low turbine intake is shown in Figure 9. Two velocity profiles measured at different times of the year but with similar density gradients and discharges of about 450 m^3/sec are presented. Other data pertaining to the test results in Figures 7, 8, and 9 are summarized in Table 1.

DISCUSSION OF RESULTS

Selective withdrawal from reservoirs can produce desirable or undesirable outflow water quality. For example, in deep reservoirs, cold water stored during the winter months can be very beneficial for municipal and industrial uses downstream. On the other hand, withdrawal of water from a layer with undesirable water quality (such as a low oxygen concentration) may cause problems downstream. Therefore it is important to have a criterion indicating whether selective withdrawal will occur and formulas for the prediction of the withdrawal layer characteristics.

Yih [1965] theoretically derived that no stagnant layers can exist when the densimetric Froude number of the total cross section is

$$F = (q/d^2)/(g\epsilon)^{1/2} \geq 0.33 \qquad (2)$$

where q is flow per unit width, d is total depth, g is acceleration due to gravity, $\epsilon = (1/\rho)\, d\rho/dz$ is the density gradient number that is positive for density increasing with depth, and ρ is the reference density and may be taken at the center line of the outlet opening. *Kao* [1970] concluded that for a given flow in a linearly stratified fluid the withdrawal layer thickness would grow to a size such that its Froude number becomes $F_1 = 0.33$; F_1 is similarly defined as F, and w_1, d_1, and $(d\rho/dz)_1$ refer to the withdrawal layer only. In a rectangular cross section with a constant density gradient, both Froude numbers are related by

$$F = (d_1/d)^2\, F_1 \qquad (3)$$

where d_1 is the withdrawal layer thickness, d is the total depth, and $F_1 = 0.33$, a universal constant, according to Kao. Hence the criterion for a stagnant layer to appear is $F < 0.33$. If $F > 0.33$, all layers move and contribute to the discharge. This theory was essentially confirmed by *Debler*'s [1959] model test results, which yielded $F_1 \approx 0.28$.

Withdrawal layer test results from 10 reservoirs are presented in Table 1. The Froude numbers are computed for the entire reservoir cross section at the indicated distances from the dam. They indicate that all layers still move at a Froude number of about $F = 0.06$, which is considerably less than 0.33. Two examples of rather uniform water movements in a stratified reservoir associated with $F = 0.066$ and $F = 0.159$ are shown in Figure 10. Because of cross-section changes, the measuring section used for the com-

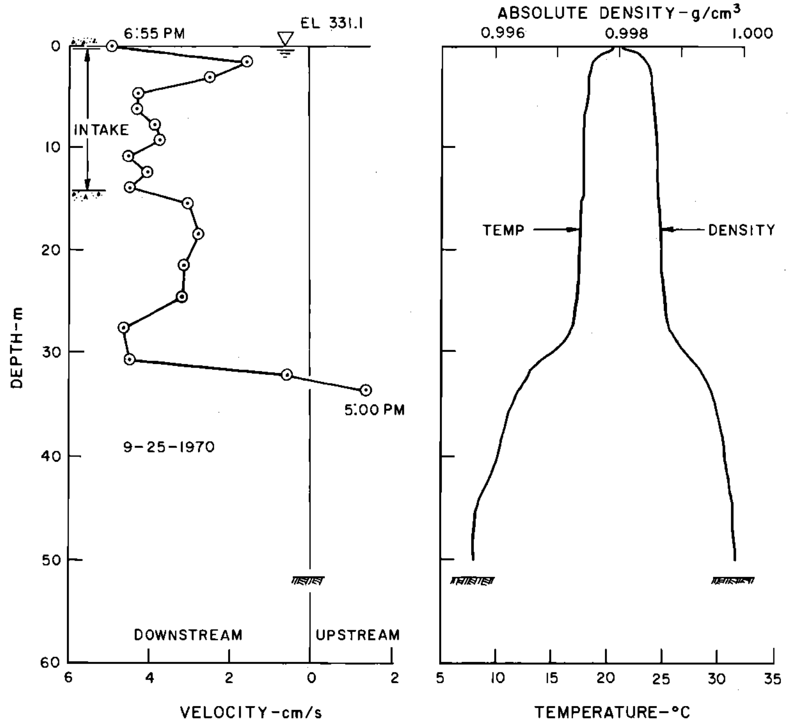


Fig. 7. Selective withdrawal through a high intake (Calderwood).

putation of F may not be the critical section that determines whether stagnant layers can exist or not. If, at the critical section, F reaches or exceeds the critical value, then the layers in all other sections must move to satisfy continuity, regardless of the Froude number. With all other parameters constant, such a critical section was assumed to exist close to the powerhouse and to run perpendicularly across an assumed streamline pattern. For both the Watts Bar and Fort Loudoun data

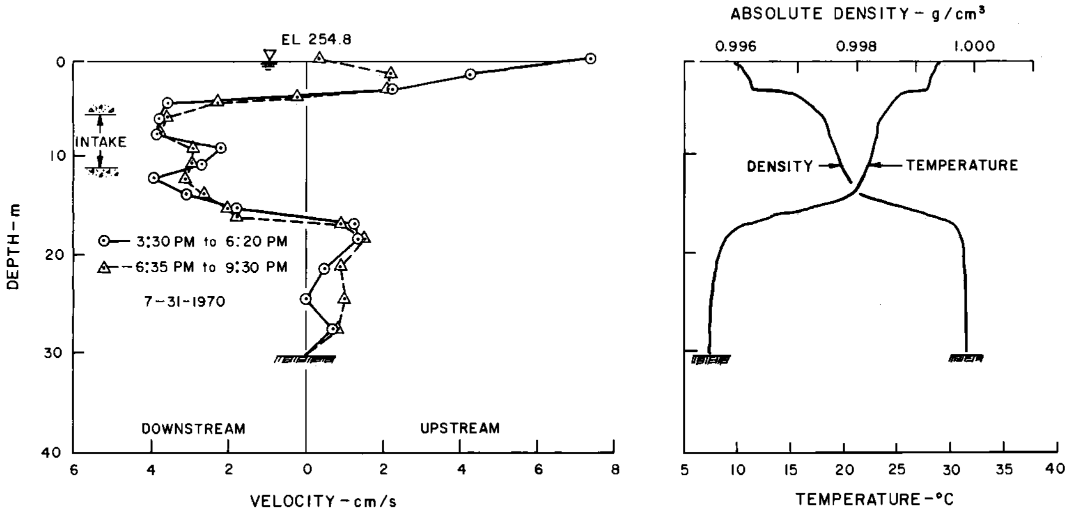


Fig. 8. Selective withdrawal through an intermediate intake (Ocoee 1).

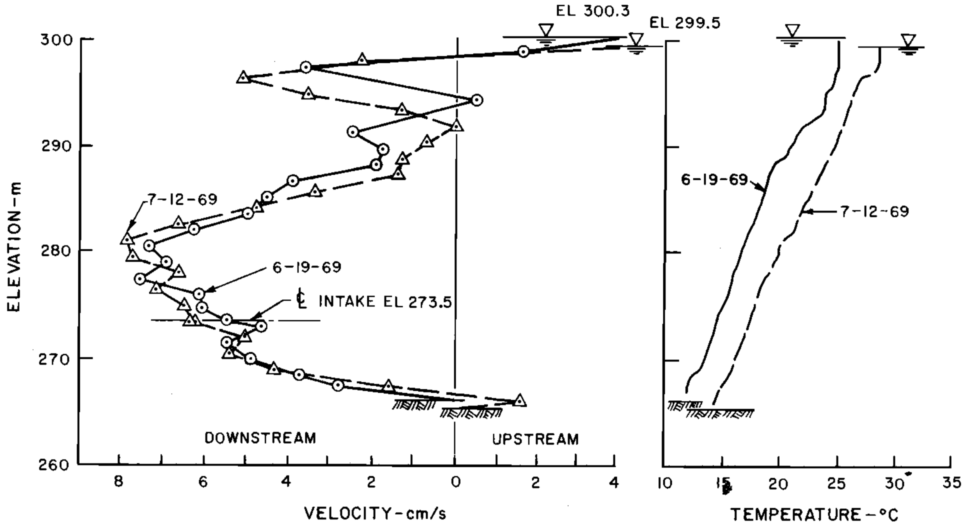


Fig. 9. Selective withdrawal through a low intake (Douglas).

the resulting reduction in width yielded Froude numbers of >0.33; this result would explain the movement of all layers in the measuring sections upstream.

For a two-dimensional linearly stratified flow the withdrawal layer thickness d_1 follows directly from (3) as

$$d_1 = (1/F_1)^{1/2}a \qquad (4)$$

wherein

$$a = F^{1/2}d = [q/(g\epsilon)^{1/2}]^{1/2} \qquad (5)$$

The term a was introduced by *Brooks and Koh* [1969] as 'scale length.' In natural reservoirs, flows are generally not two dimensional. Also, other flow in addition to withdrawal layer flow may be present in the cross section, and the density gradient may not be constant over the entire

TABLE 1. Froude Numbers of Reservoir Cross Section

Reservoir	Distance from Dam x, km	Depth d, meters	Area $10^{-3}A$, m^2	Gradient $10^4\varepsilon$, m^{-1}	Flow Q_T, m^3/sec	Velocity Q_T/A, m/sec	$10^2(g\varepsilon)^{1/2}$, sec^{-1}	Froude Number F*
Cherokee	2.7	44.8	46.0	0.732	311	0.007	2.68	0.006
Douglas	0.8	34.3	17.3	0.728	462	0.027	2.67	0.029
	0.8	33.8	16.4	0.916	430	0.026	3.00	0.026
	0.8	29.9	12.2	0.430	110	0.009	2.05	0.014
	0.8	34.1	17.1	0.988	227	0.013	3.12	0.012
	0.8	32.0	15.3	0.935	212	0.014	3.03	0.014
Fort Loudoun	3.2	22.9	9.3	0.420	799	0.086	2.03	0.185†
Melton Hill	1.2	20.7	4.2	1.063	275	0.065	3.23	0.097†
Watts Bar	0.6	24.4	11.7	0.591	453	0.039	2.41	0.066†
	0.6	22.6	11.5	0.846	1198	0.104	2.88	0.159†
Fontana	1.0	104.5	18.4	0.295	161	0.009	1.70	0.005
Calderwood	0.4	51.8	8.7	0.348	198	0.023	1.85	0.024
Chilhowee	1.6	16.5	5.0	1.148	207	0.041	3.36	0.075
Ocoee 1	0.8	30.2	10.7	1.302	68	0.006	3.58	0.006
Barren	1.0	23.2	13.9	0.971	78	0.005	3.09	0.008

*$F = [Q_T/(Ad)]/(g\varepsilon)^{1/2}$, where Q_T is turbine discharge.
†All layers move.

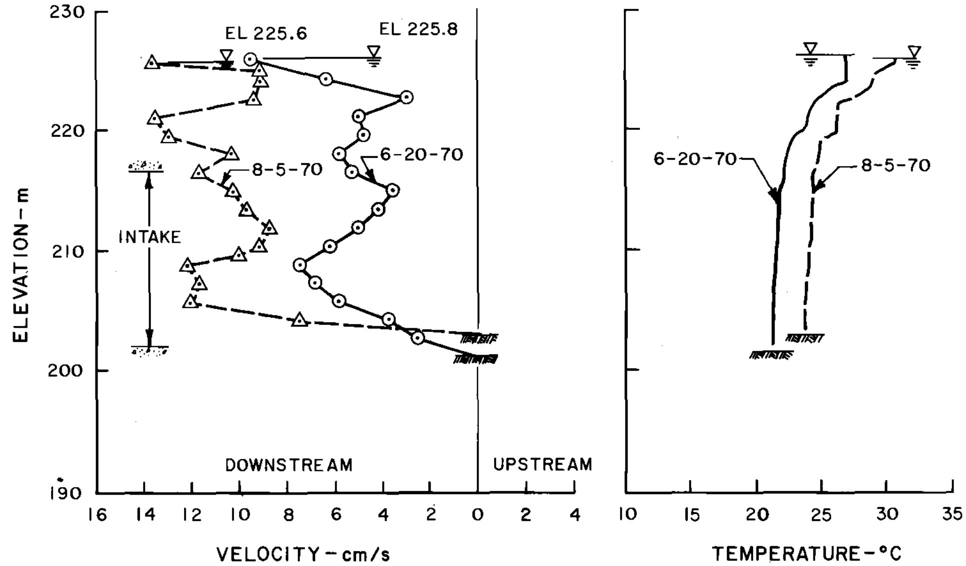


Fig. 10. Nonselective withdrawal through a low intake (Watts Bar).

depth. If it is assumed that under these different conditions the theoretical concepts can still be used, the withdrawal layer thickness can be expressed by

$$d_1 = (1/F_1)(Q_1/A_1)/(g\epsilon_1)^{1/2} \qquad (6)$$

Introducing $A_1 = w_1 d_1$ leads to

$$d_1 = (1/F_1)^{1/2} a_1 \qquad (7)$$

where $a_1 = [q_1/(g\epsilon_1)^{1/2}]^{1/2}$. The index 1 refers to the withdrawal layer. Equations 6 and 7 can be solved only by repeated trials, since all terms with index 1 are functions of d_1. For this reason, (6) was found to be convenient in practical applications. From the above discussion it also follows that d_1 should be evaluated in a narrow cross section and close to the intake (approximately within one reservoir width).

Values of $1/F_1$ and F_1 based on the field data and (7) are summarized in Table 2. A value of

TABLE 2. Withdrawal Layer Froude Number

Reservoir	Thickness d_1, meters	Area $10^{-3}A_1$, m^2	Gradient $10^4\epsilon_1$, m^{-1}	Flow Q_T, m^3/sec	Velocity Q_T/A_1, m/sec	$10^2(g\epsilon_1)^{1/2}$, sec^{-1}	Froude Number F_1*	$1/F_1$
Cherokee	29.6	20.4	0.696	311	0.015	2.61	0.020	50.4
Douglas	27.7	11.5	0.810	462	0.040	2.81	0.051	19.5
	25.1	10.1	0.879	430	0.043	2.94	0.057	17.4
	14.0	4.0	0.843	110	0.027	2.88	0.068	14.6†
	21.0	7.2	0.712	227	0.031	2.64	0.057	17.6
	19.4	6.6	0.945	212	0.032	3.03	0.055	18.2
Fort Loudoun	22.9	9.3	0.420	799	0.086	2.03	0.185	5.4†
Melton Hill	20.7	4.2	1.063	275	0.065	3.23	0.097	10.3
Watts Bar	24.4	11.7	0.591	453	0.039	2.41	0.066	15.2
	22.6	11.5	0.846	1198	0.104	2.88	0.160	6.3
Fontana	32.3	11.0	0.381	161	0.015	1.93	0.024	42.5
Calderwood	32.3	6.2	0.413	198	0.032	2.02	0.049	20.4
Chilhowee	13.1	3.8	0.466	207	0.055	2.14	0.194	5.1
Ocoee 1	12.8	4.8	1.978	68	0.014	4.41	0.025	40.1†
Barren	14.9	7.4	1.486	78	0.011	3.82	0.018	54.2†

*$F_1 = [Q_T/(A_1 d_1)]/(g\epsilon_1)^{1/2}$, where Q_T is turbine discharge.
†Major discrepancy between turbine discharge and integrated withdrawal layer flow.

$1/F_1 \approx 41$, or $(1/F_1)^{1/2} = 6.4$, is obtained for intermediate intakes, such as Fontana. For surface and bottom intakes, $1/F_1 \approx 20$, or $(1/F_1)^{1/2} = 4.5$, seems to be appropriate, as is shown by the data for Douglas and Calderwood. Cherokee and Barren also have low intakes, but the factor $1/F_1$ turns out to be much larger than was expected, perhaps owing to the very irregular cross section in both cases and to a major departure from a linear density distribution in the second case [*Tennessee Valley Authority,* 1967, 1969*a*]. In contrast to these two latter cases, Douglas [*Tennessee Valley Authority,* 1969*b*] and Calderwood have rather regular cross sections.

As is indicated in Table 2, in some cases the flow rates obtained by integration of the velocity profiles did not satisfactorily match the turbine discharge to which the measured withdrawal layer velocities were attributed. The discrepancies between integrated flow and measured turbine flow are in part due to the fact that the flow through the measuring cross section is related to the water balance of the reservoir between the measuring section and the dam rather than to turbine discharge alone. Therefore Table 2 was recomputed, and integrated flow rates instead of measured turbine discharges were used. The resulting Froude numbers for the principal moving layer did not substantially change the results of Table 2.

Based on inviscid theory of stratified flow into a bottom slot [*Brooks and Koh,* 1969] the withdrawal layer thickness can be expressed by (7). Adaptation of this solution to an intermediate intake [*Brooks and Koh,* 1969] yields

$$d_1 = (1/F_1)^{1/2}(2)^{1/2}a_1 \qquad (8)$$

Hence, if (7) and (8) are used, $(1/F_1)^{1/2} = 4.5$ is the same for all intakes.

At the present time the true causes for the low values of F_1 for prototype withdrawal layers are not known. The above discussion may point at some of them. It has also been suggested that the presence of turbulent heat diffusivity may be one cause [*Brooks and Koh,* 1969; *King,* 1969]. In addition, the internal velocity and flow distribution in the withdrawal layer [*Elder and Wunderlich,* 1969; *Wunderlich and Elder,* 1970], intake geometry, nonlinearity of density gradients [*Bohan and Grace,* 1970], and the presence of other flows besides the withdrawal flow may be factors.

CONCLUSIONS

Theoretical results as well as laboratory and field data are used to interpret the mechanics of density-stratified reservoirs. Many problems remain to be clarified, especially those related to water movements of inflows, including all categories such as overflow, underflow, and interflow. Discrepancies between theoretical and field results concerning selective withdrawal also require further investigations to pinpoint their true causes. If predictions are required, (7) is suggested for bottom and surface withdrawal intakes and (8) is suggested for intermediate intakes by using $(1/F_1)^{1/2} = 4.5$ in both cases. These equations and the experimentally modified Froude number $F_1 \approx 0.05$ should account to some extent for geometries and flow characteristics generally encountered in real reservoirs.

NOTATION

A,	total cross-sectional area of the reservoir, m^2;
A_1,	cross-sectional area of the withdrawal layer, m^2;
A_0,	cross-sectional area of the reservoir at critical section where inflow becomes overflow or under flow, m^2;
a,	scale length after *Brooks and Koh* [1969] for the entire cross section, meters;
a_1,	scale length with q_1 and ϵ_1 for the withdrawal layer only, meters;
d,	maximal depth of total cross section, meters;
d_1,	thickness of withdrawal layer, meters;
d_0,	depth of the critical cross section A_0, meters;
g,	acceleration due to gravity, m/sec^2;
F,	Froude number of total reservoir cross section, equal to $(Q/Ad)/(g\epsilon)^{1/2}$;
F_1,	Froude number of withdrawal layer only, equal to $[Q_1/(A_1d_1)]/(g\epsilon)^{1/2}$; a universal constant, equal to 0.33 after *Kao* [1970];
F_0,	Froude number of the critical inflow section where overflow or underflow starts, assumed to be about 0.5;
Q,	total flow in reservoir cross section, m^3/sec;
Q_1,	withdrawal layer flow, m^3/sec;
Q_T,	total turbine discharge, m^3/sec;
q,	flow per unit width in total cross section, equal to Q/w, m^2/sec;
w,	mean width of total reservoir cross section, defined as $w = A/d$, meters;
w_1,	mean width of the withdrawal layer, defined as $w_1 = A_1/d_1$, meters;
ϵ,	density gradient number, in stably stratified fluids always positive, equal to $(1/\rho)\ d\rho/dz$, 1/m;
ϵ_1,	density gradient number for withdrawal layer only, equal to $(1/\rho)\ (d\rho/dz)_1$, 1/m;
$\Delta\rho$,	density difference, in stably stratified fluids always positive, kg/m^3.
ρ,	reference density, a representative density of the moving fluid, inflow density in (1), the density at intake center line in the gradient numbers ϵ and ϵ_1, kg/m^3.

REFERENCES

Bohan, F. P., and F. L. Grace, Mechanics of stratified flow through orifices, *J. Hydraul. Div. Amer. Soc. Civil Eng., 96*(HY12), 1970.

Brooks, N. H., and R. C. Y. Koh, Selective withdrawal from density stratified reservoirs, *J. Hydraul. Div. Amer. Soc. Civil Eng., 95*(HY4), 1969.

Churchill, M. A., and W. R. Nicholas, Effects of impoundments on water quality, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng., 93*(SA6), 1967.

Debler, W. R., Stratified flow into a line sink, *J. Eng. Mech. Div. Amer. Soc. Civil Eng., 85*(EM3), 1959.

Elder, R. A., and W. O. Wunderlich, Evaluation of Fontana Reservoir field measurements, Proceedings of the American Society of Civil Engineers Conference on Current Research into the Effects of Reservoirs on Water Quality, Portland, Oregon, January 1968, *Rep. 17*, Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Elder, R. A., and W. O. Wunderlich, The prediction of withdrawal layer thickness in density-stratified reservoirs, paper presented at the 13th Conference of the International Association for Hydraulic Research, Sci. Counc. of Jap., Kyoto, Japan, Aug. 31 to Sept. 5, 1969.

Harleman, D. R. F., Stratified flow, in *Streeter's Handbook of Fluid Dynamics*, sect. 26, McGraw-Hill, New York, 1961.

Harleman, D. R. F., Mechanics of condenser water discharge from thermal power plants, in *Engineering Aspects of Thermal Pollution*, edited by F. L. Parker and P. A. Krenkel, chap. 5, pp. 144-164, Vanderbilt University Press, Nashville, Tenn., 1969.

Kao, T. W., Free streamline theory for inviscid stratified flow into a line sink, *Phys. Fluids, 13*(3), 1970.

King, D. L., Hydraulics of stratified flow, Second progress report, Selective withdrawal from reservoirs, *Rep. HYD-595*, Bur. of Reclam., U.S. Dep. of the Interior, Denver, Colo., Sept. 1969.

Tennessee Valley Authority, Cherokee Reservoir—Selective withdrawal, *Water Resour. Res. Lab. Rep. 13*, Div. of Water Contr. Plann., Eng. Lab., Norris, Tenn., 1967.

Tennessee Valley Authority, Barren and Nolin reservoirs—Selective withdrawal, *Water Resour. Res. Lab. Rep. 21*, Div. of Water Contr. Plann., Eng. Lab., Norris, Tenn., 1969*a*.

Tennessee Valley Authority, Douglas Reservoir—Selective withdrawal, *Water Resour. Res. Lab. Rep. 20*, Div. of Water Contr. Plann., Eng. Lab., Norris, Tenn., 1969*b*.

Tilton, L. W., and J. K. Taylor, Accurate representation of the refractivity and density of distilled water as a function of temperature, *J. Res. Nat. Bur. Stand., 18*, 1937.

Vigander, S., and W. O. Wunderlich, Calibration and use of a low velocity current meter, paper presented at National Water Resources Engineering Meeting, Amer. Soc. of Civil Eng., Phoenix, Ariz., Jan. 1971.

Wunderlich, W. O., and R. A. Elder, The influence of reservoir hydrodynamics on water quality, Proceedings of the 6th Annual Sanitary and Water Resources Engineering Conference, June 1-2, 1967, *Tech. Rep. 13*, Dep. of Sanit. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1967.

Wunderlich, W. O., and R. A. Elder, The mechanics of stratified flow in reservoirs, in *Reservoir Fisheries Resources Symposium*, edited by C. E. Lane, American Fisheries Society, Washington, D. C., 1968.

Wunderlich, W. O., and R. A. Elder, Effect of intake elevation and operation on water temperature, *J. Hydraul. Div. Amer. Soc. Civil Eng., 95*(HY6), 1969.

Wunderlich, W. O., and R. A. Elder, Selective withdrawal from density-stratified reservoirs, Discussion, *J. Hydraul. Div. Amer. Soc. Civil Eng., 96*(HY5), 1970.

Yih, C. S., *Dynamics of Nonhomogeneous Fluids*, Macmillan, New York, 1965.

Stratified Reservoir Density Flows Influenced by Entering Streamflows

L. S. SLOTTA
Oregon State University, Corvallis, Oregon 97331

Density stratification due to seasonal temperature variations in temperate zone lakes is a well-known occurrence. Variations of fluid density in a reservoir, coupled with environmental effects, give rise to internal flow patterns that can have a considerable effect on reservoir water quality. In determining how such currents might be controlled, major efforts in the past have been directed toward examining withdrawal current effects on the internal reservoir flows. However, little concern has been directed to characterizing the influences of entering streamflow on the current patterns of a stratified reservoir. This paper discusses several important hydrodynamic effects related to cold or dense streamflow waters entering a stratified reservoir having less dense surface strata.

ENTRANCE MIXING

When a streamflow enters an impoundment at its particular temperature, it mixes and descends to an elevation at which the resident water has the same density (or temperature). Exchanges of thermal energy within stratified lakes or reservoirs are closely coupled to the magnitude of hydrologic surface inflows and corresponding internal currents. It has been found that the entrance mixing effect changes thermal regime simulation predictions for heat budget analysis of reservoirs as significantly as changes by orders of magnitude of the vertical effective diffusion coefficient for heat transport [*Slotta*, 1970; *Huber and Harleman*, 1968; *Ryan and Harleman*, 1971]. Assumptions are made somewhat arbitrarily in the presently available simulation models regarding the mixing of reservoir surface waters and inflowing streams.

Experimental work also has led to the conclusion that entrance mixing of entering streamflows is more significant than was previously considered [*Slotta et al.*, 1969; *Ryan and Harleman*, 1971]. It has been found that changes in the amount of entrance mixing have a very strong effect on model reservoir temperature profiles. Examples of entrance mixing or entrainment rates of typical inflows are listed by *Ryan and Harleman* [1971] as inflow at surface (i.e., warm water), 50% entrainment; inflow at intermediate depth, 200% entrainment; and inflow at reservoir bottom (i.e., cold water), 500% entrainment. Fieldwork is necessary to fill the gap in selecting physically reasonable values for simulation applications using entrainment and stream-pool mixing ratios.

INTERNAL CURRENTS

Laboratory experiments conducted at Oregon State University (1969) showed that reproducible major current patterns develop as streamflows enter a stratified reservoir [*Slotta et al.*, 1969]. The laboratory model reservoir was 7.62 meters (25 feet) long and was filled in gradient salt solution layers to provide the desired density stratification. The experimental setup is sketched in Figure 1, and flow parameters are indicated. Flow field current patterns and velocity measurements were determined photographically. Time-lapse movies of an experiment would compress a 2-hour study to a 3-min movie for review. The major currents found in the laboratory model are indicated in Figure 2.

Selective withdrawal releases from the laboratory model were programed to balance the incoming streamflows. The selective withdrawal current was observed as a major current that had a coupling action to the inflows. Inflow and mixing currents occurred at levels different from the level of the withdrawal current.

Conclusions drawn from these laboratory studies were:

1. Two possible main inflow currents can be expected in a stratified reservoir.
2. The upper inflow current increased in magnitude as the streamflow Reynolds number

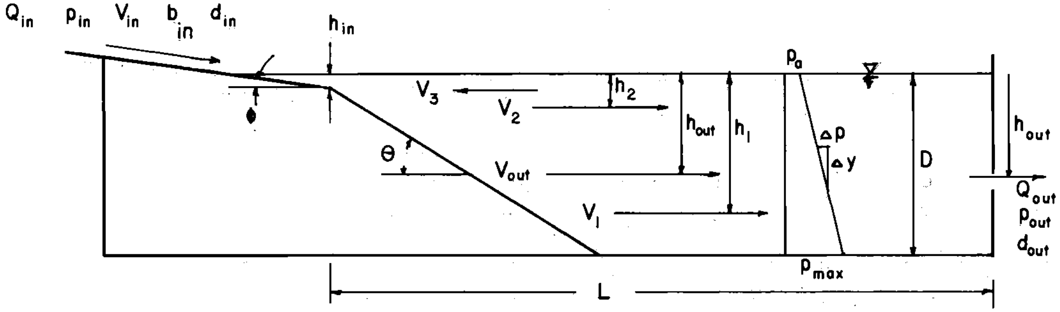


Fig. 1. Experimental reservoir with indicated test parameters.

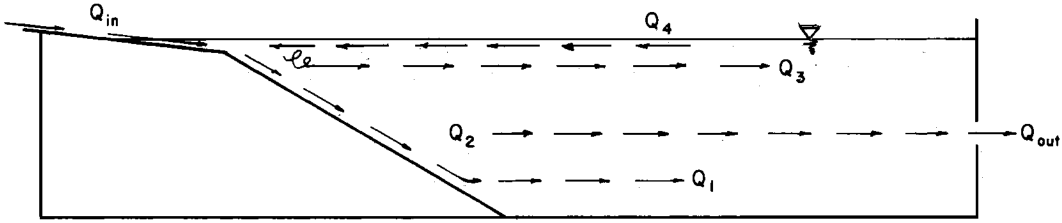


Fig. 2 Major current patterns.

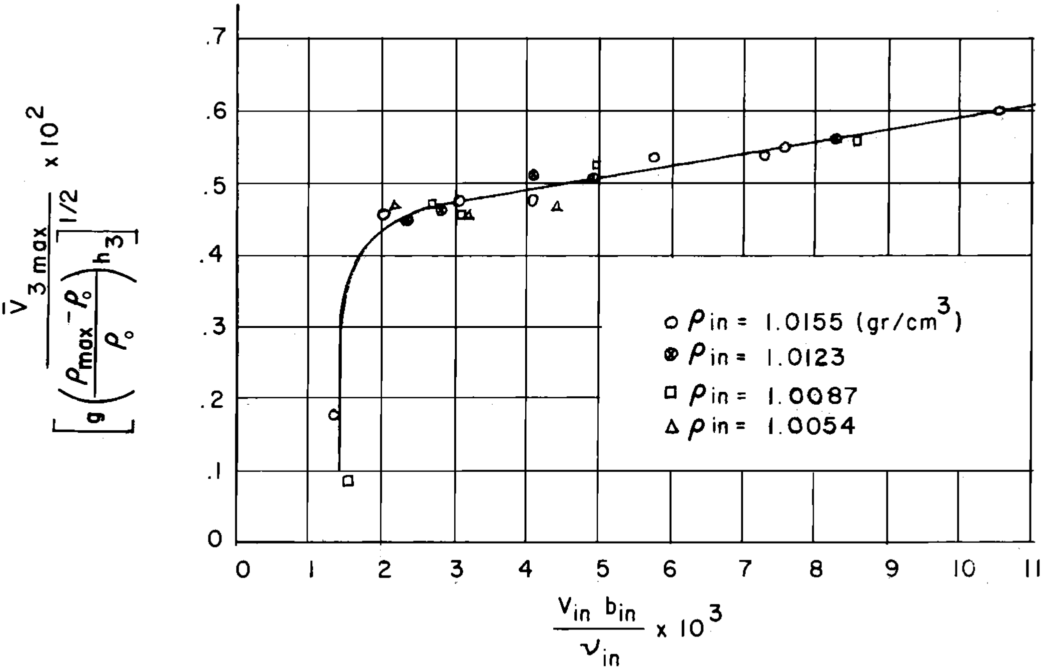


Fig. 3. Densimetric Froude number of Q_3 versus streamflow Reynolds numbers.

was increased. An empirical relation between the densimetric Froude number and Reynolds number was obtained. However, the elevation of the upper inflow current was independent of stream velocity and density (see Figure 3).

3. The lower inflow current was present only at a streamflow Reynolds number below a critical value. The elevation of the lower inflow current was dependent on the entering density and mixing that occurred at the stream mouth (see Figure 4).

4. Interaction and reinforcement of currents can be expected particularly when the effects of withdrawal releases are considered.

5. The influence of environmental factors (such as wind) is important in developing surface and seiche currents.

6. Topography and reservoir geometry have significant effects on internal reservoir currents.

Regarding experiments conducted at Froude scale with laminar flows to model actual reservoir currents, it can be related that the eddy scales of motion found in the hypolimnion of actual reservoirs are of the order of molecular scales. Thus the eddy diffusion coefficient for mass transport nearly approximates the eddy viscosity coefficient for these stable waters. Experiments conducted in the laboratory with large inflow turbulent discharges entering into a stratified pool showed spread phenomena similar to those obtained in the laminar flow experiments.

Predictions from lake and reservoir measurements give effective diffusion coefficients within hypolimnetic waters ranging from 0.1 to 10 cm²/sec [*Bella,* 1969; *Orlob and Selna,* 1970]. The validity of this model-prototype Froude scaling is limited by insufficient field evidence.

FIELD STUDIES

Field measurements of inflows to reservoirs are scarce. Some data on flow passage through the Tennessee Valley Authority (TVA) system have been reported by *Elder and Wunderlich* [1968]. Field measurements on Fontana Reservoir inflows, traced by dye concentrations, indicate interflows as expected from laboratory experiments.

The causes, sources, and means for controlling turbidity found in Hills Creek Reservoir, Oregon, are being studied by Oregon State University researchers. Clear, cold inflows entering this reservoir create an easily discernible interface with the turbid pool (see Figure 5). The turbidity interface shown in Figure 5 shows typical inflow currents as depicted in laboratory studies. It is hoped that research support can be obtained to

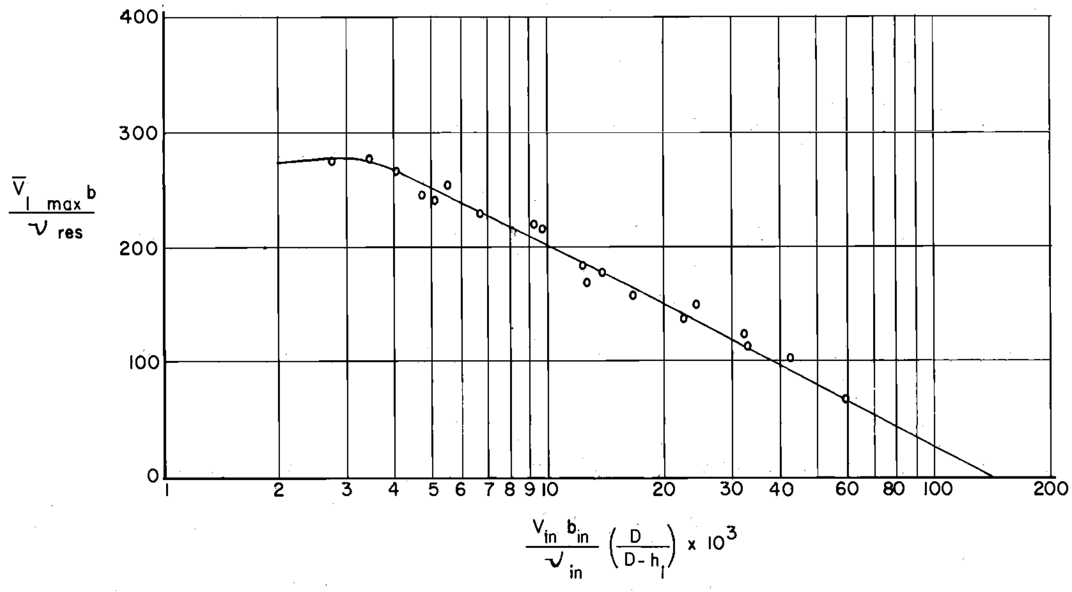
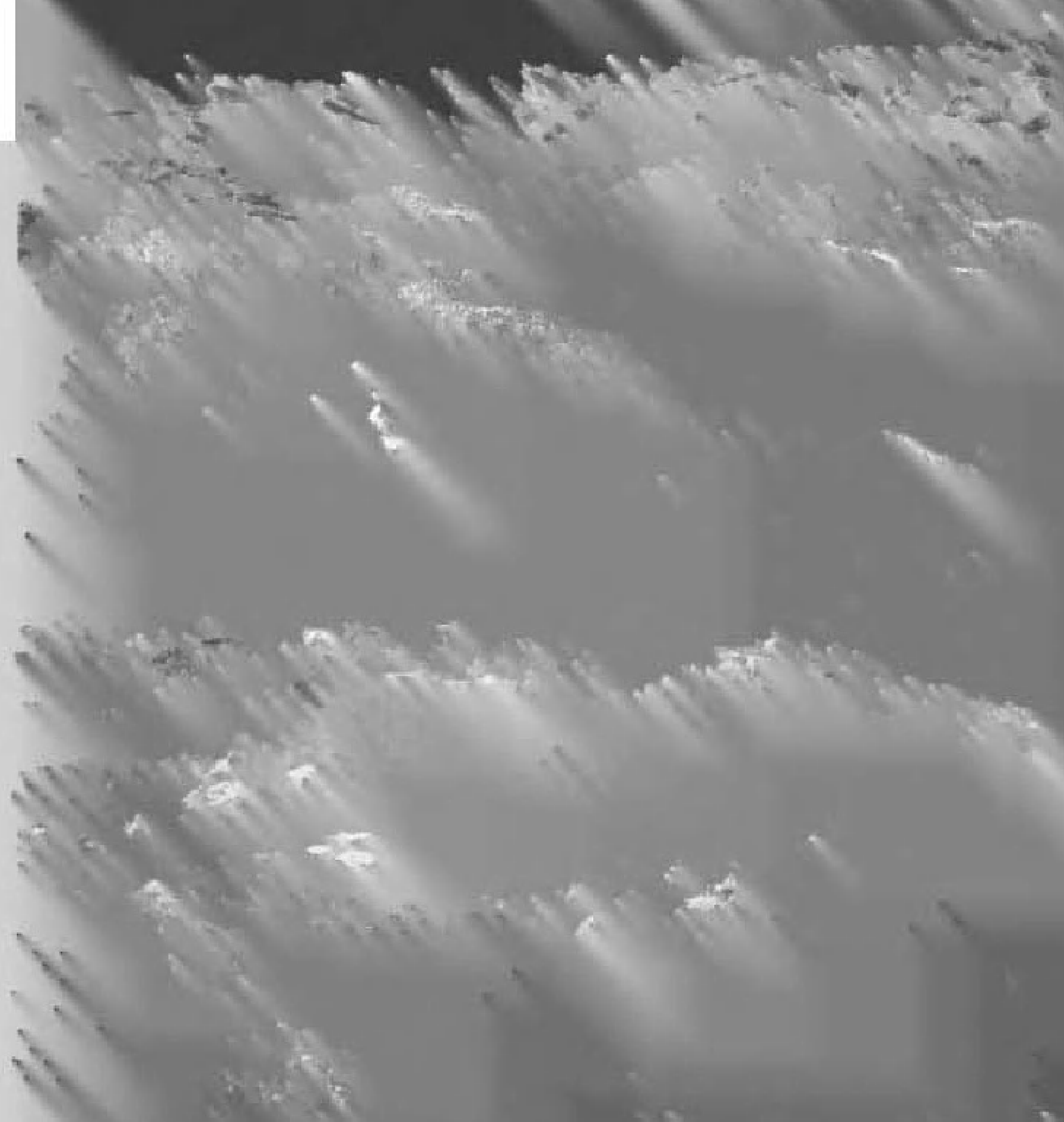


Fig. 4. Logarithmic plot of scaled streamflow Reynolds number versus the number of Q_1.



[illegible]

[illegible]

[illegible]

$$V_{3\max} = \left[\left(\frac{\rho_{\max} - \rho_o}{\rho_{\max}}\right)h_3 g\right]^{1/2} \cdot \left(1.67 \times 10^{-4}\,\frac{V_{\text{in}} b_{\text{in}}}{\nu_{\text{in}}} + 0.42\right)$$

(See Figure 4.)

NOTATION

D, total reservoir depth;
ϕ, angle of inflow;
θ, reservoir bed slope angle;
h_{in}, depth of slope change;
h_{out}, depth of outlet;
L, length of reservoir;
b, width of channel;

Inflow

Q_{in}, inflow rate;
V_{in}, inflow velocity;
b_{in}, inflow width;
d_{in}, inflow depth;

Outflow

Q_{out}, outflow rate;
V_{out}, outflow velocity;
ρ_{out}, outflow density;
d_{out}, outflow diameter;

Ambient fluid

$\Delta\rho/\Delta\rho$, density gradient;
ρ_o, bottom density;
$\rho_{\max}$, bottom density;
g, gravitational acceleration;
ν, kinematic viscosity;
Q_1, low-level density current;
h_1, low-level current depth;
Q_2, selective withdrawal current;
h_2, current level;
Q_3, upper-level mixed current;
h_3, upper-level current depth.

Acknowledgments. The support by Oregon State University and by the Federal Water Quality Administration for research on stratified reservoir currents is gratefully acknowledged (grant WP-00983-03, 1680 DRX).

REFERENCES

Bella, D. A., The effects of sinking and vertical mixing on algal populations in lakes and reservoirs, *J. Water Pollut. Contr. Fed., 42*(5), part 2, 1970.

Elder, R. A., and W. O. Wunderlich, Evaluation of Fontana Reservoir field measurements, Proceedings of the American Society of Civil Engineers Conference on Current Research into the Effects of Reservoirs on Water Quality, Portland, Oregon, January, 1968, *Rep. 17,* Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Ewing, M., and E. M. Thorndike, Suspended matter in deep ocean water, *Science, 147,* 1291–1294, 1965.

Huber, W. C., and D. R. F. Harleman, Laboratory and analytical studies of thermal stratification of reservoirs, *Hydrodyn. Rep. 112,* Mass. Inst. of Technol., Cambridge, Oct. 1968.

Jacobs, M. B., and M. Ewing, Mineral source and transport in waters of the Gulf of Mexico and Caribbean Sea, *Science, 163,* 805–809, 1969.

Orlob, G. T., and L. G. Selna, Temperature variations in deep reservoirs, *J. Hydraul. Div. Amer. Soc. Civil Eng., 96*(HY2), 391–410, 1970.

Ryan, P. J., and D. R. F. Harleman, Prediction of the annual cycle of temperature changes in a stratified lake or reservoir: Mathematical model and user's manual, *Tech. Rep. 137,* Parsons Lab. for Water Resour. and Hydrodyn., Mass. Inst. of Technol., Cambridge, April 1971.

Slotta, L. S., Numerical simulations of the thermal regimes of Lake Norman, incorporated report, project 7098.0034, Hydronautics, Laurel, Md., Oct. 1970.

Slotta, L. S., et al., Stratified reservoir currents, *Bull. 44,* Eng. Exp. Sta., Oreg. State Univ., Corvallis, Oct. 1969.

Some Results of 20-Year Network Observations on Currents in Tchudsko-Pskovskoe Lake

T. N. FILATOVA
State Hydrological Institute, Leningrad, USSR

T. O. KALEJARV
Estonian Hydrometeorological Service, Tallin, USSR

Despite the urgent need for observational data on inland water bodies, a sufficient amount of reliable data of direct measurements does not exist at present. The schemes of currents corresponding to certain hydrometeorological conditions are unavailable not only for large reservoirs of our country but for middle size and small lakes and reservoirs as well. There are no such data on reservoirs in other countries either. At present, currents are the least-studied element of the hydrologic regime of continental water bodies. The inadequate knowledge of the currents in the inland water bodies is accounted for by the complex character of the process of water movement; by the lack of sensitive, small, and reliable instruments; by the difficulty of instrument installation during the period when there is no ice cover; and by the impossibility of carrying out synchronous surveys of currents over the area and along the depth. In the analysis of observational data, certain difficulties arise from the lack of data on hydrometeorological elements, processes, and phenomena that influence the generation, development, and stabilization of currents.

The present report shows the main results of generalization of observational data on currents in Tchudsko-Pskovskoe Lake that were obtained at the Tyirikoya lake station during the periods without ice cover of 1949–1968. Special attention is paid to the direction of currents and maximum velocities. This 20-year series of observational data on currents is the longest for the reservoirs of our country; thus these data are of great practical and scientific interest. These data might be used for plotting generalized schemes of currents, for checking the methods of mathematical and physical modeling, and for rational choice in the location of water intakes and waste water discharges.

Tchudsko-Pskovskoe Lake (area of 3550 km^2) is one of the largest lakes of the Soviet Union and of Europe. According to area, this lake occupies the fifth place in Europe after Ladoga, Onega, Vänern, and Vättern lakes. The streamflow of the Narva River flowing out of the lake is controlled. The lake is situated in a wide and flat lake basin that is 143 km long and has an average width of 24.6 km and a maximum width of 48.8 km. The lake consists of two parts: the northern part is the larger of the two parts and is called Tchudskoe Lake, and the southern part is called Pskovskoe Lake. The two lakes are connected by a narrow straight named Teploe Lake.

The present report is based on the data of regular observations performed at eight permanent verticals whose locations are shown on Figure 1. Observations of these verticals were carried out from anchored ships and boats by means of modernized sea current meters and captive floats. The latter were used only for measurements in the surface layer. Modernized sea current meters served for measurements at half depth of the verticals and in the bottom layer. The accuracy of the measurements of the direction of the currents was estimated to be ±20°–30°, and the accuracy of the current velocity was estimated to be ±3–5 cm/sec. The most frequent observations (daily and 10 day) were made on verticals 2 and 15, situated 9 km from the town of Mustvee and in the narrow part of Teploe Lake near the town of Mehikoorma, respectively. On the rest of the verticals, measurements were performed once a month. All together, >5000 measurements were made. Most

Fig. 1. Location and number of permanent verticals used in this study.

of these were made under the conditions of calm weather with winds of not more than 10 m/sec.

These observations provided the data that were generalized from the point of view of current direction frequency and were presented in diagrams. Such use of the statistical characteristic makes it possible to determine water body areas with stable and unstable directions of water currents; such a determination is most important for the development of the rational use of lakes and reservoirs for economic purposes. In addition, the above generalization is made for different water layers and wind directions. Thus it is possible to determine the areas of deep compensation currents under different wind conditions and to explain their location by the morphometric features of the water body. Current direction frequency diagrams help to determine the conditions under which discharge and drift currents are most liable to develop in Pskovskoe and Teploe lakes.

When observational data were analyzed, diagrams of direction frequencies in the surface and bottom layers on verticals 1–7 and 15 for winds of the four cardinal points were used (Figures 2 and 3). Verticals 1–7 are in the central part of Tchudskoe Lake, which is characterized by a gradual change of depth within 3–10 meters, and vertical 15 is in the deepest part of the lake, where the depth is 15 meters. Wind frequencies for which the analysis is performed lie within 8.4–15%. Eastern winds have the lowest frequency as a rule and high speed, i.e., >15 m/sec.

The results were analyzed separately for the coastal and central zones of Tchudskoe Lake and for the narrow part of Teploe Lake. The currents in Teploe Lake are the most stable. The analysis of the diagrams showed that Tchudskoe Lake is characterized by drift, compensation, and discharge currents. The following regularities were observed:

1. In Tchudskoe Lake when winds are blowing along the main axis of the lake, drift currents in the coastal zone (verticals 1, 6, and 7) penetrate to the bottom (1*a*, *b*, 6*a*, *b*, and 7*a*, *b* in Figure 2 and 7*a*, *b* in Figure 3). The drift currents of the northern direction (1*a*, *b* in Figure 3) that are generated near the western shore are an exception. These currents do not penetrate to the bottom because their development is hindered by the shape of the western shore, i.e., the narrowing of the lake 6–7 km south of the town of Mustvee. Penetration of the drift current down to the bottom is observed most clearly at the eastern shore during northern winds. In such a case the width of the alongshore stream may reach 7–8 km. The intensive development of southward currents largely depends on the straightness of the eastern shore and the absence of any wind obstacles to the south from the town of Gdov. The width of the alongshore stream at the same shore during southern winds is 2–3 km less than it is during northern winds. This difference might be due to the narrowing of the lake to the north from the town of Gdov and to the closeness of the northern shore. Thus, near vertical 6, compensation currents of a southern direction are developed either in the whole water layer or in the bottom layer only during southern winds, which cause cyclonic circulation near verticals 6 and 7 (6*a*, *b* and 7*a*, *b* in Figure 3).

2. In the central part of Tchudskoe Lake, compensating currents are widely developed in the bottom layer during winds of different directions. With northern and southern winds the width of these currents reaches 25–30 km, and the currents are located approximately between verticals 2 and 6. With northern winds the compensation

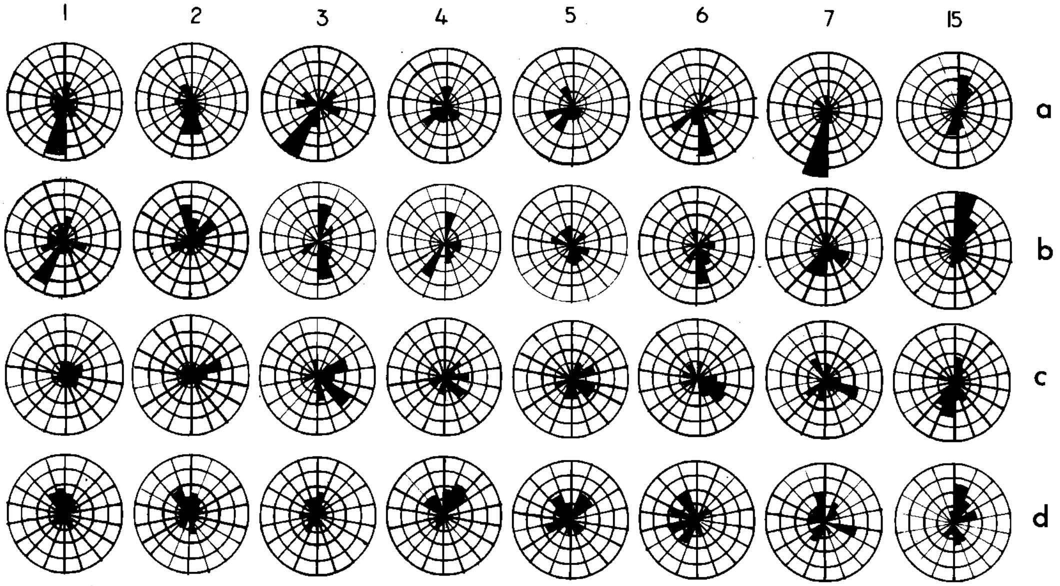


Fig. 2. Diagram of current direction frequencies in percentage from the number of observations in the surface and bottom layers on verticals 1-7 and 15 during northern and western winds. The distance between the circumferences is assumed to be 10% of frequency.

current is most clearly observed on vertical 2 (2*b* in Figure 2). The development of compensation currents directed southward on this vertical is strongly influenced by the above-mentioned shape of the western shore south from the town of Mustvee. For the same reason, during southern winds (2*b* in Figure 3) the drift-gradient current on vertical 2 is less distinct than that on

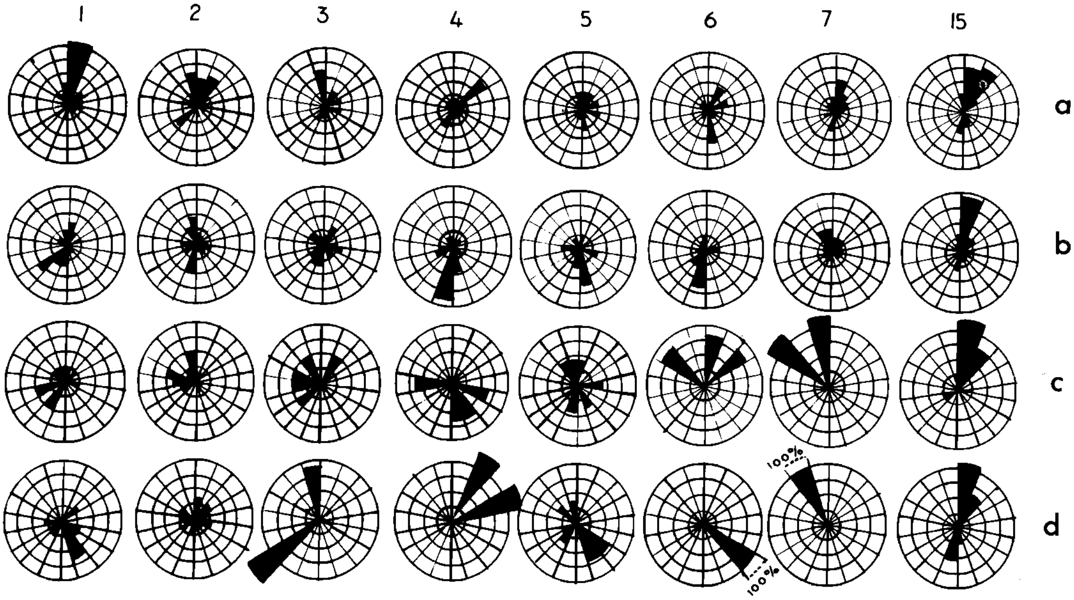


Fig. 3. Diagram of current direction frequencies in the surface and bottom layers on verticals 1-7 and 15 during southern and eastern winds. The distance between the circumferences is assumed to be 10% of frequency except for 6*d* and 7*d*, where the distance between the neighboring circumferences is assumed to be 20%.

verticals 4–6. Such regularity might be explained by the fact that because of morphometric peculiarities the drift currents in the surface layer of vertical 2, as well as vertical 1, are less intensive than those of verticals 4–6 situated in the open part of the lake; as a result, less stable compensation currents occur in the bottom layer of vertical 2.

In case of transverse drift currents, compensation currents are observed along the whole profile. However, at the windward rectilinear deep shore (*7d* in Figure 2), they are less distinct than at the windward shore of a bay with less depth of water (*1d* and *2d* in Figure 3). The data from special observations of 1970 showed that during eastern winds of 5 m/sec the compensation current is observed in the bottom layer 2.5 km away from the western shore.

3. On vertical 15 during winds of all directions (15*a* in Figure 2 and 15*a, c* in Figure 3) except for western winds (15*c* in Figure 2), northward currents are observed in the surface layer and are most distinct during southern (15*a* in Figure 3) and eastern (15*c* in Figure 3) winds. During these winds, drift currents develop and are superimposed on discharge currents caused by the water inflow from the Velikaya River (the average annual discharge is 142 m^3/sec). During eastern winds, water is detained near the western shore of Pskovskoe Lake. Thus water outflow is stimulated toward the north to the extent that the fall of the water stage is observed during this time in the southeastern part of Tschudskoe Lake, where the main exchange with Teploe Lake takes place, because of the transfer of water into the western part of the lake.

In the case of northern and western winds, water transfer both in the northern and southern directions takes place in the surface layers of vertical 15 (15*a, c* in Figure 2). In this case, intensive southward water transfer is stimulated by the situation of all three lakes. Therefore, during western and northern winds, wind-induced surge is created and results in compensation currents that mix with discharge currents and thus form discharge-drift currents directed northward in the surface layer.

The bottom layer of vertical 15 is characterized by prevailing northward currents during winds of all directions. Only a few observations showed southward currents. Water movement in the northern direction both in the bottom and surface layers is caused by two factors, i.e., the water inflow from the Velikaya River and compensation currents created during northern and western winds. Deepwater transfer in the southern direction is most clearly observed during western winds (15*d* in Figure 3). Water masses reaching the southern part of Tchudskoe Lake during strong eastern winds cannot penetrate quickly into the open part of the lake because of the morphometric features of the lake basin, the small depth, the presence of islands and narrow straights, and the return (caused by the surge) into Pskovskoe Lake that forms a compensation stream.

The change of the direction of water movement on vertical 15 with the change of wind direction is also evidence of the important role of the drift currents in the most narrow part of the lake. It is impossible to deny the possibility of seiche currents in Tchudsko-Pskovskoe Lake, but the observational data show that the role of these currents is less important than that of the drift currents.

Measurements of current velocities showed that maximum velocities are observed in Teploe Lake near Mehikoorma. They reach 50 cm/sec at the surface and 35 cm/sec at the bottom. In Tchudskoe Lake, maximum velocities are 30–35 cm/sec at the surface and 20 cm/sec at the bottom. Despite the instability of the wind coefficient at the same wind speed on the same vertical, the average value of wind coefficients (1.45%), estimated on the basis of observational data of all the verticals, conforms to the values of wind coefficients on other water bodies.

In conclusion it should be noted that Tchudsko-Pskovskoe Lake is the location of the start of the first limnological studies in Russia. Even the first scientists who studied the lake pointed out the different direction of water transfer from Pskovskoe Lake into Tchudskoe Lake and vice versa near Mehikoorma. They also noted the difference in the thickness of the ice cover in Pskovskoe and Teploe lakes compared with that in Tchudskoe Lake, which is explained by the lower stream velocities in Tchudskoe Lake. The present report summarizes and specifies the works by previous scientists and needs, in its turn, further specification.

Hydraulic Transients in Man-Made Lakes

JEAN-PIERRE GRANJU, JACK GARRISON, AND JAMES PRICE
Flood Control Branch, Tennessee Valley Authority, Knoxville, Tennessee 37902

The movement of water in man-made lakes is directly coupled to the operation of the structures that create these impoundments. In the multipurpose man-made lakes of the Tennessee Valley Authority (TVA) system, hydropower generation, particularly power-peaking operations, is the main cause of the spatial and temporal variation in flow along the principal axis of these reservoirs. Because these waters are the vehicle for the transport of heat from generating plants, for dissolved oxygen, and for waste from industrial and municipal sources, a precise knowledge of water behavior is imperative if one is to meet the increasing demands on water use and maintain and improve water quality. This paper describes the application of a computerized mathematical model to some of these complex flow problems associated with the man-made lakes of the TVA.

GENERATION OF TRANSIENTS IN MAN-MADE LAKES

Transient water movements unique to man-made lakes are caused by the operation of hydroelectric plants, sluices, spillways, locks, and so on. This behavior results mainly from the propagation of shallow-water translatory waves through these bodies of water. There are four basic types of these translatory waves. These are depicted schematically in Figure 1 for an idealized reservoir bounded by control structures at its extremities. Cases *a* and *b* show the translatory waves created, respectively, by a sudden increase and decrease in flow due to the operation of the upstream control structure. Cases *c* and *d* depict similar waves caused, respectively, by a sudden increase and decrease in flow due to the operation of the downstream structure.

The speed with which these wave fronts advance through the reservoir is dependent on the depth of the water body, whereas the magnitude of the motion induced at any point by the passage of the wave depends on the rate of the flow change at the boundary and the magnitude of the change. The effect of a single translatory wave generated at either boundary is quite long lasting. The wave is transmitted and reflected through the reservoir many times before boundary shear and viscous resistance finally overcome the induced motion.

In man-made lakes where operational changes at the boundaries occur frequently (as is the case in power-peaking operations) the actual motion of the water at any location and time is a superposition of many transmitted, reflected, and interfering waves of the four basic types shown in Figure 1. Consequently, the transient water behavior is quite complex. A computerized solution to a mathematical model that uses the hydraulic equations of continuity and momentum governing this motion offers the only feasible and practical solution for analyzing this complex water behavior.

For the past several years, TVA has been using a mathematical model for the analysis of these complex flow problems. This model and some of the excellent results obtained have been described in previous papers [*Buehler et al.*, 1968, 1969; *Garrison et al.*, 1969].

KENTUCKY LAKE TRANSIENTS

Maintaining or improving the quality of the waters in the TVA system is a major concern of the authority and the pollution control boards of the states in which TVA is located. To achieve this goal, both TVA and the Tennessee Stream Pollution Control Board now require that certain waste treatment standards be met before liquid wastes are released into the waters of the system within Tennessee. In addition, it may be required that waste discharges to the system be released in a certain proportion to the instantaneous flow passing the point of release in order to insure that the waste release does not in any way impair the water quality of the receiving reservoir. This re-

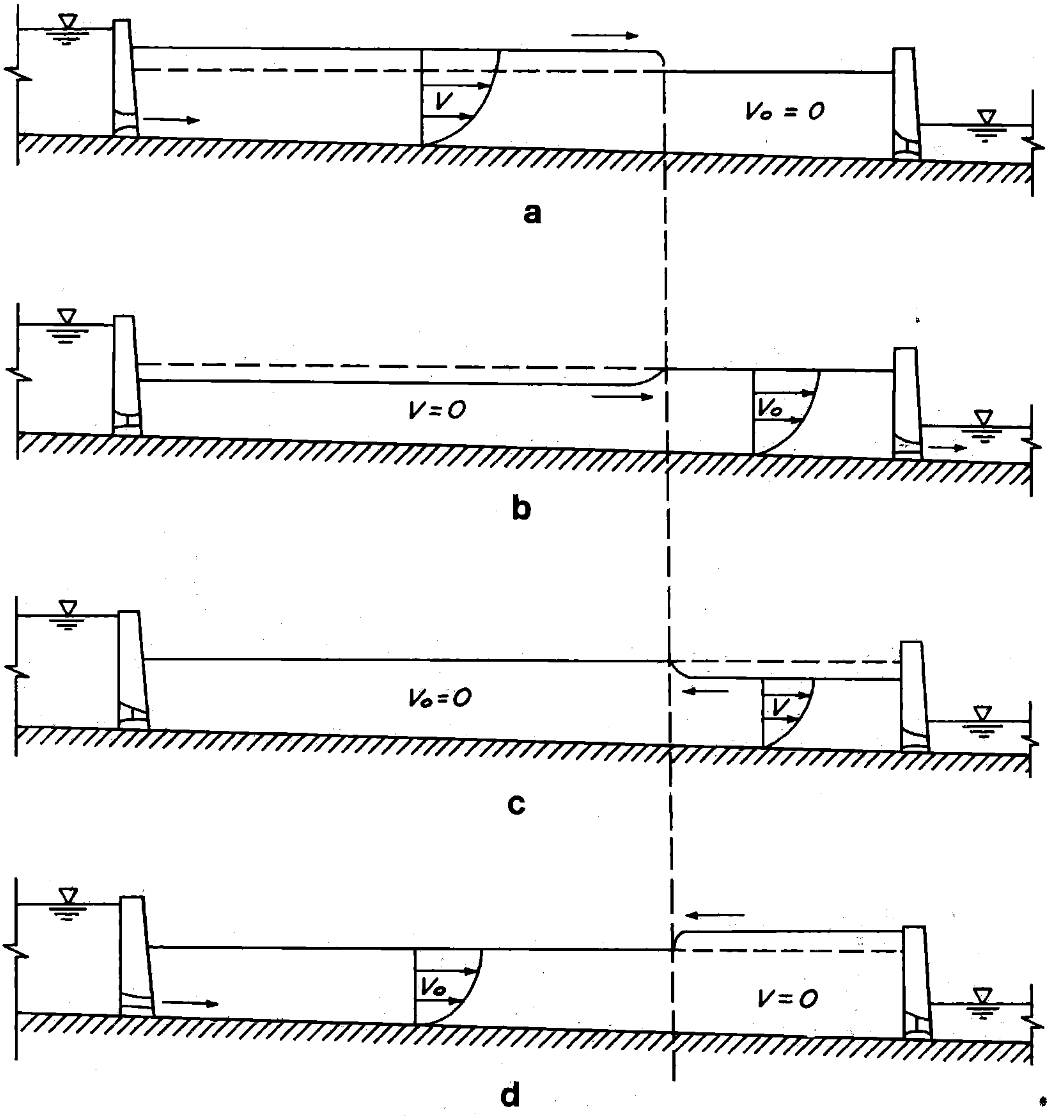


Fig. 1. Four basic waves in man-made lakes.

quirement was the case for a recently completed industrial plant located on Kentucky Lake near New Johnsonville, Tennessee.

Kentucky Lake, which is almost 300 km long, is bounded upstream and downstream by Pickwick and Kentucky dams, as shown in Figure 2. Turbine operations at these two plants are intermittent, and as a result the flow at any given time and location within the reservoir is quite variable. In addition, Kentucky and Barkley lakes are connected by an uncontrolled navigation canal just upstream from Kentucky and Barkley dams, as shown in Figure 3. Variations in water surface at the two ends of this canal determine the flow that takes place to or from Kentucky Lake. This flow is quite variable and is a contributor to the overall transient flow behavior of this reservoir.

Quantitative daily flow forecasting to achieve the multipurpose objectives of the reservoirs of the system has always been practiced by TVA. Among the data available for these forecasts are the anticipated hourly turbine releases required to meet the generating demands for power. A

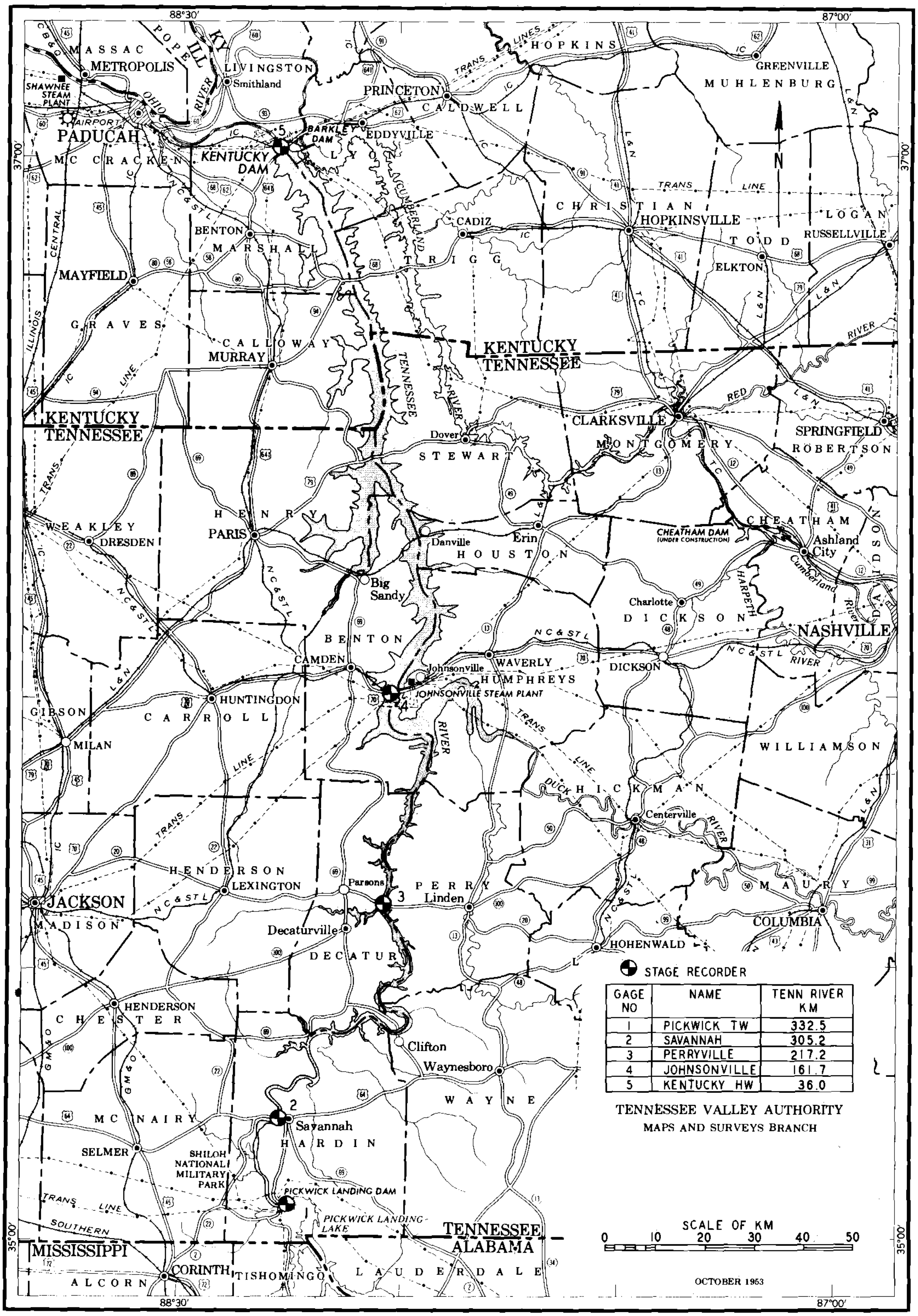
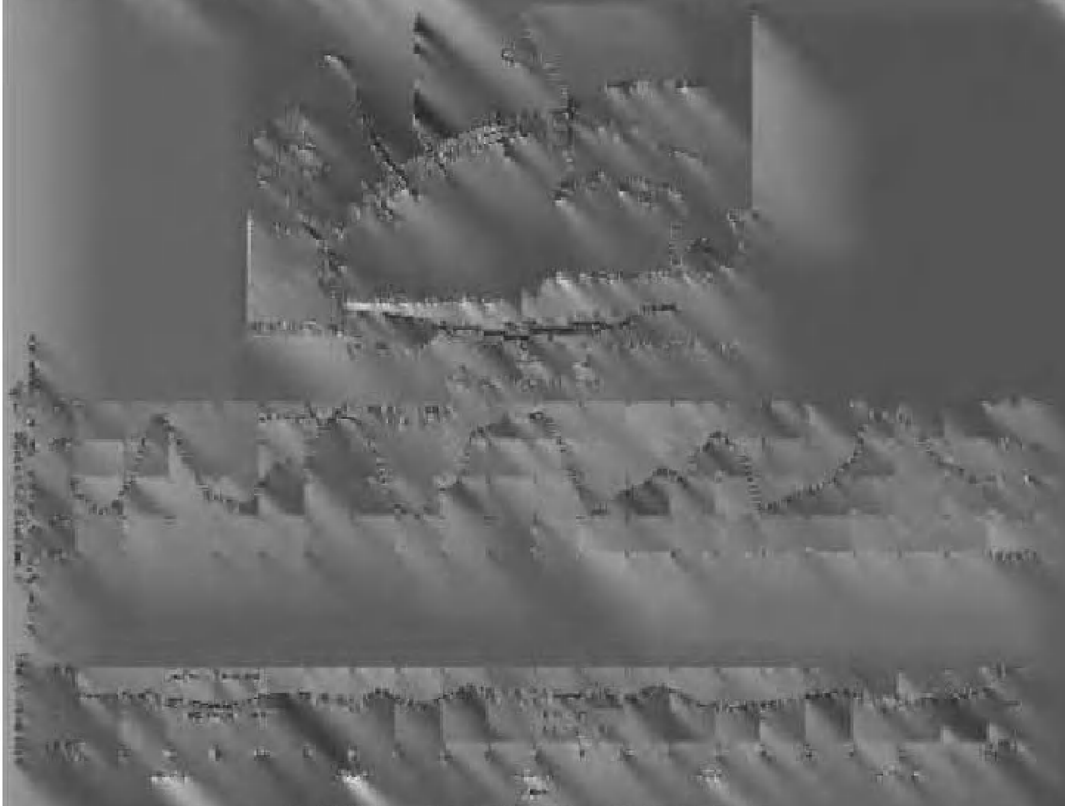


Fig. 2. Map of the Kentucky Lake vicinity.



[illegible]

[illegible]

It was found that the differences in stages computed by method 1, 2, or 3 were negligible, all of them being in complete agreement with the observed stages. Differences in computed flows by the three methods amounted to <100 m^3/sec in the middle portion of the reservoir, where Johnsonville is located. This result was of great practical significance, since generally the local inflows are uncontrolled and therefore are not as predictable as the boundary flows. It is also valuable to know that only daily values for all local inflows are required; input data preparation is thus greatly reduced.

Once the reliability of the model with the 3.4-

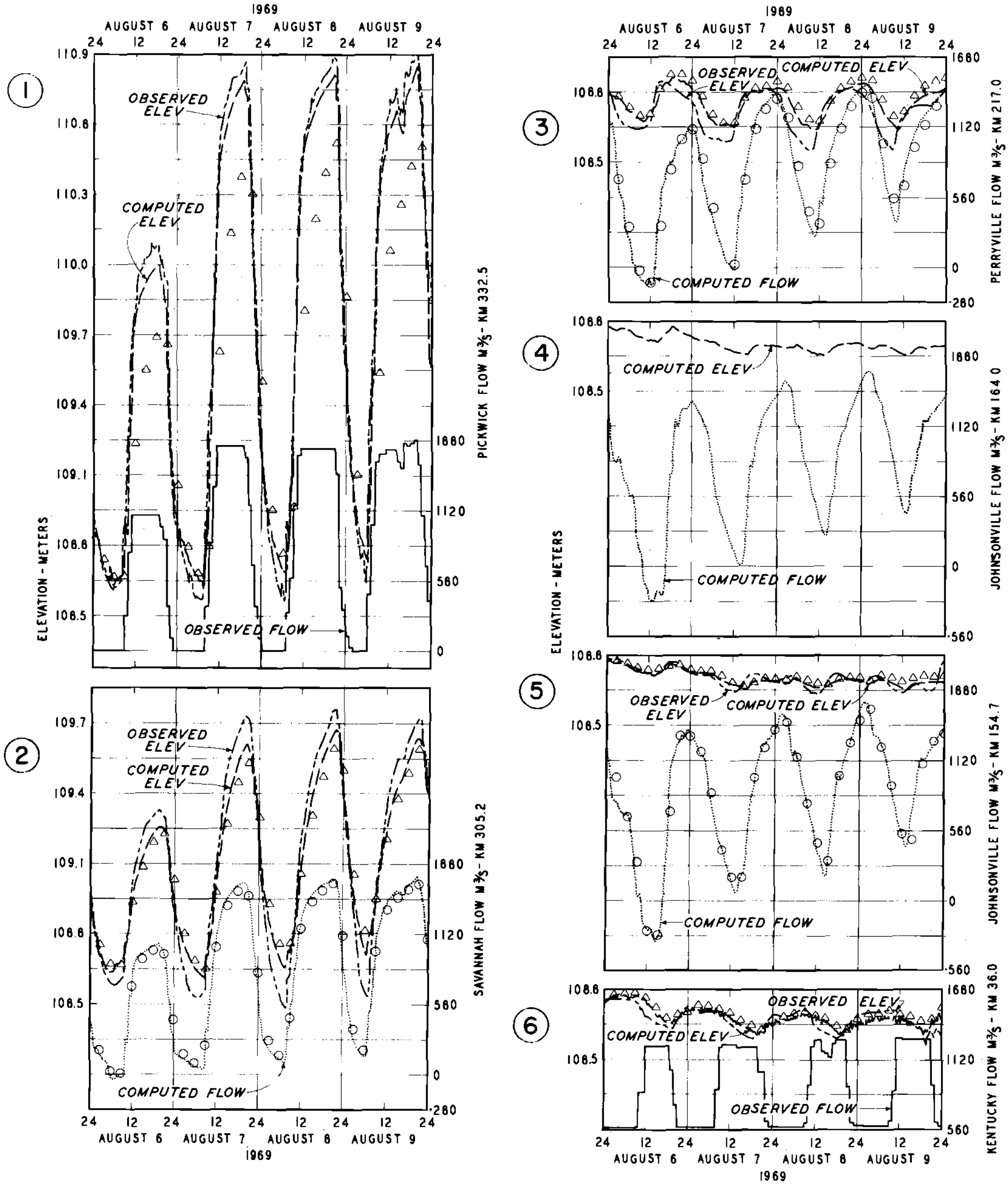


Fig. 4*a*. Comparison of observed and computed flow conditions.

km steps was established, simplification procedures were undertaken. The main disadvantages of the 3.4-km reach model are the large core storage requirement, lengthy input data preparation (initial conditions must be given for 89 cross sections), and long computation time. For these reasons the 14.8-km reach model was developed by using 21 average cross sections. It was found that at the common locations in the two models the computed flow was practically the same and that, except in the extreme upper reach of the reservoir, where there is considerable slope, the stages also agreed. In this part of the reservoir a 14.8-km reach is too long to accurately reproduce the water surface profile. This comparison is presented in Figure 4*a*.

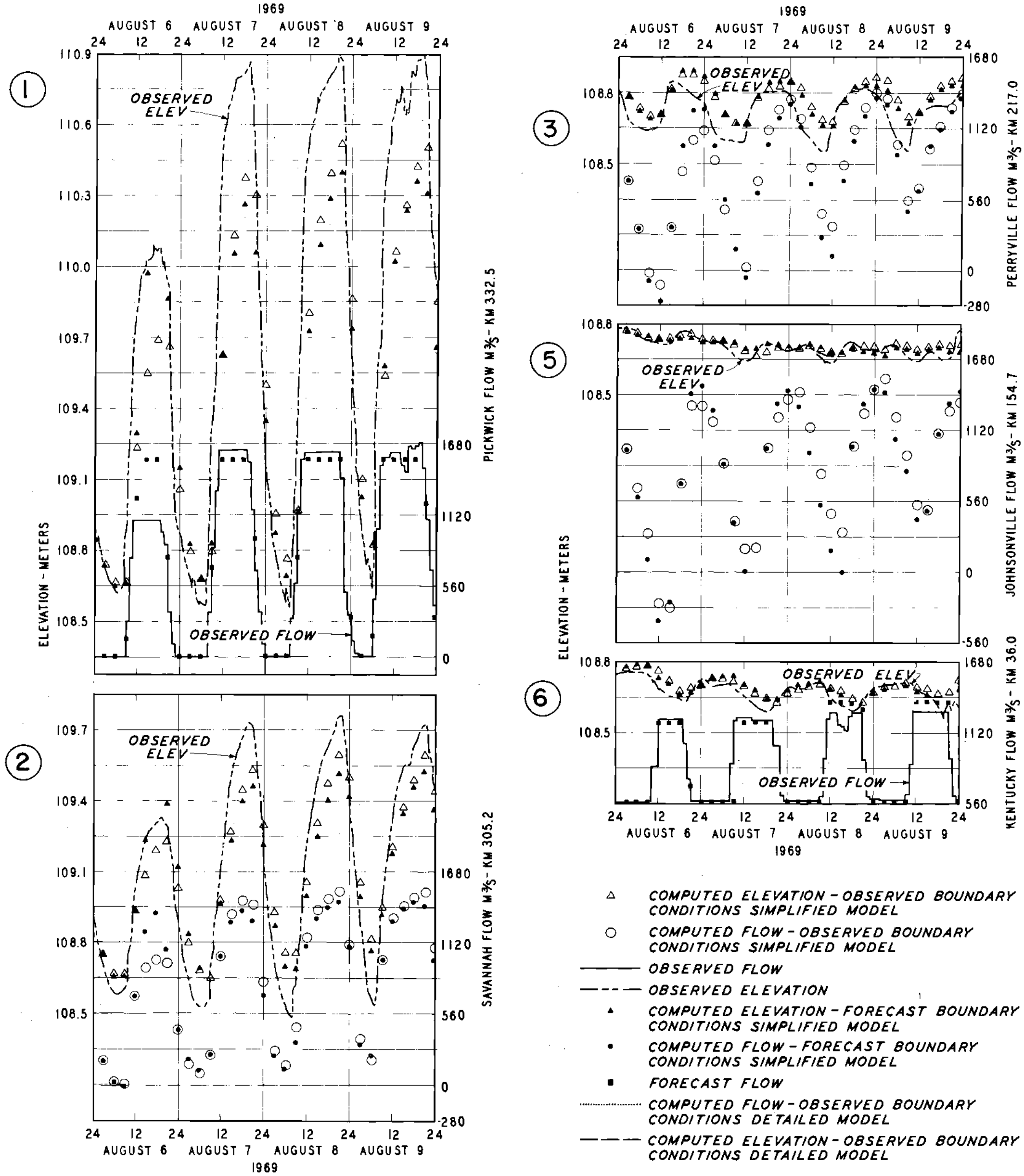


Fig. 4*b*. Comparison of observed and forecast flow conditions.

Because the point of waste release is located in the central portion of the reservoir where the results from the simplified model are satisfactory, it was decided to use this model for these predictions. The anticipated hourly turbine releases are determined by the System Loading Branch of the Office of Power, and the River Control Branch of the Division of Water Control Planning performs the actual routing and furnishes the forecast hourly flows to the industrial plant daily. The program requires initial conditions of stage and discharge at each of the 21 cross sections. These conditions are obtained from the previous day's forecast and are checked against the observed stages at the five gages located in the reservoir (see Figure 2) and the hourly anticipated turbine flows. All this computation requires only 15 punched cards. Less than 1 min of computer time on an IBM 360/50 system yields predicted flows and stages at 1-hour intervals for a 42-hour forecast period at any of the 21 cross sections along the reservoir. For the simplified model, Figure 4*b* shows a comparison between the results that were obtained by using forecast flows and the flows that were later observed.

It must be pointed out that the reliability of these predictions depends on how closely the actual operating schedules for the Pickwick and Kentucky turbines follow the anticipated schedules on which these predictions are based. Fortunately, in the past the predicted and actual operations of these plants have usually been nearly identical.

Although the simplified model approach is aimed specifically at providing instantaneous flows at 1-hour intervals at a particular point within Kentucky Lake, values of stage, discharge, and velocity at each of the 21 points in the reservoir are also determined and available from a single prediction run. The TVA has agreed to furnish these transient flow forecasts on a trial basis for a 1-year period to establish the usefulness and practicality of the method as a means for improving water quality control. Such an approach in all man-made lakes where the boundary operating conditions can be predicted with some degree of reliability offers hope for optimizing the use of these reservoir waters to meet the diverse and frequently conflicting demands placed on them.

REFERENCES

Buehler, B. J., J. T. Price, and J. M. Garrison, Transient flow investigations for TVA's Browns Ferry generating station, Proceedings of the 7th Annual Sanitary and Water Resources Engineering Conference, *Tech. Rep. 16*, edited by E. L. Thackston, Dep. of Sanit. and Water Res. Eng., Vanderbilt Univ., Nashville, Tenn., May 1968.

Buehler, B. J., J. M. Garrison, J. P. Granju, and J. T. Price, Digital computer simulation of transient flows in the TVA system, paper presented at 13th International Conference, Int. Ass. for Hydraul. Res., Kyoto, Japan, Aug. 31–Sept. 5, 1969.

Garrison, J. M., J. P. Granju, and J. T. Price, Unsteady flow simulation in rivers and reservoirs, *J. Hydraul. Div. Amer. Soc. Civil Eng., 95*(HY5), 1559–1576, 1969.

Movement of Heated Water Discharges from Power Plants in Man-Made Lakes

BARRY A. BENEDICT, EDWARD M. POLK, JR., FRANK L. PARKER, AND LOUIS H. MOTZ
Department of Environmental and Water Resources Engineering
Vanderbilt University, Nashville, Tennessee 37235

JOHN E. EDINGER
Towne School of Engineering, University of Pennsylvania
Philadelphia, Pennsylvania 19104

Man-made lakes have become commonplace throughout the world. With this development have come added uses of these new waters by man. Of special interest in this paper is their use for receiving discharges of heated waters. The theoretical developments cited in this paper will be seen to be applicable to any man-made lake.

The potential dangers and magnitude of the thermal pollution problem have been explicated in several recent references [*Parker and Krenkel*, 1969*a*, *b*; *Krenkel and Parker*, 1969; *Federal Water Pollution Control Administration,* 1968]. *Parker and Krenkel* [1969*a*] point out many areas of needed research in both the biological and engineering aspects of thermal pollution. Of real importance to assessment of any potential biological damage is an understanding of the temperature distributions resulting from cooling water discharges. To meet this need, Vanderbilt University has carried out several analytical and laboratory studies and a number of surveys of the heated water distributions near several Tennessee Valley Authority (TVA) fossil-fueled steam electricity generating plants. One must understand that these TVA sites are really man-made lakes and that flow occurs as a result of inflow and outflow and the varying operating schedules of dams. Therefore experimental verifications obtained at these sites should justify extension of the proposed models to any man-made lake. In fact, the results are also quite applicable to rivers of sufficient depth.

CLASSIFICATION OF HEATED WATER DISTRIBUTIONS AND MODELS

Several forms of temperature distribution, both upstream and downstream, can develop; their development is dependent on discharge characteristics, including temperature and flows in the receiving lake. Upstream movement of heat may occur if the densimetric Froude number F_D is sufficiently low. Equation 1 defines F_D, which represents the ratio of inertial forces to buoyant forces:

$$F_D = v/[(\Delta\rho/\rho)gd]^{1/2} \qquad (1)$$

where v is the mean ambient velocity; $\Delta\rho = \rho_2 - \rho_1$, the difference in density between the two layers; g is the acceleration due to gravity; and d is the depth of ambient flow.

Theoretically, values of 1.0 or greater prevent upstream movement of the heated water; in practice [*Keulegan*, 1949; *Harleman*, 1969], values of F_D of about 0.7 are sufficient to prevent such wedges. Predictions of wedge formation and size are important, owing to the possible recirculation of heated water through the plant, which decreases efficiency and raises effluent temperatures.

If the ambient velocity is 0, the heated discharge will move both upstream and downstream, depending on the orientation of the discharge structure. If the ambient flow densimetric Froude number exceeds 0.7, all heated

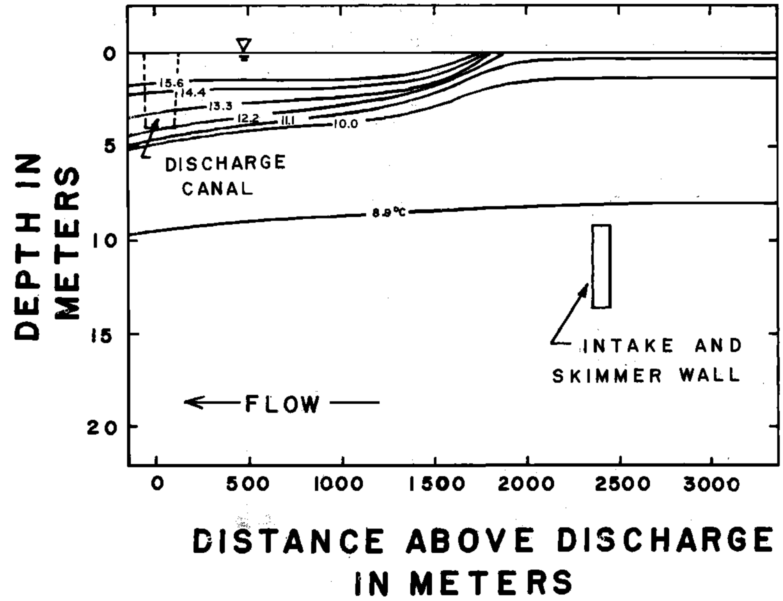


Fig. 1. Longitudinal temperature profile upstream from Gallatin steam plant.

water will move downstream. If the Froude number lies between 0 and 0.7, an upstream wedge will form, though, of course, the net transport must be downstream. Several models have been developed to describe these distributions. The principal means for effluent temperature reduction are dilution and heat exchange with the atmosphere. Dilution is primarily attributed to two mechanisms, diffusion and entrainment. Diffusion is the movement of the heated water that occurs as a result of turbulent velocity fluctuations. Entrainment is the lateral mixing that occurs because of velocity differences between the discharged water and the ambient flow and the resultant eddy generation and shear forces. The two mixing mechanisms are, of course, not completely independent inasmuch as the velocity differences give rise to higher local degrees of turbulence and the resultant increases in mixing by diffusion. All the presently proposed models, including those at Vanderbilt, are formulated with a mixing mechanism based on either diffusion or entrainment. The resulting empirical coefficients obtained are therefore lumped parameters representing both processes.

TABLE 1. Data on Warmwater Wedge Lengths

Parameter	Gallatin 4/3/69	Johnsonville 5/29/69	Gallatin 6/23/69	Bull Run 7/24/69
Capacity, Mw	1050	1200	1050	900
Load during survey, Mw	1050	1200	1050	490 to 900
Plant flow, m^3/sec	41	62	41	30
Plant temperature rise, °C	6.9	6.1	7.2	5.6 to 10.3
Streamflow, m^3/sec	328	754	885	...
Average stream width, meters	152	610	152	228
Average stream depth, meters	23	15	23	8
Average stream velocity, m/sec	0.13	0.18	0.45	0.05
Densimetric Froude number	0.38	0.623	0.970	0.257
Measured length, meters	1875	122	no wedge	520
Predicted length, meters				
Bata [1957] equation	2040	204	<1	1750
TVA modified Bata equation	1905	100	no wedge	1220

PROPOSED MODELS

Warmwater Wedges

Present analysis of field data on wedges is proceeding by means of the two-layer flow model developed by *Bata* [1957] and subsequently modified by the *Tennessee Valley Authority* [1966]. Bata considered a system of two layers, each with a distinct density and velocity. Writing equations of continuity and motion for each layer yields a system of four equations; there are four unknowns, the velocity and depth of each layer. Theory shows a zero wedge length for a value of the ambient densimetric Froude number of 1.0; the observed value is 0.7. This discrepancy is probably due to the two-layer assumption and the fact that a circulation is established in the upper layer and is not merely a unidirectional flow. The *Tennessee Valley Authority* [1966] incorporated into the Bata equation a condition specifying $F_D = 0.75$ as the critical value for no wedge formation. The following equation for wedge length is obtained:

$$
\begin{aligned}
f\frac{L}{H} &= \frac{2}{F_D{}^2}\left(1 - k^4 F_D{}^{8/3}\right) \\
&+ \frac{1}{F_D{}^2}\,\frac{8}{3}\,\alpha\left(1 - k^3 F_D{}^2\right) \\
&+ \frac{4\alpha(1+\alpha)}{F_D{}^2}\left(1 - k^2 F_D{}^{4/3}\right) \\
&+ \frac{8}{F_D{}^2}\left[\alpha(1+\alpha)^2 - k^3 F_D{}^2\right]\left(1 - k F_D{}^{2/3}\right) \\
&- \frac{8\alpha}{F_D{}^2}\left[(1+\alpha)^3 - k^3 F_D{}^2\right] \\
&\cdot\left[\ln\left(1 + \alpha - k F_D{}^{2/3}\right) - \ln\alpha\right] \qquad (2)
\end{aligned}
$$

where

f, friction factor, water-bottom interface;
f_i, friction factor, interface between layers;
L, total wedge length;
H, total receiving flow depth;
F_D, ambient densimetric Froude number;
α, f_i/f ;
k, 1.0 for Bata equation, 1.21 for TVA version.

In the original papers, as well as in *Harleman* [1969], the equations for the full shape of the wedge can be found. The depth, as well as the length, of a wedge may be important in assessing its potential harm to the aquatic environment.

The modified Bata equation has been used successfully by Vanderbilt University in analyzing field data. An example of an observed wedge above TVA's Gallatin steam plant is shown in Figure 1. The observed length was 1875 meters, and the length computed by (2) was 1905 meters. It should be noted, however, that F_D for the calculation was based on measured temperature profiles rather than on a theoretically predicted density difference between the two layers. Results of some other comparisons of theory and data are shown in Table 1. The difficulty in the Bull Run calculations is due to the extreme unsteadiness of the flow during the survey.

Diffusion Models

Two of the 'diffusion models' have been developed by *Edinger and Polk* [1969]. Both are solutions of the diffusion equation for a point source located on the bank and injecting heated water into the stream along the bank with the same velocity as that of the ambient flow. Both are also solutions in a semi-infinite field; i.e., there is no far boundary. One model (two-dimensional) balances advective transport in the x direction with turbulent diffusion in the lateral, or y, direction. The other model (three-dimensional) also includes transport in the vertical, or z, direction by diffusion. Analytical solutions can be found for both cases. To simplify data comparison, results are framed in terms of the surface area contained within a given temperature rise contour and (for the three-dimensional case) the cross-sectional area within a given temperature contour. Figures 2 and 3 illustrate typical observed contours. The significant characteristics arising from the analysis by *Edinger and Polk* [1969] are abstracted below.

Two-dimensional distribution. 1. The surface area varies with the cubic power of the concentration ratio T_c/T_o, where T_c is the initial discharge temperature rise. Applicability of the two-dimensional conservative case can therefore be judged by comparison of the slopes of the theoretical and data plots.

2. For a given concentration ratio the area varies with the cubic power of the plant pumping rate. This relation provides a very simple scaling rule for projecting observations made at one plant size to predictions for an increased plant size. It also indicates that variation in plant pumping rate is an important factor when field test conditions are chosen.

3. For a given concentration ratio the area

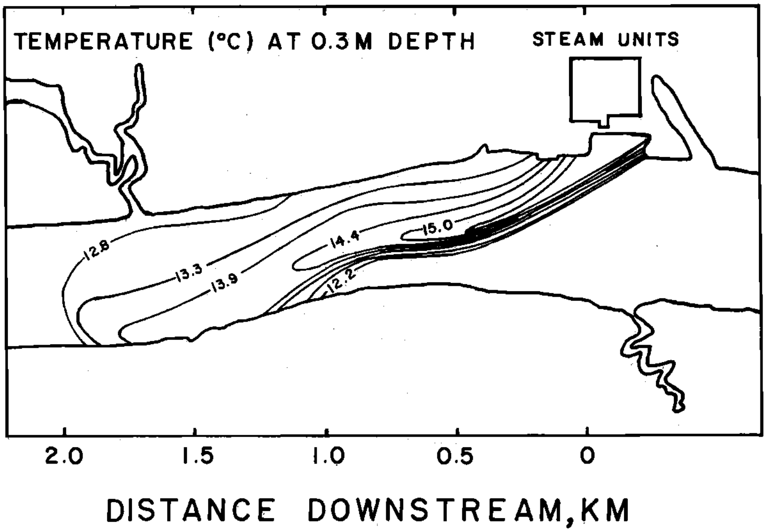


Fig. 2. Surface temperatures in the vicinity of Widows Creek steam plant, November 20, 1968.

varies inversely with the square of ambient flow. The smaller the ambient flow, the larger the surface area required to achieve the same degree of mixing.

4. The distance from the discharge to the fully mixed contour L_m for a discharge into an ambient flow is

$$L_m = WQ_R/\pi D_y d\,[1 - (Q_P/Q_R)^2] \qquad (3)$$

where d is ambient depth, W is ambient water body flow, Q_R is ambient flow, Q_P is plant flow, and D_y is the lateral diffusion coefficient; L_m is also a function of the ratio of the plant pumping rate to ambient flow as well as a function of the ambient flow itself.

Three-dimensional distribution. 1. The surface area within a concentration contour varies inversely with the $^3/_2$ power of the concentration ratio. This decrease is more rapid than that for the two-dimensional nonconservative distribution at the largest estimated die-away.

2. The distance from the discharge to the

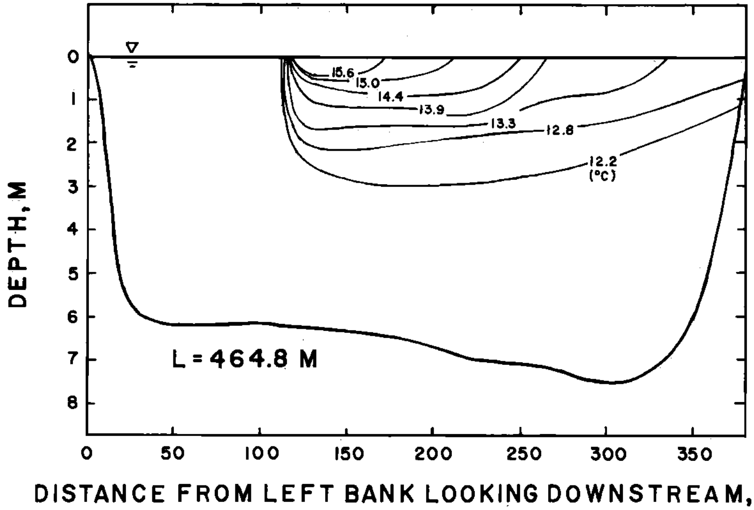


Fig. 3. Temperatures in the cross section 465 meters downstream from Widows Creek steam plant, November 20, 1968.

completely mixed contour L_m is given by

$$L_m = Q_R/\pi(D_yD_z)^{1/2}\,[1 - (Q_P/Q_R)] \qquad (4)$$

where D_z is the vertical diffusion coefficient. This distance varies linearly with the ratio of the plant pumping rate to ambient flow as compared with the square of the ratio for the two-dimensional case.

3. The three-dimensional case can be described by the fraction of cross-sectional area within a concentration contour as a function of distance from the discharge. At a given cross-section location the concentration ratio is a log-linear function of location of the cross-sectional area. The inverse slope of the log-linear relation is a simple linear function of distance from the discharge.

Figure 4 demonstrates the fitting of two- and three-dimensional models to field data collected by Vanderbilt University below the Widows Creek steam plant on Guntersville Lake. Values of D_y and D_z found by fitting the models to this data are shown. It can be seen that the three-dimensional theoretical curve perhaps fits the overall data better but that the two-dimensional theoretical curve fits the first several data points better. The work of *Ellison and Turner* [1959] provides an explanation for the physical observations. The buoyant forces acting in the vertical direction oppose the mixing tendencies created by entrainment and/or diffusion. The densimetric Froude number of the discharge itself is

$$F_j = V_j/[(\Delta\rho/\rho)\,gh_j]^{1/2} \qquad (5)$$

where V_j is the velocity in the plume at the point of interest and h_j is the depth of the plume at the point of interest.

As the Froude number in (5) decreases, this buoyant influence becomes more important. Therefore, for typical field discharge cases, one might expect (1) an initial region of some vertical mixing due to higher velocities, (2) a region with little vertical mixing (two dimensional) taking place due to lower velocities and lower values of F_j, and (3) a region in which vertical mixing again occurs at a more rapid rate. This third region occurs because of a decrease of the plume temperature rise with distance, which causes the denominator of (5) to approach 0; thus it is implied that the buoyant forces have a negligible effect in comparison with the inertial forces. It therefore appears that, from a physical viewpoint at least, the two-dimensional distribution is more appropriate for this set of data.

Heated Surface Jet

A review of Figure 2 reveals that some consideration must be given to the initial velocity and angle of the discharge. When the velocity field of the ambient water body is influenced by the cooling water discharge and the heat initially advected is almost perpendicular to the ambient flow, then the spatial distribution of the temperature can be described in terms of a surface jet discharging at some initial angle to the ambient flow and being deflected downstream by the momentum of the ambient velocity. The surface jet can be approximated as being two dimensional when the buoyancy force due to the temperature difference between the jet and the ambient fluid is large or when the Richardson number of the jet is approximately 1.0 or greater.

A study conducted at Vanderbilt University by *Motz and Benedict* [1970], which is based on the Morton technique of integral analysis, develops a system of equations that, when solved numerically, predicts the jet trajectory, width, velocity, and temperature decrease. For the case

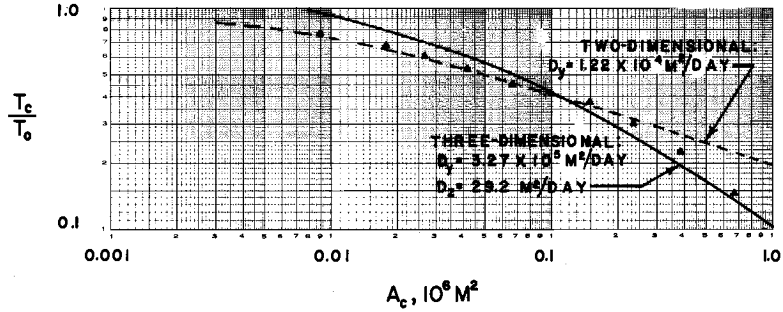


Fig. 4. Temperature rise ratio versus surface area within the temperature rise contour for Widows Creek steam plant data, November 20, 1968.

of a two-dimensional surface jet, this study extends the integral technique of analysis to include (1) the effect of varying the initial angle of discharge and velocity ratio, (2) the empirical relations describing the zone of flow establishment, (3) an entrainment mechanism based on the vector difference between the jet and ambient velocities, and (4) the effect of the pressure gradient that exists across the jet parallel to the ambient flow, expressed as a drag term.

To test the proposed model, data were collected from both laboratory experiments and field surveys. The laboratory experiments were designed to study the entrainment coefficient, a drag coefficient (representing the pressure gradient), and the zone of flow establishment as they relate to the velocity ratio and to the initial angle of the discharge. The field surveys were made to compare observed conditions at several TVA steam plants to the predicted conditions based on the laboratory data. For the case of a two-dimensional surface jet discharged into a flowing ambient stream, the entrainment and drag coefficients and the zone of establishment are determined as functions of the velocity ratio and discharge angle (see *Motz and Benedict* [1970] for complete details).

Entrainment 'velocity' is expressed as a coefficient E times the vector difference of the jet and ambient velocities. Other assumptions include no vertical mixing, no surface cooling, and lateral temperature (and velocity) profiles that are similar from section to section and Gaussian in form.

The integrated mass, momentum, and temperature rise equations give a system of four equations and four unknowns:

Continuity

$$d/ds\,(Ub) = [2E/(\pi)^{1/2}]\,(U - U_a \cos\beta) \qquad (6)$$

x component momentum

$$\frac{d}{ds}\,(U^2 b \cos\beta) = (2)^{1/2}\frac{2E}{(\pi)^{1/2}}\,(U - U_a \cos\beta)\,U_a + \frac{(2)^{1/2}}{(\pi)^{1/2}}\frac{C_D U_a^2 \sin^2\beta}{2} \qquad (7)$$

y component momentum

$$\frac{d}{ds}\,(U^2 b \sin\beta) = -\frac{(2)^{1/2}}{(\pi)^{1/2}}\frac{C_D U_a^2 \sin\beta \cos\beta}{2} \qquad (8)$$

Temperature rise

$$d/ds\,(UTb) = 0 \qquad (9)$$

The geometry of the jet trajectory gives two additional equations and unknowns:

$$dx/ds = \cos\beta \qquad (10)$$

$$dy/ds = \sin\beta \qquad (11)$$

where

b, half width of jet;
C_D, drag coefficient;
E, entrainment coefficient;
s, coordinate axis of jet;
T, center line temperature rise;
U, center line jet velocity;
U_a, ambient velocity;
x, y, standard Cartesian coordinates;
β, angle between jet and ambient current.

Thus there are six unknowns (U, T, b, β, x, and y) and six equations, all functions of the jet axis distance s. In addition, there are two experimentally determined coefficients, C_D and E.

This system of equations can be solved numerically by standard Runge Kutta techniques. The center line temperature could, of course, be translated into an entire temperature field by use of the Gaussian profile assumed.

An example of fitting the model to observed data is shown in Figures 5 and 6, which show the trajectory and temperature decrease, respectively. Fortuitously, from the standpoint of data analysis the drag coefficient has little influence on the decay curve. Table 2 gives a summary of some field results obtained. The Waukegan site is on Lake Michigan, and the data were reported by *Beer and Pipes* [1968]. The model has also been applied to predictions for a prospective power plant site on Lake Michigan [*Benedict*, 1970]. Although Lake Michigan is not a man-made lake, it certainly exhibits the same conditions.

FURTHER WORK

Several additional features are presently being considered at Vanderbilt University. Surface cooling, considered for the two-dimensional case by *Edinger and Polk* [1969], is being added to the jet solution. Surface cooling has little influence in the initial regions of higher temperature, owing to the smaller areas; for smaller rises encompassing large areas, cooling can significantly reduce the area. This influence is especially true for discharges into lakes of large areal extent and for low-velocity discharges.

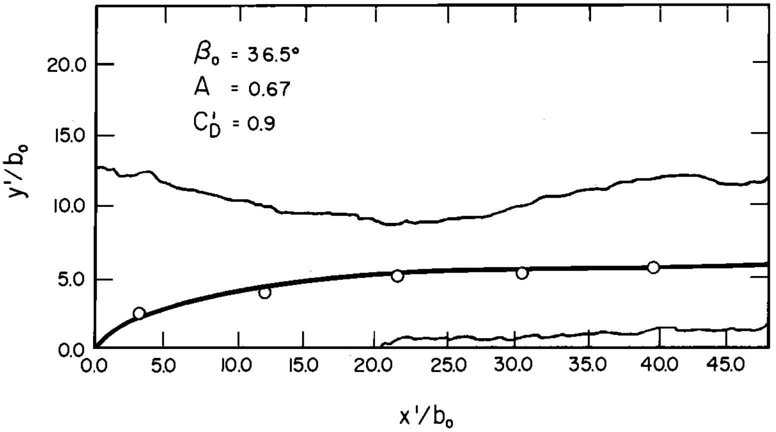


Fig. 5. Observed and fitted trajectories, Widows Creek. Data are taken from second survey conducted by Vanderbilt University at Widows Creek.

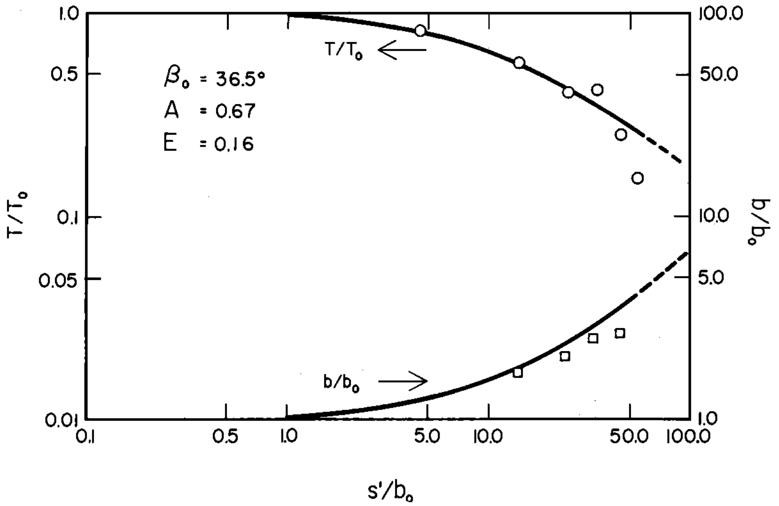


Fig. 6. Observed values and fitted curves for temperature and width, Widows Creek. Data are taken from second survey conducted by Vanderbilt University at Widows Creek.

Work is presently under way to enhance the information from the reports by *Edinger and Polk* [1969] and *Motz and Benedict* [1970] to enable choice of D_y, C_D, and E for a given set of hydraulic conditions. This research includes work to separate pure diffusion from entrainment and to enable selection of diffusion coefficients by presently available means. The ultimate goal of all the described work is the provision of tools for the design engineer, i.e., a predictive model. A diffusion model, including a finite width source and boundary reflections, has also been developed by Polk. This model is being tested against data.

All the work described has helped to build a

TABLE 2. Summary of Field Results

	U_a/U_o*	β_o'	F_o	E	C_D
Widows Creek					
VU 1†	0.50	85.0	2.13	0.16	0.6
VU 2§	0.67	85.0	1.24	0.16	0.6
TVA	0.75	85.0	0.91	0.16	0.3
New Johnsonville	0.57	60.0	0.55	0.04	0.5
Waukegan	0.00	...	10	0.44	...

*Subscript o indicates conditions at the point of jet efflux.

†This was the first survey conducted by Vanderbilt University at Widows Creek.

§This was the second survey conducted by Vanderbilt University at Widows Creek.

better knowledge of the movement of heated discharges in man-made lakes. A better basis is thus being formed for decisions concerning the many environmental problems of thermal pollution that must be faced.

Acknowledgments. The work described herein was supported by the Federal Water Quality Administration under its establishment at Vanderbilt University of a National Center for Research and Training in the Hydrologic and Hydraulic Aspects of Water Pollution Control. Thanks are also due to the Tennessee Valley Authority for its cooperation in conducting the fieldwork.

REFERENCES

Bata, G. L., Recirculation of cooling water in rivers and canals, *J. Hydraul. Div. Amer. Soc. Civil Eng., 83*(HY3), 1-27, 1957.

Beer, L. P., and W. O. Pipes, Environmental effects of condenser water discharge in southwest Lake Michigan, consulting engineer report, 106 pp., Environ. Sci. Ind. Bio-Test Lab., Chicago, Ill., 1968.

Benedict, B. A., Use of heated surface jet model for Lake Michigan analysis, Physical and Ecological Effects of Waste Heat on Lake Michigan, report, U.S. Dep. of the Interior, Washington, D. C., 1970.

Edinger, J. E., and E. M. Polk, Jr., Initial mixing of thermal discharges into a uniform current, *Rep. 1,* Nat. Center for Res. and Training in the Hydrol. and Hydraul. Aspects of Water Pollut. Contr., Vanderbilt Univ., Nashville, Tenn., Oct. 1969.

Ellison, T. H., and J. S. Turner, Turbulent entrainment in stratified flows, *J. Fluid Mech., 6*(3), 423-448, 1959.

Federal Water Pollution Control Administration, Industrial waste guide on thermal pollution, report, 112 pp., Pac. Northwest Water Lab., Corvallis, Oreg., Sept. 1968.

Harleman, D. R. F., Mechanics of condenser water discharge from thermal power plants, in *Engineering Aspects of Thermal Pollution,* edited by F. L. Parker and P. A. Krenkel, pp. 144-164, Vanderbilt University Press, Nashville, Tenn., 1969.

Keulegan, G. H., Interfacial instability and mixing in stratified flows, *J. Res. Nat. Bur. Stand., 43,* 1949.

Krenkel, P. A., and F. L. Parker (Eds.), *Biological Aspects of Thermal Pollution,* Vanderbilt University Press, Nashville, Tenn., 1969.

Motz, L. H., and B. A. Benedict, Heated surface jet discharged into a flowing ambient stream, *Rep. 4,* Nat. Center for Res. and Training in the Hydrol. and Hydraul. Aspects of Water Pollut. Contr., Vanderbilt Univ., Nashville, Tenn., Aug. 1970.

Parker, F. L., and P. A. Krenkel, Thermal pollution: Status of the art, *Rep. 3,* Nat. Center for Res. and Training in the Hydrol. and Hydraul. Aspects of Water Pollut. Contr., Vanderbilt Univ., Nashville, Tenn., Dec. 1969*a*.

Parker, F. L., and P. A. Krenkel (Eds.), *Engineering Aspects of Thermal Pollution,* Vanderbilt University Press, Nashville, Tenn., 1969*b*.

Tennessee Valley Authority, Browns Ferry nuclear plant preliminary intake-outlet design studies, *Lab. Rep. 1,* Div. of Water Contr. Plann., Norris, Tenn., Nov. 1966.

Selective Withdrawal as a Water Quality Management Tool for Southwestern Impoundments

E. GUS FRUH AND HERMAN M. CLAY, JR.[1]

Environmental Health Engineering Program, University of Texas
Austin, Texas 78712

The objective of this study was to develop a preliminary simulation model of impoundment water quality that included an accurate description of stratified flow and selective withdrawal. Two stratified flow solutions were examined to test their applicability to describe reservoir withdrawal hydraulics under field conditions. Although both solutions appeared capable of accurate prediction of the outflow velocity profile, the Bohan-Grace solution, which required less input data, was selected; this solution can be applied to impoundments for which field data are minimal. The simulation model, including the Bohan-Grace solution for reservoir withdrawal hydraulics, was assessed for a 2-year period for which sufficient field data were available. The error in penstock temperature prediction ranged from 0° to 2.78°C (0° to 5°F).

REGIONAL NEED AND PURPOSE OF THE STUDY

The *Texas Water Development Board* [1968] has considered a number of alternatives for transporting water from east Texas and from other states to south Texas as well as to west Texas and the High Plains. A number of waters of different quality will be mixed, stored in existing and 53 proposed reservoirs, and transported by conveyance systems to points approximately 1620 km (1000 miles) away. The effect of impoundment on the water quality of Texas streams is not known. Thus a model that simulates long-term water quality changes is vitally needed.

A priori review of the impoundment water quality problem indicated that several separable but dependent components had to be included in a complete model: (1) a description of the inflows in terms of temperature and chemical concentrations, (2) inflow thermal and chemical routing within the impoundment, (3) meteorological and hydrologic sources and sinks of heat, (4) turbulent diffusion of heat and chemical substances within the impoundment, (5) chemical-biological changes of nonconservative chemicals within the impoundment, (6) a description of reservoir withdrawal hydraulics under stratified and nonstratified flow conditions, and (7) an accounting for continuous changes in the water, heat, and chemical budgets of an impoundment.

The first four components in various forms have been applied with some success to other geographic areas, and in the preliminary phase of modeling it appears only necessary to adapt them for application to the relatively shallow southwestern reservoirs. The chemical-biological changes represent complex interactions that still lack quantitative description; hence preliminary modeling endeavors are applicable only to throughput of water temperature and conservative chemical substances. Accurate impoundment data are vitally needed to fill this void.

The component describing the outflow hydraulics under stratified flow conditions has been developed on a theoretical basis and verified in a laboratory flume by *Koh* [1964]. The Koh stratified flow solution has been found to be adequate as a description of the velocity profile based on reliable field velocity measurements in two deep reservoirs, Lake Roosevelt [*Battelle Memorial Institute,* 1969] and Lake Fontana [*Brooks and Koh,* 1968]. However, field verification of the Koh solution has not been attempted for deep southwestern reservoirs nor for any shallow reservoirs that are more representative of this area of the country. In addition, the Koh solution assumes that there is a linear density variation with depth and that K_2, the turbulent exchange parameter, can be estimated accurately for a priori use in the solution. Both assump-

---

[1] Now at O'Malley & Clay, Consulting Engineers, Houston, Texas.

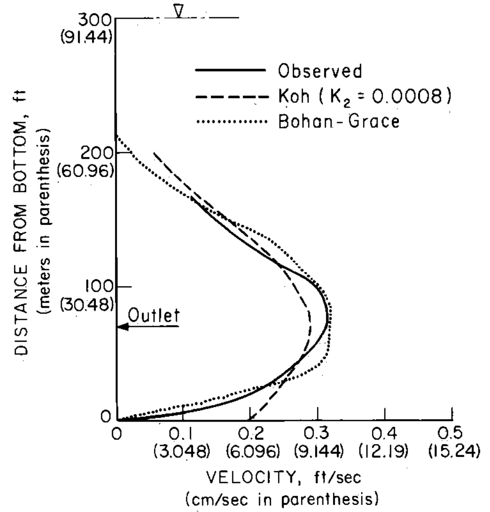


Fig. 1. Velocity comparisons, Lake Roosevelt, August 26, 1967. The flow is 1.96 km^3/sec (69,500 cfs), and the distance from the dam is 1.6 km (5280 feet).

tions for southwestern impoundments have been questioned by *McGill* [1970].

Bohan and Grace [1969] developed a hydraulic flow solution employing dimensional analysis in the evaluation of laboratory scale data. The Bohan-Grace solution avoids the assumptions of the Koh solution but has not been verified by any field studies.

In this study a preliminary water quality impoundment simulation model is assembled from the components outlined above. Particular emphasis is placed on determining by field measurements which stratified flow solution is the best description of the reservoir withdrawal hydraulics occurring in southwestern impoundments.

EVALUATION OF STRATIFIED FLOW SOLUTIONS

The output from the Koh and Bohan-Grace stratified flow solutions is the velocity profile of the outflow as it moves through the impoundment toward the penstock or other release structure. Thus the first stage in the evaluation process was to compare the velocity distributions predicted by each method with observed velocity measurements. Unfortunately, the only reliable field velocity measurements available were from deep reservoirs in other geographic areas. One result from the testing program is illustrated in Figure 1. A more detailed hydraulic analysis is presented by *Clay et al.* [1970].

Because published field velocity measurements are not available for southwestern impoundments and because accurate data are very difficult to obtain [*Wilson and Masch,* 1967], it has been proposed that velocity profile predictions can be verified indirectly by monitoring outflow temperature or chemical concentrations [*Brooks and Koh,* 1968]. Thus the vertical profile of some water quality characteristic that varied with depth could be measured in the impoundment, and comparison of the predicted and observed outflow concentration of that particular characteristic would indicate implicitly the fraction that each vertical layer in the impoundment contributed to the total flow.

The applicability of the two predictive techniques to southwestern impoundments first was tested by a comparison of predicted and observed penstock temperatures for Lake Travis in south central Texas. Figure 2 is a graphic comparison of the results. Although both hydrodynamic solutions produced some scatter, the Bohan-Grace method appears to be superior during the period of low outflow temperature. No clear superiority exists for the period of warmer outflows.

The Bohan-Grace solution was chosen for further development and inclusion in the simulation model since its predictive capability appeared to be at least equal to the Koh solution. In addition, the Bohan-Grace input data re-

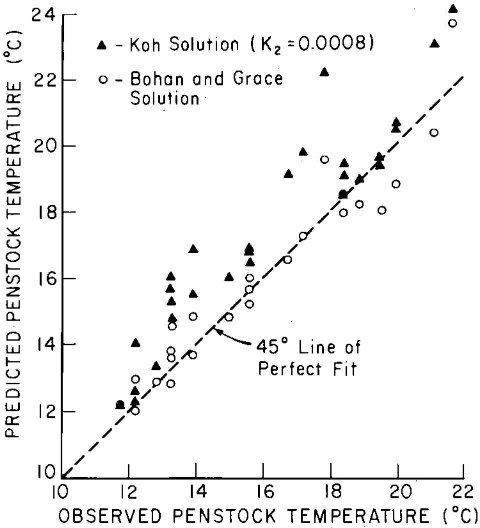


Fig. 2. Observed and predicted penstock temperatures, Lake Travis.

TABLE 1. Comparison of Predicted and Observed Outflow Chemical Concentrations for Lake Travis, August 9, 1968

	Gradient Bottom to top	Observed Outflow Concentrations	Predicted Bohan-Grace Outflow Concentrations
Hardness, mg/l as $CaCO_3$	198 to 154	177	181
Alkalinity, mg/l as $CaCO_3$	159 to 127	146	150
Conductivity, μmhos/cm	472 to 420	463	465
Silica, mg/l as SiO_2	9.2 to 6.3	7.8	8.1
Ammonia, mg/l as N	0.42 to 0.00	0.41	0.37

quirements are less stringent, and therefore this solution can be applied to impoundments for which field data are minimal.

Because interest in selective withdrawal in the southwest is based on the release concentrations of many water quality characteristics other than temperature, the Bohan-Grace solution was used to predict the outflow chemical concentrations of several Texas impoundments. Typical results for deep reservoirs are presented in Table 1, and those for reservoirs as shallow as 16.76 meters (55 feet) are presented in Table 2. The mean difference between the predicted and observed values, expressed as a percentage of the observed gradient, for two separate simultaneous releases from Lake Livingston was approximately 9%.

IMPOUNDMENT WATER QUALITY MODEL

Temperature data from Lake Travis in south central Texas were used to assess the results of the preliminary simulation model. The inflow and thermal structure components were calculated from actual field data. In this manner the results reflected the accuracy of the hydraulic flow solution selected to represent the reservoir withdrawal component.

TABLE 2. Comparison of Predicted and Observed Outflow Chemical Concentrations for Lake Livingston

	Impoundment Gradient from Bottom to Top	Observed Outflow Concentration	Predicted Bohan-Grace Outflow Concentration
	*Spillway Outlet with Flow of 50.5 m^3/sec (1785 cfs)**		
Temperature, °C	18.5 to 24.0	23.0	23.7
$NO_3 + NO_2$, mg N/l	0.72 to 0.52	0.53	0.52
Fe, mg/l	0.17 to 0.08	0.09	0.09
	Spillway Outlet with Flow of 46.4 m^3/sec (1640 cfs)†		
Temperature, °C	22.8 to 31.5	28.7	29.1
NH_3, mg N/l	0.31 to 0.00	0.05	0.03
Total P, mg/l	1.19 to 0.13	0.21	0.16
Fe, mg/l	0.48 to 0.03	0.04	0.03
Si, mg/l	11.75 to 1.75	2.00	2.00
	Tower Outlet with Flow of 6.7 m^3/sec (238 cfs)§		
Temperature, °C	22.8 to 31.5	29.0	30.5
NH_3, mg N/l	0.31 to 0.00	0.00	0.01
Total P, mg/l	1.19 to 0.13	0.19	0.14
Fe, mg/l	0.48 to 0.03	0.04	0.03
Si, mg/l	11.75 to 1.75	1.70	1.80

*The water depth at this outlet is 16.76 meters (55 feet), and the distance from the outlet to the bottom is 12.50 meters (41 feet). These data were recorded on April 25, 1970.

†The water depth at this outlet is 19.81 meters (65 feet), and the distance from the outlet to the bottom is 12.50 meters (41 feet). These data were recorded on July 2, 1970.

§The distance from the outlet to the bottom is 17.37 meters (57 feet).

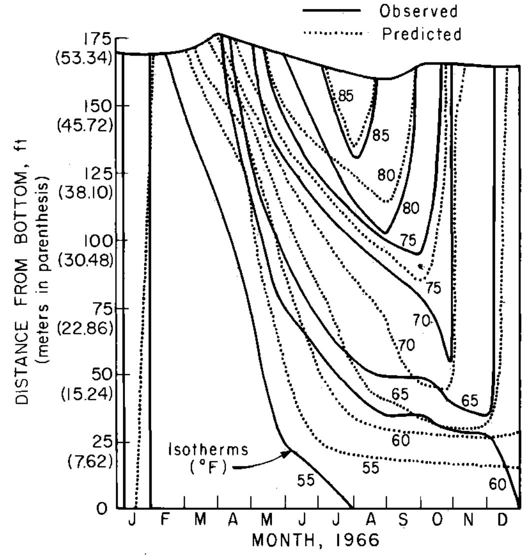


Fig. 3. Temperature structure, Lake Travis, 1966.

Inflow components. Discharges into Lake Travis from upstream Lake Marble Falls and from the unregulated Pedernales River were monitored. Local runoff was computed from a water balance computation.

Although the data [*Applied Research Laboratory*, 1966, 1967; Lower Colorado River Authority, unpublished data, 1970] were the most comprehensive temperature measurements available for a Texas reservoir, a complete record of the thermal properties of the impoundment and its inflows and outflows was not available. The inflow temperature records were particularly lacking, and only approximate monthly estimates of the two principal flow inputs were possible. As an additional approximation for the case reported herein, the mean temperature of the combined inflows was calculated, and the total incoming volume was considered mathematically as a single input.

The inflow was assumed to flow isothermally along the reservoir bottom until it reached a level of density (based only on temperature) equal to that of the inflow. The incoming water subsequently was spread homogeneously across the impoundment at the equal density level, and thus the level of all layers originally above the inflow level was raised. New temperatures then were calculated for all new depths.

Thermal structure components. Division of thermal prediction into two components, the external thermal budget and the internal heat exchange, allows maximum use of the thermal budget, which frequently can be measured or computed accurately. *Water Resources Engineers, Inc.* [1966, 1967] found that it is preferable to exclude advection from the net heat exchange rate because of the frequently large annual hydrologic variations and because all major sources and sinks except advection necessarily are transferred across the water surface. The heat carried by the inflow and outflow then must be accounted for by a separate computational procedure. However, because the magnitudes of some important sources and sinks of the thermal budget depend on the impoundment surface temperature and because the inflow and outflow components are affected by the vertical temperature component, the thermal budget cannot be computed accurately from meteorological and hydrologic data independently of the internal thermal energy transfer.

For computational purposes it is necessary to calculate the heat exchange to the impoundment during a short time increment on the basis of knowledge of the existing internal temperature and the external sources and sinks. Then the new temperature structure within the impoundment can be computed from the mathematical description of the internal heat exchange mechanisms. The computational cycle is repeated for successive time increments.

To simulate the thermal structure components as accurately as possible, the total net heat ex-

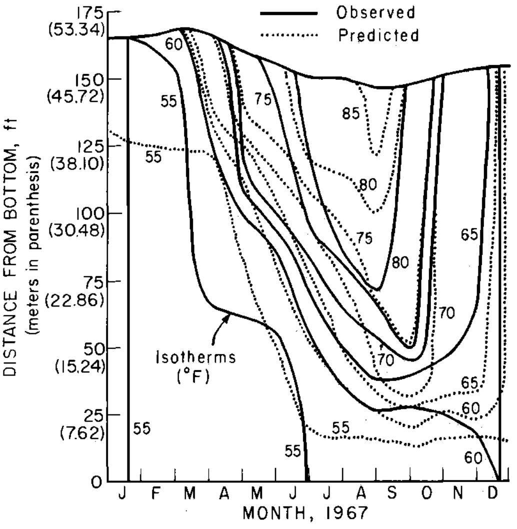


Fig. 4. Temperature structure, Lake Travis, 1967.

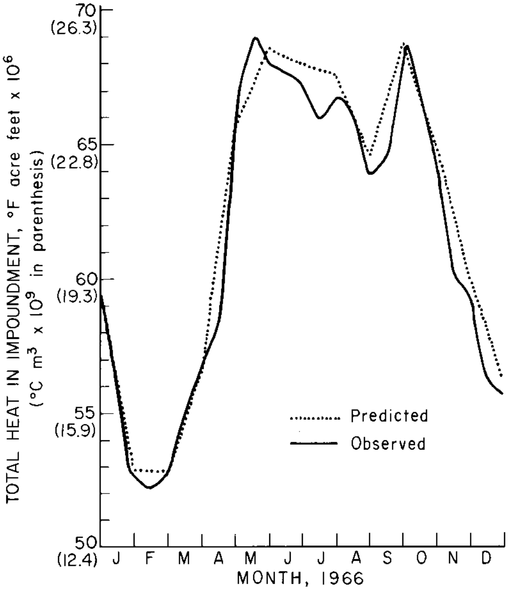


Fig. 5. Total heat content, Lake Travis, 1966.

change rate was computed by integrating graphically the changes in the observed Lake Travis temperature profiles. The advective and evaporative heat contributions were computed on the basis of the volume and temperature of the water added or removed. The heat changes from advection and evaporation then were subtracted from the total heat exchange, and the contributions of the meteorological sources and sinks were left.

Review of the existing temperature prediction techniques [*Water Resources Engineers, Inc.*, 1966] indicated that numerical differentiation of Fick's first law would provide a mathematically simple description of the downward flux of heat within the impoundment. Assumption of horizontal homogeneity within the impoundment reduced the heat exchange to the vertical direction. It also was necessary to include vertical convective mixing, particularly during the fall when stratification still existed but when the flow of energy was away from the impoundment. Details are described by *Clay et al.* [1970].

Reservoir outflow component. Changes in the water and heat content of the impoundment caused by releases were accounted for in a manner similar to that used for the inflow. An outflow velocity profile was calculated by the Bohan-Grace method, and then the resulting volume withdrawn from each layer was computed. The outflow from each layer was assumed to leave a void that was subsequently filled by water from higher layers. The resulting contents of each layer were subsequently mixed, and new temperatures and a new impoundment depth were computed.

Evaluation. Three comparative criteria were used in evaluating the performance of the simulation model. Comparisons were made of the observed and predicted temperature profiles, the impoundment heat content, and the penstock temperatures for the 1966–1967 period.

Figures 3 and 4 illustrate the 1966 and 1967 variation in predicted and observed temperature profiles for Lake Travis. The errors that exist are believed to be caused by the limiting assumptions inherent in the simulation model: one dimensionality and the Fickian description of the internal heat exchange process.

The external sources and sinks, the internal heat exchange, and the volumes of water advected are significantly interrelated. For example, failure to predict accurately the temperature profile will cause an incorrect amount of heat to be advected away by outflows and by evaporation. In that case the predicted impoundment heat content with time would diverge increasingly from the observed values. Similarly, any other type of malfunction in the predictive process, either thermal or volumetric, will cause a noticeable divergence. Therefore, the total impoundment heat content is the best single indicator of the accuracy of the simulation. The

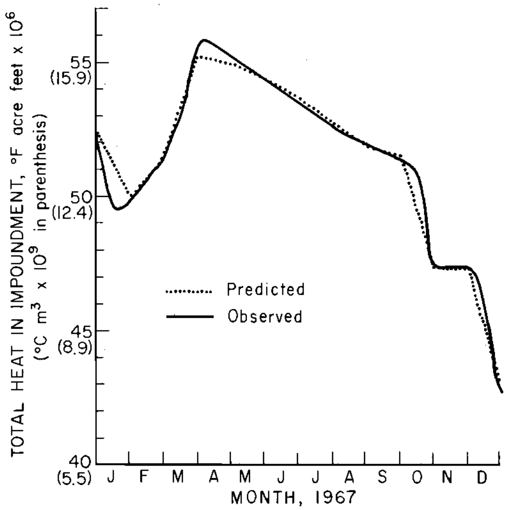


Fig. 6. Total heat content, Lake Travis, 1967.

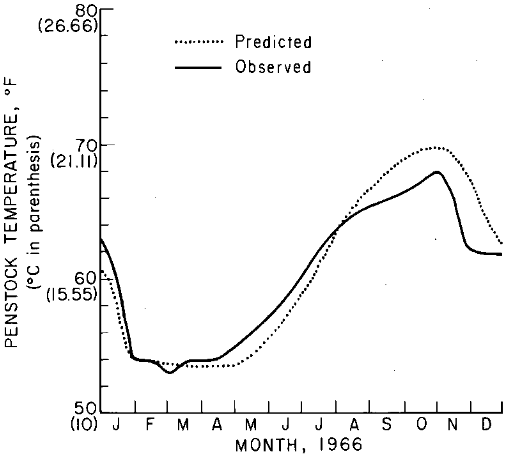


Fig. 7. Penstock temperatures, Lake Travis, 1966.

differences in the predicted and observed values in Figures 5 and 6 were largely caused by the use of average monthly values as input to the model, whereas the observed values reflect measurements at considerably smaller intervals. Thus the predictions were not expected to exactly follow the observed short-term variations and, on a monthly basis, were considered to be satisfactory.

Figures 7 and 8 illustrate the predicted and observed penstock temperatures for 1966 and 1967, respectively. The outflow predictions were within 2.78°C (5°F) of the observed values. This correspondence is particularly significant since parts of the input information were relatively crude estimates. Such data are frequently the best information available; therefore the use of rough approximations was considered a stringent test of the capability of the model's selective withdrawal component to function under realistic conditions.

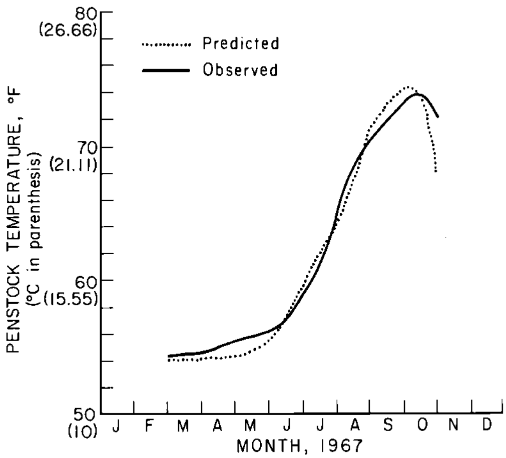


Fig. 8. Penstock temperatures, Lake Travis, 1967.

CONCLUSIONS

Extensive testing indicated that the Bohan-Grace solution was at least as accurate as the Koh solution in describing reservoir withdrawal hydraulics in a stratified impoundment. Since its input data requirements were less stringent, the Bohan-Grace solution was included in the preliminary impoundment water quality simulation model. The simulation model was a realistic representation of the behavior of seasonally stratified impoundments. The error in predicted penstock temperatures for Lake Travis over a 2-year simulation ranged from 0° to 2.78°C (0° to 5°F); this error range indicated satisfactory compatibility of the Bohan-Grace solution with other components of the simulation model.

Acknowledgments. Stipend support for the junior author was provided by the Federal Water Quality Administration through training grant 5T1-WP-183-02 and research fellowship grant 1-F1-WP-26, 518-01. Additional research support was provided by the Department of the Interior OWRR grant 14-01-0001-1948 with matching support by the University of Texas Center for Research in Water Resources.

Dr. Frank Masch contributed much from his experience in hydrodynamic and transport simulation. Mr. A. E. Hall and Mr. D. L. Burford of the Trinity River Authority, Mr. H. L. Frantzen of the Lower Colorado River Authority, Mr. G. R. Drummond of the Ohio District of the U.S. Army Corps of Engineers, and the staff of the U.S. Geological Survey, Austin, Texas, were very cooperative in use of facilities and data. The Lower Colorado River Authority, in particular, was very helpful regarding their unpublished records of hydroelectric operations. It is a pleasure to acknowledge the work of Mr. R. C. Patyrak, who was responsible for field sampling, and Mr. J. M. McGill, who was responsible for preliminary evaluation of the hydrodynamic models.

REFERENCES

Applied Research Laboratory, DRL limnographical report for Lake Travis 1 January 1966 to 31 December 1966, Def. Res. Lab., Univ. of Tex., Austin, 1966.

Applied Research Laboratory, DRL limnographical report for Lake Travis 1 January to 31 December 1967, Def. Res. Lab., Univ. of Tex., Austin, 1967.

Battelle Memorial Institute, A three dimensional study of parameters related to the current distribution in Lake Roosevelt, research report, Richland, Wash., 1969.

Bohan, J. P., and J. L. Grace, Jr., Mechanics of flow from stratified reservoirs in the interest of water quality, report, U.S. Army Eng. Waterways Exp. Sta., Vicksburg, Miss., 1969.

Brooks, N. H., and R. C. Koh, Selective withdrawal from density-stratified reservoirs, Proceedings of the American Society of Civil Engineers Conference on Current Research into the Effects of Reservoirs on Water Quality, Portland, Oregon, January 1968, *Rep. 17,* Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Clay, H. M., Jr., E. G. Fruh, and F. D. Masch, Selective withdrawal at Lake Livingston, An impoundment water quality model emphasizing withdrawal, *EHE Rep. 70–18,* Environ. Health Eng. Program, Univ. of Tex., Austin, 1970.

Koh, R. C., Viscous stratified flow toward a line sink, *Rep. KH-R-6,* W. M. Keck Lab. of Hydraul. and Water Resour., Calif. Inst. of Tech., Pasadena, 1964.

McGill, J. M., An evaluation of selective withdrawal models, M.S. thesis, Univ. of Tex., Austin, 1970.

Texas Water Development Board, *The Texas Water Plan,* Austin, Texas, 1968.

Water Resources Engineers, Inc., Development of a mathematical model for prediction of temperature in deep reservoirs, phase 2, High discharge-volume ratio reservoirs, progress report, Lafayette, Calif., 1966.

Water Resources Engineers, Inc., Prediction of thermal energy distribution in streams and reservoirs, final report, Dep. of Fish and Game, Sacramento, Calif., 1967.

Wilson, J. R., and F. D. Masch, Field investigation of mixing and dispersion in a deep reservoir, *Rep. HYD 10-6701,* Univ. of Tex., Austin, 1967.

Summary: Sedimentation of Reservoirs

LOUIS M. GLYMPH

Soil, Water, and Air Sciences, Agricultural Research Service
Washington, D. C. 20250

Reservoirs for storage or regulation of water are often the key features in man's innovations to use or control the water resources available to him. Reservoirs serve many essential purposes, and many reservoirs serve more than one purpose. Reservoirs range in size from ponds of small capacity and surface area to major lakes of the world.

Though distinctive in their physical features and in their impact on man's innovations, reservoirs have one thing in common: all of them are collecting basins for sediment. Usually, sediment accumulation in a reservoir is unwanted, but sometimes it is beneficial.

As background and substance for our consideration of reservoir sedimentation, several excellent papers have been included in this book. Each paper contains much more information than can be condensed into this introductory presentation, and I recommend for study the papers that follow in this section.

All streams transport some sediment, and there is a natural tendency for this sediment to be deposited when streams enter a dry basin or body of water impounded behind a dam or other obstruction across a stream. Sedimentation of reservoirs, then, is not something new. It has been going on since man's first efforts to impound or divert a flowing stream. Archaeologists and historians tell us that man has always lived near streams, and we suspect that he has been occupied with their management almost from the beginning. As *Biswas* [1970] points out, '. . . evidences of earliest civilizations are found along the banks of rivers: the Tigris and Euphrates in Mesopotamia, the Nile in Egypt, the Indus in India, and the Huang-Ho (Yellow River) in China.' According to the historian Herodotus, a dam was built on the Nile River around 3000 B.C. when King Menes diverted its course 20.1 km (12.5 miles) south of Memphis. This dam, a gravity structure, had a maximum height of about 15.2 meters (50 feet) and a crest length of about 448 meters (1470 feet).

The remains of what is called the oldest dam in the world can still be seen on the Wadi el-Garawi, about 28.9 km (18 miles) south of Cairo, Egypt. This dam (Sadd el-Kafara Dam) was built about 2850 B.C. It was a rubble masonry structure some 106 meters (348 feet) long at the top with a crest height of some 11.2 meters (37 feet) above the stream bed. The drainage area above the dam was 186.4 km^2 (72 mi^2), and the reservoir capacity was about 5.7×10^5 m^3 (460 acre-feet). The absence of sediments upstream from this dam indicates a short life for the structure, or it may have failed during its first flood season. Another dam built by the early Egyptians, around 1319–1304 B.C., on the Nahr el Asi (Orontes) near Homs in Syria is still in use. This rock-fill dam is about 6 meters (20 feet) high and 1999.4 meters (6560 feet) long.

PROBLEM

The amount of sediment deposited in a given reservoir depends on the amount of sediment delivered to it and the reservoir's ability to retain the sediment. Therefore reservoirs differ greatly in the amount of sediment deposited in them because of the tremendous variability, both in time and space, in the amount and characteristics of the sediment carried by streams and the circumstances causing its deposition.

Extent

About 1.235×10^9 m^3 (1 million acre-feet) of sediment are deposited in the reservoirs of the United States each year [*Dendy et al.*, this volume; *Glymph and Storey*, 1967]. Summarizing results from reservoir sediment deposition surveys on 1105 reservoirs made in the United States through 1965, *Dendy et al.* [this volume] point out the great variation among reservoirs in rates of sediment accumulation. The data show, however, a striking inverse relationship between rates of storage loss and reservoir size. The average storage loss was 3.5% annually for reservoirs with a capacity of $<1.235 \times 10^4$ m^3(<10 acre-feet) but decreased to about 0.16% for reservoirs with a capacity of $>1.235 \times 10^9$ m^3 (>1 million acre-feet). For reservoirs with a storage capacity of $\leq 1.235 \times 10^5$ m^3 ($\leq$100 acre-feet) the average annual storage loss was 2.7%, and the median was 1.5%. These statistics suggest that one-half of these smaller reservoirs will be half filled with sediment in 33 years or less. For reservoirs with $>1.235 \times 10^9$ m^3 (>1 million acre-feet) of initial storage capacity, however, the rate of storage loss to sediment averages only 0.16%/yr, whereas the median rate is 0.11%/yr.

The paper by *Cyberski* [this volume] presents information about sediment deposition in 19 reservoirs in Central Europe having initial storage capacities ranging from 1.49×10^5 m^3 to 23.15×10^6 m^3 (120 to 183,000 acre-feet). The rate of storage depletion has averaged 0.51%/yr for these 19 reservoirs. This average is 2½ times greater than the weighted average of 0.20%/yr reported by *Dendy et al.* [this volume] but is based on a much smaller sample of reservoirs. Cyberski gives rational reasons for the difference in silting rates of the European reservoirs, but we have no basis at present for rationalizing the differences between the United States and European experiences except, perhaps, the great disparity in the number of reservoirs in the two cases.

An annotated bibliography prepared by the *Israel Program for Scientific Translations* [1965–1969] contains many entries about reservoir sedimentation from the literature of non-English-speaking countries, notably, Russia, Germany, France, Bulgaria, Poland, Japan, Italy, Hungary, Rumania, and Czechoslovakia. Information on the subject from literature of the United States and Canada is contained in a series of publications published by the *Water Resources Council* [1970]. A new publication series from the *U.S. Department of the Interior* [1968–1971] contains information from United States literature since 1968.

Data on the silting of 44 reservoirs in the central Chernozem provinces of Russia have been summarized by *Yakovleva* [1965]. Thirty-three of these reservoirs had initial storage capacities of $<1.235 \times 10^4$ m^3 (<10 acre-feet), and their average rate of storage loss was 0.71%/yr. This average rate is substantially less than that reported for reservoirs of similar size by *Dendy et al.* [this volume]. Such comparisons, of course, have little meaning without full consideration and evaluation of the causes of the differences, but they do point up the universality of the problem and widespread concern about reservoir sedimentation.

Consequences

Functions. The effects of sediment deposition in reservoirs are evidenced in many ways but perhaps most significantly in terms of the reservoir's ability to perform its intended functions. Water resource functions most commonly served by reservoirs include water supply (domestic, municipal, and industrial), irrigation, flood control, hydroelectric power, navigation, water quality management, recreation (swimming, skiing, boating, and fishing), wildlife habitat, beautification (aesthetics), and sediment storage.

To the extent that sediment distracts from the services provided or expected from a reservoir, it is a liability expressible as the lesser of either (1) the cost of services foregone because of the sediment or (2) the cost required to remove the sediment from the reservoir or to keep it out in the first place.

When the presence of sediment in a reservoir is beneficial, the values added should be recognized and included among the assets of the development. Should circumstances arise requiring an increase in the amount of sediment available to a reservoir, the cost of providing the additional sediment would be an item of cost for maintaining the reservoir.

Upstream effects. Depletion of storage capacity is but one of the effects of reservoir sedimentation. The stream channel is likely to aggrade for some distance above the reservoir because of backwater effects on sediment transport. The formation and growth of deltas tend to accelerate and extend the process still farther upstream. Thus channel gradients become flatter, channel cross sections are reduced, flooding occurs more frequently, and drainage of floodplain lands is impeded because of reservoir sedimentation. Such detrimental effects are severe in some instances and may require compensation. *Busby* [1961] has discussed some of the legal and engineering considerations involved in adjudicating disputes in the United States arising from sediment deposition, including that upstream from reservoirs.

Downstream effects. Bondurant and Livesey [this volume] point out that the total capacity for sediment transport below a dam will be reduced from 25 to 75%, depending on the comparative sediment transport characteristics of the controlled releases and the normal flows.

It is not uncommon, however, for reservoir sedimentation to cause channel degradation and stream bank erosion downstream. The sediment-free water passing through the reservoir can entrain another sediment load and proceeds to do so where the material is available. The phenomenon applies downstream from both large and small reservoirs. It is most likely to occur when a dam is built on an alluvial channel that previously had a generally stable relationship between such factors as stream discharge, sediment load, channel gradient, and widths and depths of stream channel.

When channels degrade downstream from dams, a new base level for erosion is established that may have more far-reaching effects than the loss of land immediately adjacent to the main stem channel. The deepening tends to extend throughout the watershed or river basin and may induce a new erosion cycle and thus generate more sediment for the next reservoir downstream.

There are circumstances, however, when channel degradation below dams is beneficial rather than detrimental. Such is the case when penstocks in power plants can be placed at lower elevations and thus result in greater heads for power generation than would be possible without the deepened channel.

Water quality. Sediment in reservoirs also greatly influences the chemical and biological processes in reservoirs and the suitability of their water for various uses. But the impacts of sediment on water quality and aquatic environments are still largely speculative.

We are just beginning to find some answers, for instance, to questions about the complicity of sediment as a source of nutrients for eutrophication. We probably know even less about how sediment in water affects light penetration for photosynthesis. Neither are we prepared to make very definitive statements about the potential of sediment in reservoirs as a sink for trapping harmful chemicals in the environment. *Ritchie et al.* [1970] have recently reported on the initiation of studies to determine the accumulation of fallout cesium 137 in sediments of widely separated reservoirs of the conterminous United States.

DEPOSITIONAL PROCESSES

Sediment in a reservoir tends to be sorted and deposited in a gradation of particle sizes along the longitudinal axis of the reservoir basin. Generally, the coarser and heavier particles are dropped in the headwaters of the reservoir, and the finer sediments are deposited toward the dam. Numerous factors, however, affect the actual patterns and processes of deposition, among which are the following: water level in the reservoir; temperature and dissolved minerals of the reservoir and influent waters; mineral composition of the sediments, especially the clay-sized fractions; volume relationships of reservoir storage capacity and influent water; configuration of the reservoir basin; and amount of sediment previously deposited within the basin.

Worsley and Dennison [this volume] effectively illustrate the complexity of depositional patterns in a delta system with data and maps from their study of Whites Creek delta in Watts Bar Lake, Tennessee. They found the coarser sediment in the upper reaches of the delta and the finest sediment in the deeper water below the effects of wave action.

The influence of the mineralogy of sediments on depositional processes is referred to by *Bondurant and Livesey* [this volume]. They comment that montmorillonitic clays may react with dissolved salts in the water and form floccules that settle out faster than kaolinitic clays. It is suggested that the dissolved minerals in water and perhaps temperature may have greater influence on depositional processes and maintenance of turbidity in reservoirs than is commonly realized.

Density currents. Deposition in reservoirs is also greatly influenced by sediment-laden density currents that may occur as underflows, interflows, or overflows, depending on the relative densities of the fluid masses involved [*Bell,* 1942]. Underflows are more commonplace. They occur when a relatively muddy stream enters a clear reservoir, plunges beneath the surface, and continues to flow downstream. The current may be dissipated enroute, or it may reach the dam.

Undoubtedly, the enabling combinations of sediment concentrations, velocity of inflowing currents, and temperature differentials are sufficiently prevalent that density flows occur frequently on all man-made lakes. Such flows explain the presence of sediment at the face of many dams where the surface waters of the impounded reservoir have never been turbid.

Trap efficiency. Some of the sediment entering a reservoir is discharged through its outlet works and thus is not deposited within the basin. The relationship between the amount of sediment remaining in a reservoir and the amount delivered to it, on a percentage basis, is termed reservoir trap efficiency. Trap efficiency is always a variable statistic affected by properties of the influent sediment, detention storage time of the reservoir, type and locations of spillways, dissolved solids in the water, and undoubtedly many other factors.

Studies have shown a workable relationship between trap efficiency and the reservoir capacity–inflow ratio (ratio of the storage capacity of the reservoir to the average annual inflow of water to it) [*Brune,* 1953]. Trap efficiency would be expected to decrease in relation to the displacement of reservoir water storage capacity by sediment. This hypothesis is confirmed by data in the paper by *Cyberski* [this volume]; those data show a decrease in the rate of sediment accumulation in three reservoirs in Bavaria when progressively larger quantities of sediment were deposited in them. Even after reservoirs become filled with sediment, they cause some deposition and thus continue to reduce the amount of sediment passing beyond the reservoir site.

Roehl and Holeman [this volume] show short-term trap efficiency ranging from 58 to 94% for 15 small upstream floodwater detention reservoirs. For the five dry reservoirs in the group the average trap efficiency of 84% (ranging from 65 to 94%) was higher than had been expected.

Heinemann et al. [this volume] found trap efficiencies associated with 28 storms on two reservoirs in Missouri to range from 33 to 99%. The 33% trap efficiency value resulted from the discharge of suspended sediment already in the reservoir; this sediment had been brought in by a storm on the preceding day.

Distribution. When a reservoir basin is completely filled with sediment, the pattern of its deposition conforms essentially to the volume distribution of the initial storage capacity. Until the basin is filled, the possible patterns for distribution of the sediment are practically unlimited. Nevertheless, information on both the location and amount of accumulated sediment is required for assessing the consequences of sediment accumulation at selected points in time. The distribution of sediment expected in multipurpose reservoirs is a critical consideration in the allocation of storage for various functions.

The paper by *Lara* [this volume] shows the effects of reservoir drawdown on the longitudinal and lateral distribution of sediment in the Guernsey Reservoir on the North Platte River. *Heinemann* [1961] has presented information on the distribution of sediment in small floodwater-retarding reservoirs in the Missouri basin loess hills land resource area, including graphic and statistical methods for predicting sediment distribution and the minimum elevation of the principal spillway with respect to sediment accumulation. *Borland and Miller* [1958] have developed and presented methods for predicting the manner in which sediment will be distributed in large reservoirs.

Volume-weight. The space occupied by sediment delivered to and remaining in a reservoir is determined by the volume-weight of the sediment on deposition and consolidation. The volume occupied by the deposited sediment will depend essentially on its texture and whether it is permanently submerged or subject to alternate submergence and aeration. Since the use and operation of a reservoir greatly affect submergence of the sediment, they also exert a major impact on the volume-weight of the sediment. The volume-weight of sediment in reservoirs ranges from 0.32 to 1.84 g/cm^3 (<20 to about 115 lbs/ft^3).

Lara and Pemberton [1965] have published equations for predicting the unit weight of reservoir sediment for four types of reservoir operations; these equations were based on 1316 measurements of unit weights in 117 reservoirs and stream reaches. Using data from Sabetha Lake in Kansas, *Heinemann* [1962] has illustrated and discussed the great variability of sediment volume-weight both in the vertical and in the longitudinal profiles of a reservoir.

Reservoir sediment deposition surveys [*Task Committee on Preparation of a Sedimentation Manual,* 1970*a*, *b*] are one source of data for estimating sediment yield from watersheds. Because of the variation in the volume-weight of reservoir sediment, it is necessary, however, to express the measured volumes on a weight basis before they are used as indices of sediment yield. Many reservoir sediment surveys include measurement of sediment volume-weight; it would be a great contribution if all surveys included such information and the results were reported. *McHenry* [1963] has developed a two-pronged gamma gage that greatly improves the accuracy of in situ measurements of the volume-weight of reservoir sediment.

Chemical transformations. Heinemann et al. [this volume] have presented data on the influence of sediment on the nutrient status of water in lakes. Bottom sediments from two eutrophic natural lakes in Minnesota were highly capable of removing orthophosphate from solution. In laboratory tests the lake sediments, by adsorption, reduced orthophosphate concentrations; in one case the reduction was from 8.2 to 0.02 ppm, and in another it was from 42.0 to 0.05 ppm.

Heinemann et al. further found that the nitrate and ammonium discharges from a reservoir in Missouri were about equal to their inflows. Total nitrogen discharge from the reservoir, however, was approximately 80% of its inflow; thus it is probable that some of the nitrogen in the organic matter was deposited in the reservoir. On the other hand, 56% of the influent phosphorus was deposited in the reservoir with the sediment. Only 16% of the influent sediment, but 44% of the phosphorus, passed through the reservoir. The sediment passing through the reservoir was of a finer texture and could adsorb more phosphorus per unit weight than the average incoming sediment. In view of the increasing concern about eutrophication and the quality of water in lakes, the term reservoir trap efficiency might well be used in reference to plant nutrients and other chemicals brought into and deposited in reservoirs, as well as to quantities of sediment.

METHODS OF SEDIMENT CONTROL

In a decision on whether the services to be derived from a reservoir are sufficient to justify the costs, it is usually assumed that the reservoir will provide uninterrupted services during a specified period of time. If it is expected that the services will be interrupted, information is required on the frequency and duration of the interruption as part of the criteria needed before the decision is made to invest in the reservoir. It is essential therefore that the amount and character of sediment be anticipated and provided for in the planning stages.

When the purpose of the reservoir is to provide flood control or water storage, the reservoir sites expected to receive the least amount of sediment should be chosen if alternatives are available. If the purpose of the reservoir is to impound sediment, then, of course, the site should be chosen with respect to the sediment source areas, and the reservoir or debris basin should be planned to attain the maximum feasible trap efficiency. In either case the amount and character of sediment involved should be one of the first considerations. A pioneering bulletin on the control of reservoir silting [*Brown*, 1944], though written nearly 3 decades ago, contains much pertinent information about reservoir site selection and other methods for sediment control.

Sediment yield estimates. Reservoir sediment deposition surveys [*Task Committee on Preparation of a Sedimentation Manual*, 1970*a*, *b*] are a significant source of data on sediment yields if adequate data on sediment volume-weight are obtained. The measured volumes must also be adjusted for trap efficiency. In their paper, *Roehl and Holeman* [this volume] refer to a long-term study initiated by the U.S. Department of Agriculture's Soil Conservation Service to obtain sediment yield and other information for improving the design of small reservoirs. *Cyberski* [this volume] strongly recommends continued investigation of reservoir sedimentation phenomena. *Priest* [this volume] presents a method that he derived for estimating sediment accumulation in reservoirs of moderate size.

Records of suspended load measurements integrated with streamflow data provide another source of information on sediment yield. *Bondurant and Livesey* [this volume] describe the concept of index suspended load measurement stations operated by the U.S. Army Corps of Engineers in the Missouri River division. A procedure for deriving sediment yield estimates from suspended load records was suggested by *Straub* [1935], was further developed by *Campbell and Bauder* [1940], was extended by *Miller* [1951], and more recently was reported on by *Piest* [1965]. Equations for estimating bedload transport have been described and compared by *Shulits and Hill* [1968]. The subject of sediment sources and yields is treated in considerable detail in a recent report by the *Task Committee on*

Preparation of a Sedimentation Manual [1970*a*, *b*].

Reduction of sediment yield. Most of the sediment delivered to reservoirs is the product of soil erosion in the watershed (catchment) area draining into the reservoirs. It comes from a multiplicity of sources, including farmlands, rangelands, forest and woodlands, gullies, stream channels, roads and highways, urban developments, and construction sites. *Cyberski* [this volume] mentions erosion of shorelines of lakes as another important source of sediment.

Stabilization of sediment sources is usually the most direct and effective means of controlling reservoir sedimentation. It is usually much more feasible and less costly to keep sediment out of a reservoir than to cope with it after it gets into the reservoir. Land use and treatment practices that reduce sediment yields also preserve the land resource and thus result in benefits both on site and off site.

The potential for reducing sediment yields by erosion control and watershed protection measures has been shown by *Gottschalk* [1962] in a summary of 157 work plans authorized for installation under the small watershed program carried out by the U.S. Department of Agriculture. The combination of land treatment and structural measures recommended for these watersheds, having a combined drainage area of 3.9×10^6 ha (9.7×10^6 acres), would reduce sediment outflow from these watersheds by 55%. *Bondurant and Livesey* [this volume] recognize the potential of soil conservation practices for reducing sediment yields from small watersheds but seem skeptical that such measures can be applied over a broad enough area to have much effect on the sediment reaching large reservoirs.

Sediment storage. Cyberski [this volume] cites data showing a reduction of reservoir silting following the construction of additional reservoirs upstream. Debris basins are sometimes called for on steep mountain channels to trap and impound sediment as an alternate to channel stabilization works. These basins are also being used increasingly in the United States to trap and contain sediment arising from construction sites, such as housing and industrial developments.

Venting of sediment. Discharge of sediment-laden waters through the outlet works of dams, especially when density currents are operative, may have more potential for controlling sedimentation of reservoirs than has been realized. *Lara* [this volume] shows that the capacity of Guernsey Reservoir increased 5.38×10^5 m^3, or 428 acre-feet (about 1%), between 1957 and 1966 as a result of discharging sediment by controlled release of water from the reservoir. *Bondurant and Livesey* [this volume] cite successful operation of reservoir outlets works to evacuate sediment from reservoirs in Algeria.

Dredging. Dredging is another method for controlling reservoir sedimentation, but it is usually too costly just to preserve or restore storage capacity. There are occasions, however, when dredging may be practical for site beautification, creation of recreation areas, maintenance of marinas, or shoreline development.

CONCLUSION

The processes of reservoir sedimentation are complex. There are many alternatives and options to be identified and evaluated in meeting the problem. In the final analysis, our concern about reservoir sedimentation cannot be separated from our concerns about water supply, irrigation, flood control, water quality management, eutrophication, navigation, recreation, fish and wildlife, and erosion. Control of reservoir sedimentation, then, becomes an integral part of man's endless endeavor to wisely develop and use the water and related land resources available to him.

REFERENCES

Bell, H. S., Stratified flow in reservoirs and its use in prevention of silting, *U.S. Dep. Agr. Misc. Publ., 491,* 46 pp., 1942.

Biswas, A. K., *History of Hydrology,* Elsevier, New York, 1970.

Bondurant, D. C., and R. H. Livesey, Reservoir sedimentation studies, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Borland, W. M., and C. R. Miller, Distribution of sediment in large reservoirs, *Trans. Amer. Soc. Civil Eng., 125*(1), 166–180, 1958.

Brown, C. B., The control of reservoir silting, *U.S. Dep. Agr. Misc. Publ., 521,* 166 pp., 1944.

Brune, G. M., Trap-efficiency of reservoirs, *Eos Trans. AGU, 34*(3), 407–418, 1953.

Busby, C. E., Some legal aspects of sedimentation, *J. Hydraul. Div. Amer. Soc. Civil Eng., 87,* 151–180, 1961.

Campbell, F. B., and H. A. Bauder, A rating-curve method for determining silt discharge of streams, *Eos Trans. AGU, 21,* 603–607, 1940.

Cyberski, J., Accumulation of debris in water storage reservoirs in Central Europe, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Dendy, F. E., W. A. Champion, and R. B. Wilson, Reservoir sedimentation surveys in the United States, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Glymph, L. M., and H. C. Storey, Sediment—Its consequences and control, Agriculture and the Quality of Our Environment, *Publ. 95*, pp. 205–220, Amer. Ass. for the Advan. of Sci., Washington, D. C., 1967.

Gottschalk, L. C., Effects of watershed protection measures on reduction of erosion and sediment damages in the United States, *Int. Ass. Sci. Hydrol. Publ. 59*, 426–447, 1962.

Heinemann, H. G., Sediment distribution in small floodwater-retarding reservoirs in the Missouri basin loess hills, *Publ. ARS 41–44*, 37 pp., U.S. Dep. of Agr., Agr. Res. Serv., Washington, D. C., 1961.

Heinemann, H. G., Volume-weight of reservoir sediment, *J. Hydraul. Div. Amer. Soc. Civil Eng., 95* (HY5), 181–197, 1962.

Heinemann, H. G., R. F. Holt, and D. L. Rausch, Sediment and nutrient research on selected corn belt reservoirs, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Israel Program for Scientific Translations, *Sedimentation, Annotated Bibliography of Foreign Literature*, vol. 1–5, U.S. Department of Agriculture and the National Science Foundation, Washington, D. C., 1965–1969.

Lara, J. M., A unique sediment depositional pattern, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Lara, J. M., and E. L. Pemberton, Initial unit weight of deposited sediments, Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963, *U.S. Dep. Agr. Misc. Publ., 970*, 818–845, 1965.

McHenry, J. R., A two-probe nuclear device for determining the density of sediments, Land Erosion, Precipitations, Hydrometry, Soil Moisture, *Int. Ass. Sci. Hydrol. Publ., 65*, 189–202, 1963.

Miller, C. R., Analysis of flow-duration sediment-rating curve method of computing sediment yield, report, U.S. Bur. of Reclam., Denver, Colo., April 1951.

Piest, R. F., The role of the large storm as a sediment contributor, Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963, *U.S. Dep. Agr. Misc. Publ., 970*, 98–108, 1965.

Priest, M. S., Sediment accumulation in reservoirs of moderate size, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Ritchie, J. C., J. R. McHenry, A. C. Gill, and P. H. Hawks, The use of fallout cesium-137 as a tracer of sediment movement and deposition, in *Proceedings of the Mississippi Water Resources Conference 1970*, pp. 149–162, Water Resources Research Institute, Mississippi State University, State College, 1970.

Roehl, J. W., and J. N. Holeman, Sediment studies pertaining to small reservoir design, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Shulits, S., and R. D. Hill, Jr., Part A, A selection of bedload formulas, Part B, Program listings for bedload formulas, *PB 194950*, Clearinghouse for Fed. Sci. and Tech. Inform., Springfield, Va., 1968.

Straub, L. G., Missouri River, *House Doc. 238*, 73rd Congress, 2nd Session, Appendix 15, 1935.

Task Committee on Preparation of a Sedimentation Manual, Sediment measurement techniques: Reservoir deposits, chapter 3, *J. Hydraul. Div. Amer. Soc. Civil Eng., 95*(HY5), 2417–2446, 1970*a*.

Task Committee on Preparation of a Sedimentation Manual, Sediment sources and yields, chapter 4, *J. Hydraul. Div. Amer. Soc. Civil Eng., 96*(HY6), 1283–1329, 1970*b*.

U.S. Department of the Interior, *Selected Water Resources Abstracts*, vol. 1–4, Office of Water Resources Research, Water Resources Scientific Information Center, Washington, D. C., 1968–1971.

Water Resources Council, Annotated bibliography on hydrology and sedimentation, 1966–1968, United States and Canada, *Bull. 10*, Hydrol. and Sedimentation Comm., Washington, D. C., 1970.

Worsley, T. R., and J. M. Dennison, Sedimentology of Whites Creek delta in Watts Bar Lake, Tennessee, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Mongr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Yakovleva, L. V., Characteristics of silting of small reservoirs of the central Chernozem provinces and computation of density of bottom deposits, in *Water Balance and Silting of Small Reservoirs in the Central Chernozem of the Russian Soviet Federal Socialist Republic, 1965*, translated from Russian by D. V. Krimgold, U.S. Department of Agriculture, Agricultural Research Service, Washington, D. C., 1967.

Reservoir Sedimentation Surveys in the United States

F. E. DENDY, W. A. CHAMPION, AND R. B. WILSON
USDA Sedimentation Laboratory, Oxford, Mississippi 38655

Periodically, usually about every 5–10 years, the Committee on Sedimentation of the Water Resources Council summarizes data from known reliable reservoir sedimentation surveys made in the United States. The latest summary includes data from surveys made through 1965 for 1212 reservoirs [*U.S. Department of Agriculture*, 1969]. It includes information on reservoir size, drainage area, sediment accumulation and reservoir storage depletion rates, and, in some cases, rainfall and runoff. This report further summarizes these data in an attempt to provide some insight into the relative magnitude of the reservoir siltation problem in the United States.

DATA

Most of the data used in this report were collected by various agencies of the federal government. Some surveys were reported by state agencies in Ohio and Illinois. The reservoirs range from small pond-type structures to those with capacities exceeding 1.2 billion m^3 (1 million acre-feet). For this study, only those reservoirs with complete information on capacity, total and net drainage areas, period of record, and sediment deposition rates were included. Small debris basins and off-stream structures were excluded. One small reservoir in Utah, which completely filled with sediment during one flash flood soon after construction, and Lake Mead, because of its enormous size and comparatively high siltation rates, were also excluded.

The accuracy of the surveys varied considerably; the surveys ranged from reconnaissance-type measurements of deposited sediment to detailed surveys consisting of closely spaced cross sections or contours. Although attempts were made to check the individual reservoir data sheets for computational and clerical errors, no attempt was made to classify the surveys according to degree of accuracy.

Reservoir sedimentation surveys were reported from each of the conterminous United States except Maine and Florida and from Puerto Rico. Geographical distribution of the selected reservoirs is shown in Figure 1. River basin boundaries and numbers were established by the *Subcommittee on Hydrology of the U.S. Inter-Agency Committee on Water Resources* [1961]. Virtually every section of the country is represented, the heaviest concentrations being in the midwestern states, Texas, and California. Many of the river basins, however, are not adequately represented, and no surveys were reported for 11 basins.

RESERVOIR STORAGE DEPLETION RATES

A general summary of the data from the 1105 reservoirs selected for this study is given in Table 1. The total drainage area includes the entire area upstream from the dam including the reservoir but generally excludes areas that do not contribute runoff. Net drainage area is defined as the net sediment-contributing area and generally does not include areas above upstream structures that were considered effective sediment traps. The initial reservoir capacity is the maximum value reported and usually represents the capacity below the crest of an ungated spillway or at the top of the gates of a gated spillway. Storage depletion is the loss of capacity due to sediment deposition. In most instances the period of record is also the reservoir age at the time of the latest survey. The capacity-weighted period of record was computed by summing the product of the reservoir capacity times the period of record and dividing by the sum of the capacities. These values more nearly represent the true period of sediment accumulation for the total capacity in each of the size categories.

As shown by the data in Table 1, the total storage loss in all of the sampled reservoirs was about 4.2 billion m^3 (3.4 million acre-feet) in

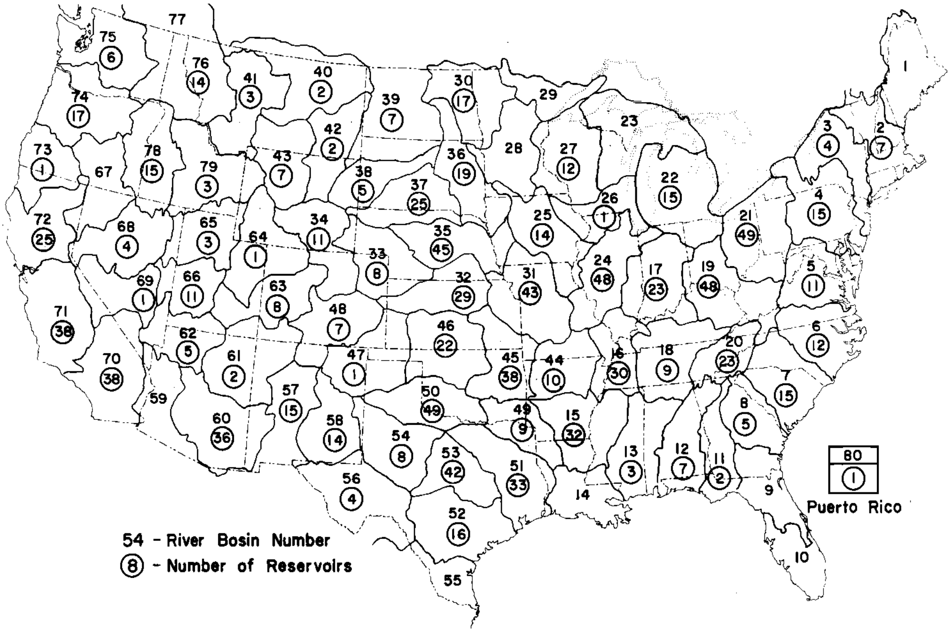


Fig. 1. Geographical distribution of reservoirs.

slightly less than 20 years. This amount represents an average annual loss of about 0.2% of the total capacity. However, this overall depletion rate may not be representative of all reservoirs in the country. The table shows that nearly all of the sampled capacity is in the large reservoirs that have the lowest average depletion rates. Available information on the number of reservoirs in the country indicates that the large reservoirs were much more intensively sampled than the smaller ones [*Martin and Hanson*, 1966; *Soil Conservation Service*, 1970]. Samples representing equal proportions of the total reservoir capacity in each of the size groups would give a higher overall storage depletion rate.

Average annual and median values of individual reservoir storage depletion rates are given in Table 2. They show a remarkably consistent decrease in storage loss rates with increasing reservoir size. For reservoirs with storage capacities of $\leq$123,300 m^3 ($\leq$100 acre-feet) the average annual storage loss was 2.7% and the median was 1.5%. These statistics suggest that one-half of these smaller structures will be half filled with sediment in $\leq$33 years.

Storage depletion rates varied widely, particularly among the smaller reservoirs; these rates ranged from 0 to 25%/yr for reservoirs with capacities of $\leq$12,330 m^3 ($\leq$10 acre-feet). This variation decreased markedly with an increase in reservoir size, as is indicated by the probable error of the mean for each size category in Table 2. Storage depletion rates did not exceed 1.1% for reservoirs with capacities of $>$123 million m^3 ($>$100,000 acre-feet) and ranged from 0 to 2.9% for those with capacities of 12.3 and 123 million m^3 (10,000 and 100,000 acre-feet).

Figure 2 shows the proportion of reservoirs in each size category with annual storage loss rates of $\geq$1%. Again, the highest proportion is in the small reservoirs, and this proportion decreases markedly to only a small fraction of those reservoirs with capacities of $>$123 million m^3 ($>$100,000 acre-feet). None of the reservoirs with capacities of $>$1.2 billion m^3 ($>$1 million acre-feet) had loss rates in excess of 0.5%. On the other hand, 6% of the reservoirs with capacities of $<$12,330 m^3 ($<$10 acre-feet) and 2% of those with capacities of between 12,330 and 123,000 m^3 (10 and 100 acre-feet) had storage loss rates of $>$10%. The proportion of reservoirs having relatively low storage loss rates corresponds closely to that reported by *Eakin* [1939], *Happ* [1941], and *Brown* [1944] approximately 35 years ago.

WATERSHED SEDIMENT YIELDS

The quantity of sediment trapped in a reservoir is not necessarily a measure of watershed sedi-

TABLE 1. Summary of Reservoir Storage Capacity and Storage Depletion by Capacity Ranges

Reservoir Capacity Range		Number of Reservoirs	Total Drainage Area		Net Drainage Area		Initial Reservoir Storage Capacity		Storage Depletion			Average Period of Record, years	Capacity-Weighted Period of Record, years
ac ft	10^3 m^3		mi^2	km^2	mi^2	km^2	ac ft	10^3 m^3	ac ft	10^3 m^3	%		
0 to 10	0 to 12.33	190	180	466	164	425	844	1,041	217	268	25.7	11.8	12.8
10 to 10^2	12.33 to 123.3	257	454	1,176	437	1,132	9,184	11,328	1,772	2,186	19.3	14.5	16.6
10^2 to 10^3	123.3 to 1,233	283	4,269	11,057	3,634	9,412	112,042	138,204	18,432	22,736	16.5	23.5	22.8
10^3 to 10^4	1,233 to 12,330	176	30,509	79,018	15,191	39,345	567,497	700,008	76,063	93,824	13.4	20.9	21.8
10^4 to 10^5	12,330 to 123,300	107	113,787	294,708	87,458	226,516	4,363,134	5,381,926	395,786	488,202	9.1	23.6	22.5
10^5 to 10^6	123,300 to 1,233,000	69	316,854	820,654	175,636	454,897	23,712,144	29,248,930	864,039	1,065,792	3.6	18.4	17.6
$>10^6$	>1,233,000	23	358,472	928,442	184,227	477,148	60,396,384	74,498,940	2,081,799	2,567,899	3.4	19.1	20.3
		1105	824,525	2,135,521	466,747	1,208,875	89,161,229	109,980,377	3,438,108	4,240,907	3.9	18.6	19.7

ment yield since it does not include deposits above the spillway elevation or sediment transported through the reservoir. Nevertheless, watershed sediment yield is usually the predominant factor controlling siltation rates in reservoirs.

Average sediment yields, as reflected by reservoir deposits, were much higher in the smaller upland watersheds and decreased markedly with increasing drainage area (Table 3). This finding is in accord with the generally held hypothesis of decreasing sediment delivery with increasing drainage area [*Glymph*, 1954; *Happ et al.*, 1940; *Roehl*, 1962]. The sharp drop in sediment accumulation rates for watersheds of ≥25.9 km^2 (≥10 mi^2) and the comparatively moderate decline as drainage area increased above 25.9 km^2 (10 mi^2) suggest that most of the reduction in sediment yield occurs in the smaller upland drainage areas. This suggestion tends to pinpoint most of the sediment problems in the smaller upland reservoirs where sediment yields are highest.

The lower Mississippi River basin (number 15) is a good example of decreasing sediment yield with increasing drainage area. Six of the 32 reservoirs in this basin had drainage areas ranging from 104 to 4000 km^2 (40 to 1545 mi^2) and an annual sediment accumulation rate of 281 m^3/km^2 (0.59 ac ft/mi^2). The remaining 26 reservoirs, all small pond-sized structures with drainage areas of <2.59 km^2 (<1 mi^2), had an average sediment accumulation rate of 3191 m^3/km^2/yr (6.7 ac ft/mi^2/yr), which is >10 times greater than that for the large reservoirs.

The proportion of reservoirs in each drainage area size category with annual sediment accumulation rates of >476 m^3/km^2 (>1 ac ft/mi^2) is shown in Figure 3. Most of these reservoirs have small drainage areas, i.e., <259 km^2 (<100 mi^2). Annual sediment accumulation rates did not exceed 310 m^3/km^2 (0.65 ac ft/mi^2) for reservoirs with total drainage areas of ≥25,900 km^2 (≥10,000 mi^2).

SEDIMENT ACCUMULATION AND RESERVOIR STORAGE LOSS BY RIVER BASINS

Average annual sediment accumulation and storage depletion rates for river basins with 10 or more surveyed reservoirs are given in Table 4. The first-line entry in this table for each river basin gives data for all reservoirs in the basin. The second-line entry gives data for reservoirs with drainage areas of ≥25.9 km^2 (≥10.0 mi^2). The

TABLE 2. Reservoir Storage Depletion Rates

Reservoir Capacity Range		Number of Reservoirs	Annual Storage Depletion Rate		Probable Error of the Mean, %	Average Date of Last Survey
ac ft	10^3 m^3		Mean, %	Median, %		
0 to 10	0 to 12.33	190	3.56	2.00	0.21	1954
10 to 10^2	12.33 to 123.3	257	2.00	1.20	0.09	1954
10^2 to 10^3	123.3 to 1,233	283	1.02	0.62	0.05	1951
10^3 to 10^4	1,233 to 12,330	176	0.81	0.55	0.05	1949
10^4 to 10^5	12,330 to 123,300	107	0.43	0.27	0.04	1949
10^5 to 10^6	123,300 to 1,233,000	69	0.23	0.14	0.02	1955
$>10^6$	>1,233,000	23	0.16	0.11	0.02	1958

area-weighted sediment accumulation rate for each basin was computed by summing the products of the net drainage areas times the sediment accumulation rate and dividing by the sum of the net drainage areas. The capacity-weighted storage loss was computed in the same manner except that the annual storage loss rate and reservoir capacity were used.

Both sediment accumulation and storage depletion rates varied considerably among river basins. There were also large variations between reservoirs in the same river basin. For this reason and because siltation rates were usually much smaller in the larger reservoirs, the area-weighted sediment accumulation rates and the capacity-weighted storage loss rates may more nearly reflect overall basin conditions. Similarly, the data for drainage areas of ≥25.9 km² (≥10.0 mi²) more accurately reflect conditions in the larger reservoirs.

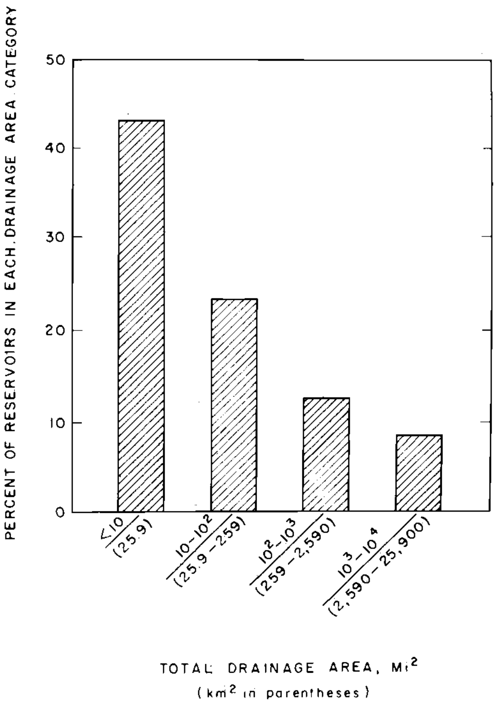


Fig. 2. Proportion of reservoirs in each size category with average annual storage loss rates of ≥1%.

The maximum sediment accumulation rate reported was 29,050 m³/km²/yr (61 ac ft/mi²/yr) for a small reservoir in Iowa. The highest area-weighted accumulation rate was 905 m³/km²/yr (1.9 ac ft/mi²/yr) in the Colorado River basin above Halls Crossing (number 63). The nine reservoirs measured in this basin were small (drainage area of <13 km², or <5 mi²) and the average period of record was only 7 years.

Although some of the highest accumulation rates were reported from arid regions, this generally true situation was not always the case. For example, in the Gila River basin (number 60) in southern Arizona the weighted rate was only 152 m³/km²/yr (0.32 ac ft/mi²/yr) for 36 reservoirs, including 28 structures with drainage areas of <25.9 km² (<10 mi²).

High siltation rates in individual reservoirs and relatively high average basin rates occurred in most sections of the country. River basins 6, 15, 16, 35, 50, 51, 70 and 72, all with an adequate number of structures, had area-weighted basin rates in excess of 286 m³/km²/yr (0.6 ac ft/mi²/yr). Accumulation rates in the larger reservoirs were also much higher than the average. These basins represent a wide range in rainfall, runoff, land use, and types and amount of vegetative cover.

DISCUSSION

Studies of selected groups of reservoirs have established relationships between reservoir siltation rates and various hydrologic, watershed, and reservoir parameters [*Brune*, 1953; *Farnham et al.*, 1966; *Flaxman*, 1966; *Maner*, 1958; *Roehl*, 1962; *Stall and Bartelli*, 1959]. Generally, however, the investigators have pointed out that their findings

TABLE 3. Sediment Accumulation per Unit of Net Drainage Area

Drainage Area		Number of Reservoirs	Average Annual Sediment Accumulation*		Median Annual Sediment Accumulation*	
mi^2	km^2		ac ft/mi^2	10^3 m^3/km^2	ac ft/mi^2	10^3 m^3/km^2
0 to 5	0 to 12.9	648	1.56	0.74	0.82	0.39
5 to 10	12.9 to 25.9	70	1.45	0.69	0.69	0.33
0 to 10	0 to 25.9	718	1.55	0.74	0.80	0.38
10 to 10^2	25.9 to 259	189	0.71	0.34	0.44	0.21
10^2 to 10^3	259 to 2,590	103	0.53	0.25	0.27	0.13
10^3 to 10^4	2,590 to 25,900	70	0.38	0.18	0.26	0.12
10^4 to 10^5	25,900 to 259,000	25	0.36	0.17	0.39	0.19

*Annual sediment accumulation rates are based on the net drainage area (sediment-contributing area).

were applicable only in the areas where developed. Many complex processes are involved, and the relative importance of controlling factors varies from region to region and even within a region.

It is not the intent or purpose of this paper to establish average reservoir siltation rates for a given locality or river basin to be used as a guide. The wide range in deposition rates in reservoirs of similar size and drainage area, even within a given land resource area, suggests that average rates would be of little value in predicting the useful life of a particular reservoir. Furthermore, the wide range in siltation rates, particularly in the smaller reservoirs, indicates that local parameters rather than climatic or geographic factors govern individual reservoir siltation rates. Widely varying siltation rates in reservoirs with drainage areas of <25.9 km^2 (<10 mi^2) no doubt reflect great contrast in vegetative cover, land use, topography, and perhaps other factors affecting sediment yield.

The data as compiled do provide some insight into the nation's reservoir siltation problems. The smaller reservoirs and ponds (capacities of <123,300 m^3, or <100 acre-feet) are filling with sediment at relatively high average rates. A median storage loss rate of 1.5% annually suggests that one-half of these smaller reservoirs and ponds will be filled with sediment in 66 years Furthermore, the utility of many of them will have been seriously impaired by the time they are half full in about 30 years.

Although the overall storage loss rate was low in the large reservoirs, rates were relatively high for many of these structures. For example, 14% of those with capacities of >1.23 million m^3 (>1000 acre-feet) and 6% with capacities of >12.3 million m^3 (>10,000 acre-feet) had average annual storage loss rates of >1%, which may not be an acceptable depletion rate for structures of this size.

It is difficult to ascertain how representative these data are of all reservoirs in the country. Many of the surveys were made a long time ago; the latest survey dates ranged from 1918 to 1965. Thus the siltation rates reported for many of these reservoirs may not be representative of current conditions. It is doubtful that the soil conservation measures applied to the land in the last 25 years are reflected in many of these data.

The size of the sample appears to be adequate for the larger reservoirs. *Martin and Hanson* [1966] reported approximately 443 billion m^3 (359 million acre-feet) of usable storage in 1562 reservoirs with individual capacities of >6.17

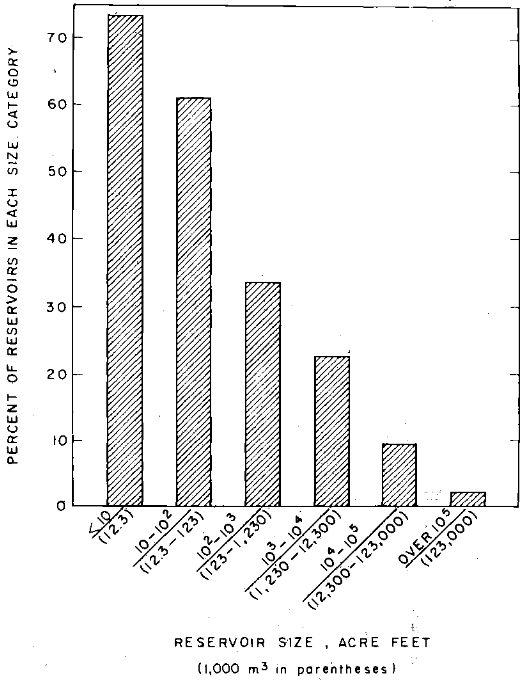


Fig. 3. Proportion of reservoirs in each drainage category with sediment accumulation rates of ≥476 $m^3/km^2/yr$ (≥1 ac ft/mi^2/yr).

TABLE 4. Summary of Reservoir Sedimentation Data by River Basins (Average Values Except as Noted)

River Basin No.	No. of Reservoirs	Total Drainage Area		Net Drainage Area		Original Reservoir Capacity		Average Annual Sediment Accumulation*		Weighted Annual Sediment Accumulation*†		Annual Storage Depletion, %		Period of Record, years
		mi^2	km^2	mi^2	km^2	ac ft	10^3 m^3	ac ft/mi^2	10^3 m^3/km^2	ac ft/mi^2	10^3 m^3/km^2	Average	Weighted§	
4	15	139.3	360.8	128.8	333.6	43,198	53,285	0.27	0.13	0.28	0.13	0.59	0.08	32
	11	188.5	488.2	174.1	450.9	58,531	72,198	0.26	0.12	0.28	0.13	0.51	0.08	32
5	11	80.1	207.5	66.8	173.0	7,441	9,178	0.58	0.28	0.35	0.17	0.91	0.30	19
	10	88.0	227.9	73.4	190.1	8,166	10,073	0.38	0.18	0.34	0.16	0.89	0.30	19
6	12	738.8	1,913.5	702.3	1,819.0	252,912	311,967	0.55	0.26	1.00	0.48	1.39	0.28	12
	8	1,106.1	2,864.8	1,051.4	2,723.1	379,272	467,832	0.66	0.31	1.00	0.48	1.64	0.28	10
7	15	630.9	1,634.0	328.3	850.3	29,613	36,528	0.46	0.22	0.45	0.21	0.76	0.50	22
	12	786.9	2,038.1	408.6	1,058.3	36,857	45,463	0.36	0.17	0.45	0.21	0.71	0.50	24
15	32	184.2	477.1	174.9	453.0	133,891	165,155	6.74	3.21	0.63	0.30	3.45	0.08	11
	6	981.5	2,542.1	931.9	2,413.6	713,918	880,618	0.59	0.28	0.63	0.30	0.08	0.08	16
16	30	53.8	139.3	49.8	129.0	24,475	30,190	1.33	0.63	0.62	0.30	0.71	0.13	21
	5	311.7	807.3	288.3	746.7	144,176	177,841	1.19	0.57	0.60	0.29	0.37	0.12	19
17	23	101.1	261.8	100.1	259.3	11,481	14,162	1.21	0.58	0.12	0.06	0.70	0.11	18
	5	460.4	1,192.4	456.3	1,181.8	51,244	63,209	0.37	0.18	0.11	0.05	0.99	0.10	15
19	48	122.8	318.1	122.0	316.0	18,622	22,970	0.79	0.38	0.17	0.08	1.63	0.11	16
	22	265.3	687.1	263.7	683.0	40,208	49,597	0.43	0.20	0.16	0.08	2.45	0.10	19
20	23	3,089.4	8,001.5	918.2	2,378.1	509,710	628,727	0.45	0.21	0.37	0.18	0.36	0.07	21
	21	3,383.4	8,763.0	1,005.4	2,604.0	558,226	688,572	0.44	0.21	0.37	0.18	0.35	0.07	20
21	49	93.9	243.2	90.8	235.2	29,636	36,556	0.53	0.25	0.30	0.14	1.52	0.09	23
	24	189.2	490.0	182.8	473.5	60,346	74,437	0.41	0.20	0.30	0.14	0.33	0.09	31
22	15	188.7	488.7	182.9	473.7	9,870	12,175	0.92	0.44	0.13	0.06	1.08	0.24	25
	6	469.9	1,217.0	455.5	1,179.7	24,575	30,313	0.59	0.28	0.13	0.06	1.11	0.24	40
24	48	30.2	78.2	29.9	77.4	2,385	2,942	1.01	0.48	0.37	0.18	1.06	0.47	31
	8	171.3	443.7	169.4	438.7	12,892	15,902	0.66	0.31	0.34	0.16	0.83	0.45	23
25	14	248.1	642.6	244.0	632.0	36,285	44,758	1.41	0.67	0.55	0.26	2.61	0.37	13
	9	384.6	996.1	378.3	979.8	56,251	69,386	1.51	0.72	0.54	0.26	3.34	0.37	10
27	12	763.0	1,976.2	71.3	184.7	8,599	10,607	0.48	0.23	0.54	0.26	0.84	0.45	19
	4	2,287.3	5,924.1	212.2	549.6	25,622	31,605	0.27	0.13	0.54	0.26	1.10	0.45	44
30	17	305.0	790.0	165.7	429.2	5,106	6,298	0.17	0.08	0.10	0.05	0.69	0.31	23
	11	470.4	1,218.3	255.2	661.0	7,857	9,692	0.07	0.03	0.10	0.05	0.62	0.31	24
31	43	328.3	850.3	325.9	844.1	49,013	60,458	1.98	0.94	0.47	0.22	2.20	0.31	13
	2	7,020.9	18,184.1	6,970.7	18,054.1	1,045,338	1,289,424	0.50	0.24	0.46	0.22	0.48	0.31	14
32	29	1,004.8	2,602.4	425.2	1,101.3	44,774	55,229	1.22	0.58	0.15	0.07	2.33	0.14	13
	4	7,281.6	18,859.3	3,080.1	7,977.5	324,444	400,202	0.22	0.10	0.15	0.07	1.31	0.14	11
34	11	2,658.8	6,886.3	1,645.8	4,262.6	111,381	137,388	0.19	0.09	0.22	0.10	0.46	0.17	24
	6	4,872.0	12,618.5	3,014.9	7,808.6	203,940	251,560	0.15	0.07	0.22	0.10	0.52	0.17	35
35	45	1.3	3.4	1.3	3.4	69	85	2.89	1.38	0.94	0.45	3.17	1.76	12
	1	41.0	106.2	41.0	106.2	1,652	2,038	0.43	0.20	0.43	0.20	1.08	1.08	33
36	19	55.5	143.7	50.7	131.3	1,200	1,480	2.27	1.08	0.14	0.07	2.00	0.57	12
	4	261.4	677.0	238.8	618.5	5,550	6,846	0.38	0.18	0.12	0.06	0.91	0.53	28
37	25	1.5	3.9	1.5	3.9	33	41	0.56	0.27	0.22	0.10	1.78	0.99	11
	2	11.1	28.7	11.1	28.7	125	154	0.07	0.03	0.06	0.03	1.05	0.58	19
44	10	472.0	1,222.5	471.4	1,220.9	6,520	8,042	0.72	0.34	0.20	0.10	0.60	1.45	10
	4	1,175.3	3,044.0	1,173.9	3,040.4	15,156	18,695	0.39	0.19	0.20	0.10	0.99	1.55	11
45	38	101.1	261.8	99.9	258.7	13,290	16,393	0.91	0.43	0.29	0.14	0.47	0.22	18
	14	269.8	698.8	267.0	691.5	34,579	42,653	1.00	0.48	0.27	0.13	0.46	0.21	18
46	22	807.0	2,090.1	513.3	1,329.4	40,722	50,231	1.05	0.50	0.30	0.14	1.92	0.38	12
	11	1,612.2	4,175.6	1,024.7	2,654.0	81,135	100,080	0.97	0.46	0.30	0.14	0.73	0.38	13
50	49	914.4	2,368.3	685.2	1,774.7	135,393	167,007	1.92	0.91	0.84	0.40	1.18	0.42	13
	8	5,590.6	14,479.7	4,187.1	10,844.6	826,273	1,019,208	1.82	0.87	0.83	0.40	0.79	0.42	18
51	33	446.2	1,155.7	408.7	1,058.5	72,147	88,993	2.34	1.11	0.69	0.33	0.85	0.38	20

TABLE 4. (continued)

River Basin No.	No. of Reservoirs	Total Drainage Area		Net Drainage Area		Original Reservoir Capacity		Average Annual Sediment Accumulation*		Weighted Annual Sediment Accumulation*†		Annual Storage Depletion, %		Period of Record, years
		mi^2	km^2	mi^2	km^2	ac ft	10^3 m^3	ac ft/mi^2	10^3 m^3/km^2	ac ft/mi^2	10^3 m^3/km^2	Average	Weighted§	
	9	1,628.8	4,218.6	1,491.8	3,863.8	261,969	323,139	1.54	0.73	0.68	0.32	0.71	0.38	14
52	16	2,298.0	5,951.8	2,294.5	5,942.8	81,531	100,568	0.87	0.41	0.15	0.07	1.07	0.42	13
	3	12,245.7	31,716.4	12,227.3	31,668.7	432,834	553,901	0.24	0.11	0.15	0.07	0.85	0.42	17
53	42	844.0	2,186.0	478.8	1,240.1	70,746	87,265	1.23	0.59	0.53	0.25	1.00	0.36	21
	14	2,528.1	6,547.8	1,432.7	3,710.7	211,485	260,867	0.45	0.21	0.53	0.25	0.71	0.36	20
57	15	3,850.6	9,973.1	1,882.6	4,875.9	206,839	255,136	1.11	0.53	0.37	0.18	3.40	0.41	13
	4	14,437.5	37,393.1	7,057.5	18,278.9	775,587	956,687	0.27	0.13	0.37	0.18	0.34	0.41	25
58	14	2,539.5	6,577.3	1,423.6	3,687.1	18,685	23,048	0.52	0.25	0.14	0.07	3.55	1.01	18
	6	5,924.5	15,344.5	3,320.8	8,600.9	43,584	53,761	0.18	0.09	0.14	0.07	1.05	1.01	27
60	36	878.5	2,275.3	693.8	1,796.9	91,706	113,119	0.26	0.12	0.32	0.15	2.69	0.24	16
	8	3,948.1	10,225.6	3,117.3	8,073.8	412,600	508,942	0.29	0.14	0.32	0.15	1.33	0.24	18
66	11	823.7	2,133.4	456.6	1,182.6	33,626	41,478	0.52	0.25	0.21	0.10	1.70	0.29	32
	8	1,129.9	2,926.4	625.1	1,619.0	45,764	56,450	0.26	0.12	0.20	0.10	2.13	0.28	27
70	38	128.5	332.8	91.5	237.0	18,160	22,400	1.77	0.84	0.66	0.31	1.30	0.32	23
	24	201.5	521.9	143.0	370.4	27,343	33,728	1.39	0.66	0.62	0.30	0.94	0.31	24
71	38	153.8	398.3	153.3	397.0	51,057	62,979	0.23	0.11	0.16	0.08	1.08	0.05	22
	13	447.4	1,158.8	445.9	1,154.9	148,972	183,757	0.24	0.11	0.16	0.08	0.47	0.05	28
72	25	50.2	130.0	49.8	129.0	9,787	12,072	0.58	0.28	0.65	0.31	3.19	0.33	18
	7	174.5	452.0	172.9	447.8	34,120	42,087	0.74	0.35	0.66	0.31	0.39	0.34	29
74	17	71.5	185.2	71.0	183.9	13,856	17,091	0.16	0.08	0.16	0.08	0.92	0.09	13
	6	201.0	520.6	199.5	516.7	39,214	48,370	0.18	0.09	0.16	0.08	0.09	0.08	21
76	14	125.8	325.8	125.8	325.8	694	856	1.32	0.63	0.36	0.17	2.19	6.52	8
	1	1,760.0	4,558.4	1,760.0	4,558.4	9,688	11,950	0.36	0.17	0.36	0.17	6.54	6.54	12
78	15	366.0	947.9	319.2	826.7	21,986	27,120	0.11	0.05	0.12	0.06	0.72	0.18	18
	5	1,006.8	2,607.6	956.6	2,477.6	65,919	81,311	0.10	0.05	0.12	0.06	1.18	0.18	30

Second-line entry for each river basin is for reservoirs with drainage areas of >25.9 km^2 (>10 mi^2).
*Sediment accumulation rates are based on net drainage area (sediment-contributing area).
†Area weighted.
§Capacity weighted.

million m^3 (>5000 acre-feet) that were completed or under construction as of January 1963. By applying a mean annual storage loss rate of 0.19% (computed from Table 1) for structures of this size, one can estimate an annual storage loss of 841 million m^3 (682,000 acre-feet) in these reservoirs.

The *Soil Conservation Service* [1970] reported 5282 multiple-purpose reservoirs with a total capacity of 5.49 billion m^3 (4.45 million acre-feet) and 9751 floodwater-retarding structures with a total capacity of 5.66 billion m^3 (4.59 million acre-feet) constructed under its various soil and water conservation programs through June 1969. In addition, 1.7 million farm ponds were reported as being on the land. Most of these multiple-purpose and floodwater-retarding structures range between 123,300 and 6.17 million m^3 (100 and 5000 acre-feet) in capacity. At an average storage depletion rate of 0.6% for reservoirs of this size the annual storage loss would be about 67.8 million m^3 (55,000 acre-feet).

Storage loss in the smaller reservoirs and ponds is more difficult to estimate. If we assume an annual loss rate of 1.25% for 1.7 million small reservoirs and ponds with an average capacity of 12,300 m^3 (10 acre-feet), the annual storage loss would be about 261.5 million m^3 (212,000 acre-feet). This loss, plus that previously computed for the large reservoirs, amounts to nearly 1.2 billion m^3/yr (1 million ac ft/yr), which agrees with earlier estimates [*Glymph and Storey*, 1967].

SUMMARY AND CONCLUSIONS

Sedimentation data are summarized for 1105 reservoirs in the United States. Average annual storage loss rates decreased markedly as reservoir size increased; these rates ranged from 2.7% for small reservoirs and ponds with capacities of <123,300 m^3 (<100 acre-feet) to 0.16% for large reservoirs with capacities of ≥1.23 billion m^3 (≥1,000,000 acre-feet).

Many of the data used in this report were obtained from reservoir sedimentation surveys made many years ago and may not reflect current conditions. If we assume, however, that the data do represent a cross section of the nation's reservoirs, some general conclusions can be made.

1. Overall storage depletion rates of <0.2% annually in the large reservoirs may be well within the design requirements.
2. A median storage loss rate of 1.5% annually for small reservoirs and ponds indicates that the utility of one-half of these will have been seriously impaired when they are half filled with sediment in about 30 years.
3. Storage loss rates in excess of 1% in 14% of the reservoirs with capacities of >1.23 million m^3 (>1000 acre-feet) may not be an acceptable depletion rate for structures of this size.
4. Wide variations in siltation rates, particularly in the smaller reservoirs, indicate that local factors such as land use, vegetative cover, and watershed topography rather than regional or climatic parameters govern individual reservoir sediment deposition rates.

REFERENCES

Brown, C. B., The control of reservoir silting, *U.S. Dep. Agr. Misc. Publ., 521*, 166 pp., 1944.

Brune, G. M., Trap efficiency of reservoirs, *Eos Trans. AGU, 34*(3), 407–418, 1953.

Eakin, H. M., Silting of reservoirs, *U.S. Dep. Agr. Tech. Bull., 524*, 168 pp., 1939.

Farnham, C. W., C. E. Beer, and H. G. Heinemann, Evaluation of factors affecting reservoir sediment deposition, Symposium of Garda, *Int. Ass. Sci. Hydrol. Publ., 71*, 747–758, 1966.

Flaxman, E. M., Some variables which influence rates of reservoir sedimentation in western United States, Symposium of Garda, *Int. Ass. Sci. Hydrol. Publ., 71*, 824–838, 1966.

Glymph, L. M., Studies of sediment yields from watersheds, paper presented at Tenth General Assembly, Int. Union of Geod. and Geophys., Rome, Sept. 15–19, 1954.

Glymph, L. M., and H. C. Storey, Sediment—Its consequences and control, Agriculture and the Quality of Our Environment, *Publ. 95*, pp. 205–220, Amer. Ass. for the Advan. Sci., Washington, D. C., 1967.

Happ, S. C., Sedimentation in artificial lakes, in *A Symposium on Hydrobiology*, pp. 35–44, University of Wisconsin Press, Madison, 1941.

Happ, S. C., G. Rittenhouse, and G. C. Dobson, Some principles of accelerated stream and valley sedimentation, *U.S. Dep. Agr. Tech. Bull., 695*, 134 pp., 1940.

Maner, S. B., Factors affecting sediment delivery rates in the Red Hills physiographic area, *Eos Trans. AGU, 39*(4), 669–675, 1958.

Martin, R. O. R., and R. L. Hanson, Reservoirs in the United States, *U.S. Geol. Surv. Water Supply Pap., 1838*, pp. 1–114, 1966.

Roehl, J. W., Sediment source areas, delivery ratios and influencing morphological factors, *Int. Ass. Sci. Hydrol. Publ., 59*, 202–213, 1962.

Soil Conservation Service, A better environment for all people—Summary of activities of the Soil Conservation Service for fiscal year 1969, *Soil Conserv., 35*(6), 135–141, 1970.

Stall, J. B., and I. J. Bartelli, Correlation of reservation sedimentation and watershed factors, *Ill. State Water Surv. Rep. Invest., 37*, 1959.

Subcommittee on Hydrology of the U.S. Inter-Agency

Committee on Water Resources, River basin maps showing hydrologic stations, Notes on Hydrologic Activities, *Bull. 11,* 79 pp., U.S. Dep. of Commer., Washington, D. C., 1961.

U.S. Department of Agriculture, Summary of reservoir sediment deposition surveys made in the United States through 1965, *U.S. Dep. Agr. Misc. Publ., 1143,* 64 pp., 1969.

Accumulation of Debris in Water Storage Reservoirs of Central Europe

JERZY CYBERSKI

State Hydrological-Meteorological Institute, Warsaw, Poland

The problem of silting of water storage reservoirs must be met wherever objects of this kind are being constructed. Naturally, in various parts of the world (owing to the different geologic structure, morphology of the country, land usage, and climatic conditions), the intensity of denudation of the catchment area from which debris is transported to the reservoirs varies considerably.

Silting belongs to the most dangerous phenomena taking place in reservoirs. It often affects both the operational plan of existing reservoirs (by causing losses of their capacity) and the economic analysis of planned investments based on reservoir use. In spite of the common character of the phenomenon of reservoir silting, it is a difficult scientific problem and for that reason has been a subject of investigation at a number of reliable research centers throughout the world. In the following text I have attempted to present this problem as exemplified in Central Europe, where, owing to the diversity of physiographic conditions, there is a large variety in reservoir silting.

SCOPE OF RESEARCH ON RESERVOIR SILTING

Investigations of materials accumulated in reservoirs concerned basically two problems: the quantity of the material deposited and its character (mostly its physical properties). The amount of materials settled in reservoirs has been calculated by geodetic surveying of reservoirs or by the method of balance of debris. If a reservoir was referred to in silting surveys as one that held water, the method of bathymetric surveying was applied, and it was carried out by means of acoustic sounding instruments. They were mounted on boats that were guided along specified control cross sections.

As a rule, this method was applied when the reservoir area was >2 km^2. However, the acoustic method of bathymetric surveying (even for large reservoirs) was adopted only in a few cases. Usually, the shallow and narrow parts of large reservoirs, as well as small ones, were surveyed by means of mechanical sounders or sounding rods.

The lowering of the water level in a reservoir or its complete emptying has always provided an opportunity to carry out surveys of silting by the method of leveling the uncovered surface of silts. During these surveys the depth of sediments at accurately specified points has been determined by driving rods through the sediment and making trial cuttings or geologic borings. Application of these results for a revision of the reservoir capacity curve or for a determination of silting intensity can raise certain objections since these results are always lower than the true ones, i.e., for wet sediment. The differences are due to the settlement of the drying silts (their higher specific gravity).

For determining the silting volume the method of debris balance has also been applied. The amount of silt was calculated in this case from the difference between bed load brought into a reservoir and that carried off from it [*Brádka*, 1966; *Cyberski*, 1966].

The mass of debris delivered was the sum of the bed load and suspended matter transported by water flowing into a reservoir and the rubble worn away from its sloping banks. The method of debris balance corresponds satisfactorily with the results of direct surveys of silting and enables regular determination of the state of reservoir silting (provided there are reliable rubble surveys). However, this method does not fix places of silt deposition, and it does not supply data for a revision of the curve of reservoir capacity. Undoubtedly, the great advantage of this method is the possibility of determining the share of each particular silting factor in the silting process at a particular reservoir. Thus the sources of materials deposited can be identified, and their identification allows the appropriate measures to be taken to limit the amount of debris transported [*Cyberski*, 1966].

Certain relationships existed between the problems analyzed above and the studies on abrasion of reservoir banks. In Poland, these studies were concentrated on the Goczakowice, Rożnów, and Dębe reservoirs and were based on documentary photographs, geologic and morphological data, and systematic surveys carried out on selected sections of banks either above or below the water level [*Cyberski*, 1970]. These studies allowed determination of the abrasion intensity and correlation to geologic and morphological conditions and to the set of hydrologic factors; thus a basis was provided for calculating the share of rubble from abraded banks in the total mass of the accumulated debris [*Cyberski*, 1966].

Usually, the survey of reservoir silting included investigation of the sediments. That work was mainly concerned with the granulation and specific gravity of the silts but gave marginal treatment to other features of silts such as physical and chemical properties. The investigation of sediments enabled the selection of reservoir zones in which a particular type of debris dominated [*Bauer*, 1968; *Bauer and Burz*, 1968; *Chomiak et al.*, 1969; *Orth*, 1934].

EXTENT OF RESERVOIR SILTING

Our investigations on the intensity of debris accumulation in selected storage reservoirs in the area of Central Europe begin with Poland. By 1968 the research on silting had covered 12 reservoirs with a total capacity of 600 million m^3 (~480,000 acre-feet), which constitutes 15% of the total number (80) of reservoirs and about ⅓ of their total capacity of 1.8 km^3 (~1,500,000 acre-feet). The work concentrated on reservoirs situated in southern Poland since the reservoirs of that region are subjected to the most intensive silting (Table 1). At present, the seriously threatened reservoirs are the Carpathian reservoirs, and among them the reservoir at Rożnów, whose average yearly loss of capacity reaches 0.78%, is the most seriously threatened.

The high rates of silting in Carpathian reservoirs (0.118–0.364 mm/yr) result from the rapidly developing processes of denudation of the diastrophic rocks consisting of the base material of which the Carpathian Mountains are built. This material is likely to be easily damaged by the effects of weather.

The progress of silting in the other two reservoirs Porąbka and Myczkowce, which are very intensely silted so far, has been radically slowed down by the construction of large storage reservoirs above them. These storages are able to intercept all debris being delivered at present. In contrast, reservoirs supplied by waters flowing from the Sudetic Mountains (built of hard, damage-resistant gneisses and granites) have very low silting rates. The yearly losses of capacity at Leśna, Pilchowice, and Lubachów reservoirs range from 0.04–0.12%, and their rates of silting also are low (average yearly level of 0.017–0.063 mm). Also, a low intensity of silting is characteristic for reservoirs situated in flat country where there is little difference in ground heights and low mean unit runoff (<10 $l/sec/km^2$), e.g., Turawa and Otmuchów. Their losses of capacity range from 0.02 to 0.21%/yr [*Chomiak et al.*, 1969; *Cyberski*, 1970; *Orth*, 1934].

Equally small and even smaller rates of silting have been shown by some reservoirs in Czechoslovakia (Brules and Vranov reservoirs in Table 1), though there as well a certain diversity in the intensity of the denudation of the catchment area can be observed. For instance, the Sázava River, which runs into the Vltava in the Vranov Reservoir, carries similar quantities of suspended matter as the Vltava whose catchment area is 3 times larger [*Brádka*, 1966]. The very low silting rate, nearly 0, in the Brules Reservoir, is worth noting. This rate has been achieved by planting forests over the whole catchment area that sends water to that reservoir.

In light of the examples in Table 1, very high silting rates have been noted for Austrian reservoirs. They range from 0.037 to 1.852 mm/yr. Such intensive denudation results from the topographic features of Austria, high gradients of rivers, and abundance of water (the average yearly unit runoff is 36–57 $l/sec/km^2$). Owing to these factors the Austrian rivers carry great quantities of debris, particularly as bed load. The consequences of transportation of those masses can be easily noticed, especially in small reservoirs in which the yearly losses of capacity balance within the range of 3.8 to >10% (Steyerdurchbruch, Tarcento, and Avisio reservoirs) and even reach 50% (Pernegg Reservoir). In extreme cases a complete filling of a reservoir with rubble can take

TABLE 1. Comparative Data on Silting in Some Selected Water Storage Reservoirs in Central Europe

Reservoir	River	Catchment Area, km^2	Observation Period	Year No.	Initial Capacity, 10^6 m^3	Final Capacity, 10^6 m^3	Silting, 10^6 m^3	Average Yearly Silt Deposit		Rate of Silting	
								10^6 m^3	% of Capacity	m^3/km^2/yr	mm/yr
					Poland						
Leśna	Kwisa	307	1905 to 1930	25	15.0	14.812	0.188	0.008	0.05	24	0.024
Pilchowice	Bóbr	1,202	1913 to 1959	46	50.0	49.08	0.92	0.020	0.04	17	0.017
Lubachów	Bystrzyca	148	1918 to 1933	15	8.0	7.862	0.138	0.009	0.12	63	0.063
Otmuchów	Nysa Klodska	2,350	1932 to 1961	29	143.0	134.5	8.5	0.294	0.21	125	0.125
Turawa	Mala Panew	1,400	1947 to 1961	14	108.9	108.6	0.3	0.021	0.02	15	0.015
Porąbka	Sola	1,082	1937 to 1965	28	32.15	28.35	3.8	0.136	0.42	125	0.125
Rożnów	Dunajec	4,885	1941 to 1965	23.5	228.7	183.6	41.83	1.780	0.78	364	0.364
Myczkowce	San	1,250	1960 to 1967	7	10.9	9.87	1.03	0.147	1.35	118	0.118
					Czechoslovakia						
Brules	...	8.3	...	...	1.6	...	...	0.0001	...	11.4	0.011
Vranov	Vltava	17,782	1935 to 1961	26	...	...	0.859	0.033	...	1.86	0.002
					Austria						
Avisio	Avisio	956	1882 to 1890	8	2.0	0.0	2.0	0.250	12.5	261	0.261
Pernegg	Mur	6,250	1925 to 1927	1.5	0.5	0.15	0.35	0.233	46.7	37.4	0.037
Pontebba	Vogelbach	10.0	1862 to 1880	18	...	...	0.280	0.016	...	1545	1.545
Steyerdurchbruch	Steyer	575	1908 to 1931	22.5	0.845	0.135	0.710	0.032	3.8	55	0.055
Tarcento	Torre	62	1892 to 1908	12.5	0.15	0.0	0.15	0.012	8.0	193	0.193
Wetzmann	Gail	324	1883 to 1884	1	0.6	0.0	0.6	0.6	100.0	1852	1.852
					German Federal Republic						
Forggensee	Lech	1,423	1954 to 1965	11	150.0	147.6	2.408	0.219	0.15	154	0.154
Saalachsee*	Saalach	940	1913 to 1960	47	3.5	...	3.644	0.088	2.51	93.6	0.094
Sylvensteinsee	Isar	1,138	1959 to 1966	7	82.0	80.9	1.1	0.170	0.41	149	0.149
					Switzerland						
Kallnach	Aar	1,360	1913 to 1919	6	1.8	0.8	1.0	0.170	9.45	125	0.125
Perolles	Sarine	1,261	1872 to 1886	14	1.0	0.0	1.0	0.071	7.13	56	0.056

*Reservoir flushed.

place within a year, as has happened in the Wetzmann Reservoir [*Orth*, 1934].

Three reservoirs in Germany that we have investigated are situated in the territory of Bavaria in the drainage basin of the upper Danube on the Lech (Forggensee Reservoir), Isar (Sylvensteinsee Reservoir), and Saalach (Saalachsee Reservoir) rivers. These rivers drain the northern slopes of the Alps and are characterized by their high unit flow (>40 l/sec/km²) and the proportionally large volume of rubble transported. Accordingly, the rates of silting observed range from 0.094 mm/yr in Saalachsee to 0.154 mm/yr in Forggensee (Table 1). Here, also, the high silting rates reflect in the intensive material deposits, especially in small reservoirs, e.g., Saalachsee [*Bauer*, 1968; *Bauer and Burz*, 1968].

We come across a similar problem in Switzerland since there is considerable likeness between that country and Austria or southern Germany with regard to their geologic, morphological, and hydrologic features. Silting, or rather the filling up, of small reservoirs with coarse-grained rubble proceeds with a loss of 7–10% of the reservoir capacity in a year [*Orth*, 1934].

CHANGES IN QUANTITY AND TYPE OF DEBRIS ACCUMULATED IN RESERVOIRS

For a certain number of Central European reservoirs, data concerning silting have been based on not one but several surveys, and it has been possible to follow a variation in the process of silting with time. That problem, though widely known in world publications, remains open to investigation because of the sparse number of reservoirs under systematic survey.

Very interesting data on that subject have been published by *Bauer and Burz* [1968] from their studies on silting in the reservoirs of Bavaria, where a gradual fall in silting intensity has been observed; this fall is due not to reduced denudation of a catchment area but to a decreasing storage capacity of a reservoir and consequently a shortened time of water exchange. This phenomenon has been taking place in an apparent form in the relatively small Saalachsee Reservoir, for which mean values calculated for time periods of 15, 24, 37, and 47 years show a distinctly decreasing average yearly silting degree of 5.57–2.51% (Table 2). In two other reservoirs (Forggensee and Sylvensteinsee) the said phenomenon has developed in a milder form, owing to the larger areas of these reservoirs and the relatively less important effects of silting progress. The loss of capacity and the fall in water storage possibilities of reservoirs are connected with certain changes in the mutual relations between the quantity of bed load and suspended silts that are deposited in reservoirs and the sedimentation of the bed load that is basically unchangeable in time and the gradually decreasing sedimentation of suspended silts. A confirmation of the above can be found in the reports on reservoirs in Germany [*Bauer*, 1968; *Bauer and Burz*, 1968]. Debris of the bed load, once deposited in reservoirs, has hardly any chance of leaving them again. Sometimes, however, cases such as the previously mentioned

TABLE 2. Variability of Intensification of Debris Accumulation and of Deposit Composition Following the Progress in Reservoir Silting

Reservoir	Investigation Period	Average Yearly Silting			Material Share, %	
		10^3 m^3	%	m^3/m^2	Suspended Matter	Bed Load
Saalachsee	1913 to 1928	195	5.57	207	64	36
	1913 to 1937	113	3.23	120	44	56
	1913 to 1950	93	2.66	98.9	35	65
	1913 to 1960	88	2.51	93.6	31	69
Sylvensteinsee	1959 to 1961	140	0.34	123	81	19
	1959 to 1963	110	0.27	96.7	80	20
	1959 to 1965	132	0.32	116	70	30
	1959 to 1966	170	0.41	149	69	31
Forggensee	1954 to 1959	330	0.22	232	73	27
	1954 to 1962	260	0.17	183	65	35
	1954 to 1964	217	0.14	153	59	41
	1954 to 1965	219	0.15	154	58	42

Table is adapted from *Bauer* [1968] and *Bauer and Burz* [1968].

Saalachsee Reservoir occur. There, as the result of nearly complete silting, water currents at the time of floods are so strong that, at the open sluices, bed load debris of a grain size of up to 10 mm can be carried out.

Intensity of silting can be affected not only by the decreasing capacity of a reservoir but also by changes in its usage. An interesting example can be furnished by the Porąbka Reservoir in Poland, which was built in 1937 and served as a flood control reservoir until 1953. A power station was built in 1953, and because of the increased storage capacity and reduced velocity of water the amount of accumulated silts has been increased 2.5 times [*Cyberski*, 1970].

However, a decisive influence is exerted by the headwater level on the location of silt deposits in reservoirs, especially at the time when inflowing waters are particularly rich in silt. In analyzing the layout of silt deposits in Rożnów Reservoir, *Cyberski* [1970] stated that the location of the main masses of deposits changed from the small overbalance in the usable zone (51% of the deposits in the usable zone and 49% in the dead zone) at the lower headwater level to an absolutely obvious one (79% of the deposits in the usable zone and 21% in the dead zone) at the higher headwater level.

A separate problem is the accumulation of debris in reservoirs located in a system of cascades. This system is most often characterized by an arrangement of reservoir capacities in decreasing or increasing order downstream. In the first case the highest reservoir takes in the largest quantities of silt, but in the second the deposits of material are distributed in a slightly different way. In a small reservoir that is situated highest, accumulation of bed load will take place, whereas, in the next reservoirs, suspended material will be likely to sediment in quantities depending on the individual cumulative features of the reservoirs. *Brádka* [1966], from surveys carried out on the Vltava River at its inflow to Vranov Reservoir (Czechoslovakia), found that the average yearly turbidity of the river water was 635 g/m^3 in 1935–1943 when there were no other reservoirs above Vranov. In 1943–1954 the Stechowice Reservoir was operating above Vranov, and, as a result, turbidity of the water fell to 300 g/m^3. In 1954–1961, another large reservoir, Slapy, was in operation also. The two reservoirs caused a decrease of water turbidity at the inflow to the Vranov Reservoir to 55 g/m^3.

Very thorough investigations of the Czchow Reservoir (Poland) were carried out in 1950–1962. This reservoir functioned as an equalizing reservoir in respect to the Rożnów Reservoir situated above it. Investigations have shown that silting in Czchow Reservoir is liable to continuous fluctuation. Because most of the debris is deposited in Rożnów Reservoir and only small quantities pass through to Czchow Reservoir (a certain amount also comes from slopes of the catchment area between the two reservoirs), the effect of floodwaters is most favorable, since they flush the Czchow Reservoir intensively by removing from it large quantities of sediment [*Chomiak et al.*, 1969].

In this paper I have attempted to outline the general problem of silting of reservoirs and the method of research on that phenomenon, as well as to present some selected questions concerning processes of accumulation of debris. It has to be assumed that the deposition of silt in reservoirs is, with few exceptions, a process resulting in steady losses of reservoir capacities. The rate of accumulation of debris in water reservoirs depends on many natural and artificial factors, and the mechanism of sedimentation varies considerably at particular objects. There arises then an urgent necessity to carry on further scrupulous research on reservoirs. This research should include not only quantitative surveys but also studies on the quality of the accumulated silts and investigations on much wider bases than those at present of the transportation of river debris and of the abrasion of reservoir banks.

REFERENCES

Bauer, F., Die Verlandung in natürlichen Seen, Talsperren und Flusskraftwerkstreppen, in *Festschrift zu Kongrefs und Austellung*, Wasser, Berlin, 1968.

Bauer, F., and J. Burz, Der Einfluss der Feststofführung alpiner Gewässer auf die Stauraumverlandung und Flussbetteintiefung, *Wasserwirtschaft, 4*, 1968.

Brádka, J., Bilance sedimentu v údolni nádrži, *Vod. Hospod., 1*, 1966.

Chomiak, T., J. Cyberski, and A. Mikulski, Accumulation of debris in water storage reservoirs, *Publ. 96*, PIHM, Warsaw, 1969.

Cyberski, J., Détermination de l'accumulation du transport solide á l'aide de la méthode du bilan du transport solide, *Ass. Int. Hydrol. Sci. Gentbrugge, 2*, 9–15, 1966.

Cyberski, J., Investigations on accumulation of debris in water storage reservoirs in Poland, *Gospod. Wodna, 2*, 1970.

Orth, F., Die Verlandung von Staubecken, *Bautechnik, 12*(26), 1934.

Reservoir Sedimentation Studies

D. C. BONDURANT AND R. H. LIVESEY

U.S. Army Corps of Engineers, Omaha, Nebraska 68101

It must be recognized that, when a reservoir is constructed on a stream, all or most of the sediment transported into the reservoir by the stream will be deposited there. With few exceptions, there is no practical method for reducing or eliminating the sediment inflow; thus it is necessary to anticipate and to provide for the resulting problems. The major problem is, of course, the accumulative loss of storage capacity. Other items of importance include the distribution of the sediment with respect to various storage increments, the effect on the chemical or physical quality of the water, ecological effects, and the possible degradation of the channel downstream.

The prediction of the quantity of sediment that will be transported into the reservoir is largely a matter of experienced judgment. During the past 20 years, there have been many stations established for the measurement of suspended sediment discharge, but the cost of operating these stations is such that they are restricted in number and location to a relatively few index areas or to specific locations where they may be operated for only a few years. Because of the normal variations in the hydrologic cycle a station must usually have a record of 10–30 years (depending on the physical and hydrologic characteristics of the area) in order to provide a dependable average. Since it is seldom that the need for sediment data at a specific location can be predicted that far in advance, it is also seldom that adequate records are available.

In the Missouri River division of the U.S. Army Corps of Engineers we maintain certain index stations continuously. In regions where the sediment discharge is reasonably consistent we operate stations at one location for 5–10 years; then, providing for an overlap of 1 or 2 years, we move to other locations to establish index values for the region. As soon as the need for data at a specific location is known and if the time available for study is adequate, we establish a station at that location.

Finally, we make an extensive ground reconnaissance of the drainage area above the site. Information from this reconnaissance is correlated with all available data from stations measuring suspended sediment discharge from comparable areas and is integrated to derive an estimate of the average annual sediment inflow to be anticipated. It is necessary to add to this estimate some quantity to account for sediments moving along the stream bed and not measured in suspended load sampling. In streams having a coarse gravel bed, this load can be computed with reasonable adequacy by bed load formulas; however, in sand bed streams it is believed that an estimate based on judgment is equally or perhaps more accurate. In small reservoirs the estimate may be reduced to account for sediment that might be transported through the pool, but, where the drainage area contributing to the project is greater than about 250 km^2, the reservoir will normally be large enough to retain all the inflowing sediment. If the project is constructed under the auspices of the federal government, sufficient storage is provided to retain the anticipated sediment load for a 100-year period without encroaching on the primary project purposes.

In some instances it is possible that the storage required for sediment might be reduced by upstream control measures. It has been demonstrated, for example, that the sediment contribution from very small drainage areas (1–5 km^2) can be reduced by about 85% by intensive soil conservation procedures. In another instance, sediment discharge reductions due to improved land management and conservation on a group of drainages varying in size from several hundred to 5000 km^2 were indicated to be 10–35%. This latter study, however, covered a period of only 3 years under the improved regimen and could well have been influenced by favorable hydrologic circumstances.

In general, it is usually found that those portions of the drainage area contributing the greatest proportion of the sediment are the areas where conservation measures are the least justified economically for improvement of the land. As an example of this condition, <15% of the structures proposed in a comprehensive conservation plan for one area have proved to be justified economically. In addition, the installation and continued maintenance of conservation measures depend wholly on the cooperation of the landowners. When it is further considered that there will already be a large quantity of sediment available for erosion in the contributing stream system, the sediment discharge reduction available from upstream conservation will probably be less than the errors inherent in the basic evaluation of the sediment storage requirements. Although conservation benefits to the land itself cannot be denied and flood flow reductions due to upstream structures will undoubtedly be beneficial to a reservoir project, it is unwise, except in rare circumstances, to reduce sediment storage requirements in anticipation of benefits from upstream controls.

In a reservoir where the entire operating storage is reserved for one purpose, the location of the sediment deposited in a reservoir might not be important. In multiple-purpose reservoirs, however, where the storage in varying zones of elevations is reserved for individual purposes such as power production, irrigation, recreation, and flood control, it is desirable to know just how much storage will be lost in each zone owing to sedimentation and what the backwater effect on upstream facilities might be. This effect will depend on several factors such as the characteristics of the sediment, the chemical character of the water, the size and shape of the reservoir, the original stream and valley slopes, and the reservoir operation. As soon as the stream enters the backwater reach above the then existing pool, the largest sediments in transport begin to deposit in the channel. The deposition occurs progressively until, some distance within the pool, all the sand-sized materials are deposited. This progression continues with the silt and, finally, the clay-sized sediments.

If the pool is relatively narrow (not more than 3 or 4 times the normal width of the stream channel), the sand materials will be deposited across the entire width of the pool, and, as the process continues, these deposits will form a delta that gradually extends downstream. Deposition of the silt-sized sediments occurs more or less immediately downstream from the sands, and the deposition of clays occurs either a short distance thereafter or perhaps much farther downstream, depending on the chemical characteristics of the sediment and water.

If the stream enters a wide pool, deposition of the sand sediment tends to progress as a finger, and a submerged channel is formed into the pool. A finite flow will continue along this submerged channel and will result in a reverse circulation in which deposition of a large portion of the silt and clay sediments will occur in that part of the pool adjacent to the sand finger. As the process continues, the sand finger extends to the water surface and forms a surface channel extending into the pool. This channel, possibly as a result of Coriolis forces, tends to follow the western or southern boundary of the pool in the northern hemisphere. Vegetation growing on the banks tends to hold this channel in place; however, a high flow will ultimately breach the channel and will start a new finger. The result is a mixture of clay, silt, and sand intrusions forming a swampy, vegetated area that may contain random pools of open water.

The character of the clay sediments in conjunction with the chemistry of the water plays an important role in the deposition of the clay materials. The active clays, the montmorillonite group, may react with the dissolved salts in the water in a manner such that the particles have a mutual attraction and tend to form clumps of floccules that settle out of the water with relative rapidity. On the other hand, these clays may form a low-density, semifluid mass that may accumulate downstream from the sand delta, may travel through the reservoir as a density flow, or may accumulate immediately at the head of the reservoir. Which of these phenomena will occur is governed by the activity and concentration of the clays, the character and concentration of the dissolved salts in the water, and the slope of the original stream channel and valley. Sediment density flows of any magnitude apparently do not occur with slopes of <0.2 m/km.

The inactive clays, the kaolinite group, do not react as readily as the active clays with the salts in the water, and the particles tend to be mutually repulsive unless they are present in sufficient concentration for mass attraction forces to be dominant. The finer particles may remain in suspension in the reservoir for days or even weeks and thus may maintain turbidity throughout the entire reservoir.

It is only in rare cases that sediment can be evacuated from a reservoir except by mechanical methods, and the use of these methods is seldom within economic reason. It is true that the debris basins used primarily in the western coastal regions of the United States to protect high-value urban areas from sediment and debris are developed to be cleaned by physical removal of the material, but these basins are a separate consideration and normally have no connection with storage reservoirs. In a few instances where openings have been made in existing dams in an attempt to flush out sediment deposits, the only result was the erosion of a deep, narrow channel to the outlet. A few small detention-type reservoirs are known to be self-cleaning, but in these instances the width of the pool is not much greater than that of the original stream channel.

There are instances where the character of the sediment and the water complex is such that density flows can be used to evacuate the reservoirs and maintain storage capacity. Insofar as is known to the authors, these instances are all in Africa, primarily in Algeria. Here, the sediment is permitted to accumulate until it reaches a predetermined density; then outlets specifically provided for the purpose are opened, and the sediment is evacuated with a minimum waste of water. In another instance a subdam at the head of the pool is designed to accumulate water and coarser sediments and then to release the entire mass through the pool. A detailed description of these operations is given in papers presented by H. Duquennois and J. Thevenin and reproduced in the minutes of an international colloquium on dams and reservoirs held at the University of Liege, Liege, Belgium, in May 1959.

In recent years, problems of ecology, water quality, and recreation have assumed major importance in the planning and operation of reservoirs. In many instances the influence of sedimentation on these functions is not completely known; however, there are many ramifications that need to be analyzed. Sediments deposited in relatively shallow areas tend to prevent the reproduction of many of the media on which fish feed or tend to result in a variation of the food pattern such that the growth of one fish species is inhibited and that of another is enhanced. The formation of a delta may block the passage of fish that must travel to the open river upstream for spawning, and at the same time the delta may form a swampy area that provides a desirable habitat for entirely different species of wildlife. Inactive or dispersive-type clays tend to remain in suspension for relatively long periods and spread throughout the reservoir to create a turbid condition. These clays will adhere to the microorganisms forming a part of the fish food cycle and will carry these microorganisms to the bottom as the particles settle; thus the food required for fish life is destroyed.

Sedimentation also plays an important role in the eutrophication processes of lakes and reservoirs. Organic material transported into the pool decomposes; during this process, available oxygen is used, and, at the same time, nutrients are released. These and other nutrients transported by the sediments result in accelerated biological activity and overproduction by both plants and animals within the photosynthetic region. These plants and animals, in turn, die off and accumulate at the bottom where they decompose and start the cycle again. In shallow waters the excessive growth of aquatic plants so generated may completely fill the reservoir; however, within reasonable limits it is beneficial to fish life. Dispersive clays that create a turbid condition in the waters restrict the photosynthesis and thus restrict the biological activity. Such a condition may be desirable for swimming, boating, and other water contact sports for which an accumulation of aquatic growth would be detrimental.

Since sediments provide large surface areas for chemical action, they may contribute significantly to the rapid degradation or detoxification of pollutants. Pollutants attached to sediment particles are not dispersed or transported as readily as dissolved pollutants. Large concentrations may build up in the stream bed or reservoir deposits. These pollutants might be removed from the water environment by burial in the deposits, or they might accumulate and be released into solution by a later significant change in the water chemistry. One of the more beneficial aspects is the removal of pesticides from solution by chemical reaction with clay materials.

The physical effect of a reservoir on the downstream channel is also an important consideration. After deposition of sediment in the reservoir the clear water released through the dam will have an unsatisfied transport capacity that it will attempt to satisfy by eroding the bed and banks of the stream. The total capacity for transport will be substantially reduced, however, because of the elimination of flood flows by reservoir operation. The degree of reduction will vary from 25% to as much as 75%, depending on the relative character of the controlled releases versus the normal flows. It should be noted, however, that in some instances the magnitude of bank caving may be severely increased if the reservoir operation results in sustained periods of near bank-full flow. These sustained periods permit the banks to become saturated, and thus they are more susceptible to caving during sustained periods than during short periods of high flows. The effects of the downstream erosion may include degradation of the channel, possible head cutting in tributaries, damage to downstream bridges or other facilities, and possibly damage to outlet works or hydroelectric power units.

Sedimentology of Whites Creek Delta in Watts Bar Lake, Tennessee

THOMAS R. WORSLEY
Department of Oceanography, University of Washington, Seattle, Washington 98105

JOHN M. DENNISON
Department of Geology, University of North Carolina, Chapel Hill, North Carolina 27514

In 1942 the Tennessee Valley Authority dammed that portion of the Tennessee River that is now Watts Bar Lake. The valleys of tributary streams were partially flooded, so that lacustrine Gilbert-type deltas [*Gilbert,* 1890, pp. 65–70] have been initiated where swift streams flow into the impounded lake. The largest active delta on the navigated segment of the Tennessee River is that of Whites Creek (Figure 1), 6 km (4 miles) southwest of Rockwood, Tennessee. Most of the 310 km² (123 mi²) of the Whites Creek drainage basin lies within the Cumberland plateau province. Whites Creek, the main source of clastics for the delta, leaves the plateau region through a water gap in the Cumberland escarpment and traverses the regional strike of the ridge and valley province until it reaches the upper end of the embayment of Watts Bar Lake where the delta is forming (Figure 2). Whites Creek and its tributaries flow over rocks of successively older ages from Pennsylvanian to Cambrian; the latter is represented by the shaly to silty Rome formation that underlies the delta. The drainage basin is principally eroded into shaly to conglomeratic strata of Pennsylvanian age, so that the delta is formed of a wide size range of clastic particles. Minor clastics are supplied by small streams and gullies in the delta vicinity, such as Smoky Run on the east. The total area of delta and prodelta sedimentation is about 1.8 km² (0.7 mi²).

Sampling was done in 1966–1967. The project was initially a master's thesis by *Worsley* [1967], who sampled 103 sites, determined percent organics, sieved the samples, and calculated moment approximation statistics by using the formulas of *Folk and Ward* [1957]. An additional 29 samples were processed by J. M. Dennison to expand the sample network and to add detail between earlier points. Preliminary results were reported at the 1968 meeting of the southeastern section of the Geological Society of America [*Worsley and Dennison,* 1969].

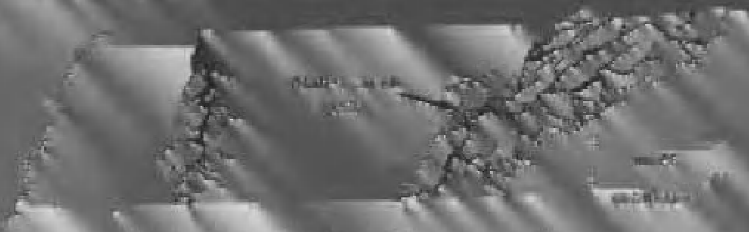
RAINFALL AND LAKE LEVEL CYCLE

Portions of Whites Creek delta are exposed periodically as the water level of Watts Bar Lake fluctuates. This exposure subjects the shallower water sediments to pauses in sedimentation and to drying, winnowing, and extensive oxidation. Mean monthly lake levels were derived for Figure 3 by averaging the published daily water levels for a 17-year period. The water level is about 1.8 meters (6 feet) lower in the winter than at other times of the year. Daily variations, controlled largely by storms, are superimposed on this annual cycle. Man-made lakes used for flood control characteristically exhibit a seasonal fluctuation analogous to slow tides, and such a cycle should produce sedimentary patterns different from those of natural lakes. Daily variations, controlled by reservoir management or affected by storms, are superimposed on this annual cycle.

Figure 3 shows monthly discharge averages for Whites Creek that were computed over a 13-year period ending in 1955, the year the gaging station ceased operation. Greater winter rainfall, coupled with an absence of foliage, results in a maximum stream discharge during the months of lowest water level of Watts Bar Lake.

SAMPLING AND ANALYTICAL PROCEDURES

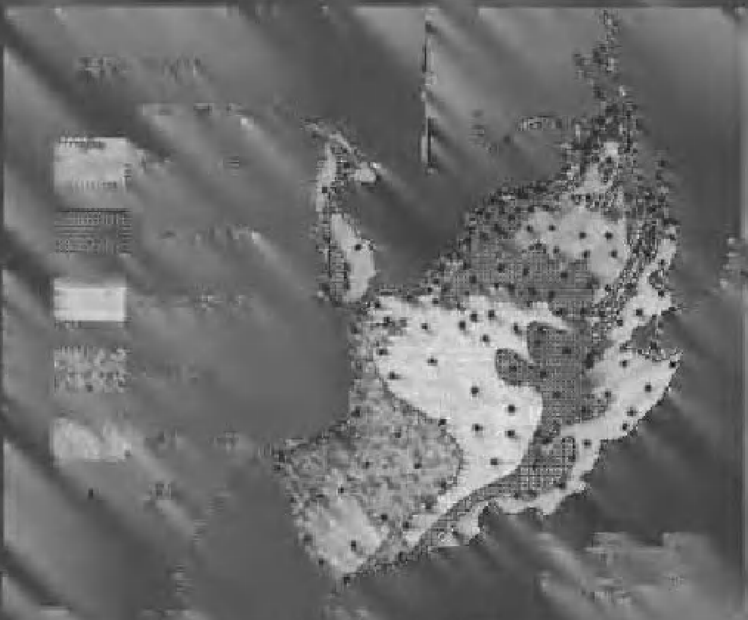
Sediment samples and water depth determinations were taken at 131 sites indicated on Figure 2 and most of the other maps presented in this paper. Depths were all corrected for a water elevation of 226 meters (741 feet), so the isobath map shows average depth in the high-water months of May, June, and July.



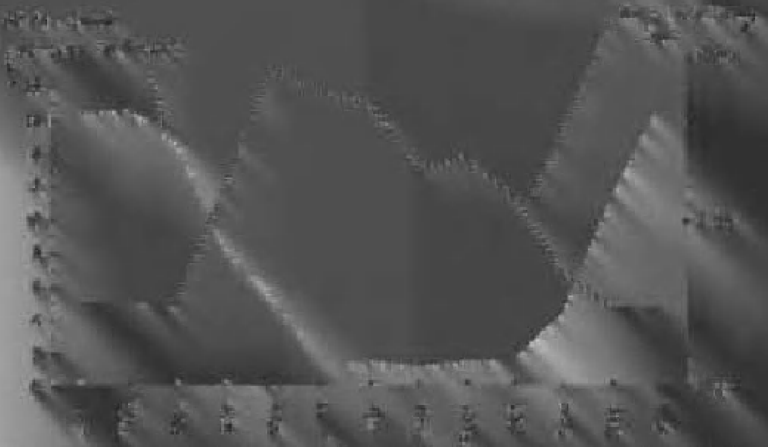
[illegible]

[illegible]

[illegible]



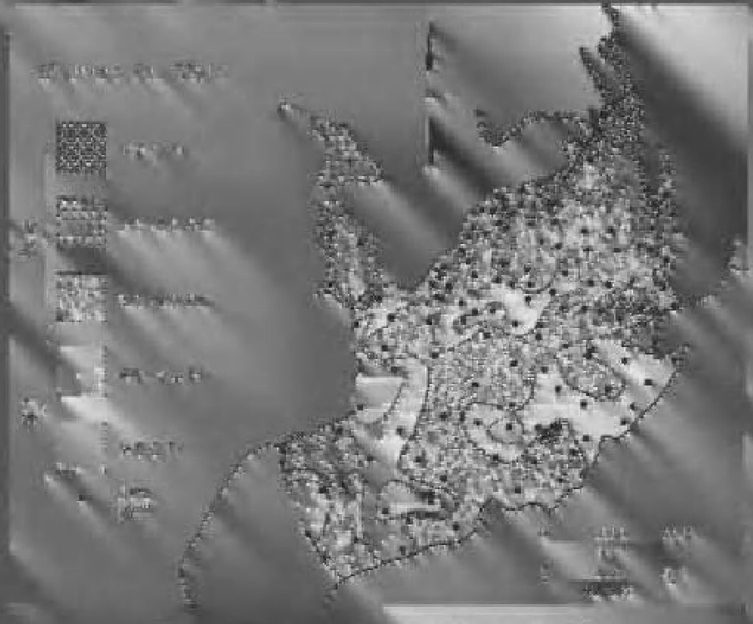
[illegible]



[illegible]

[illegible]

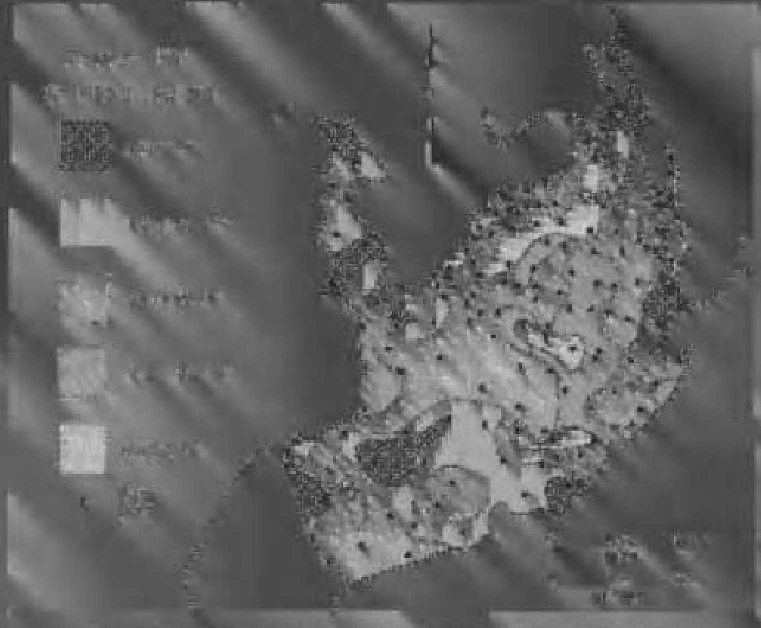
[illegible]



[illegible]

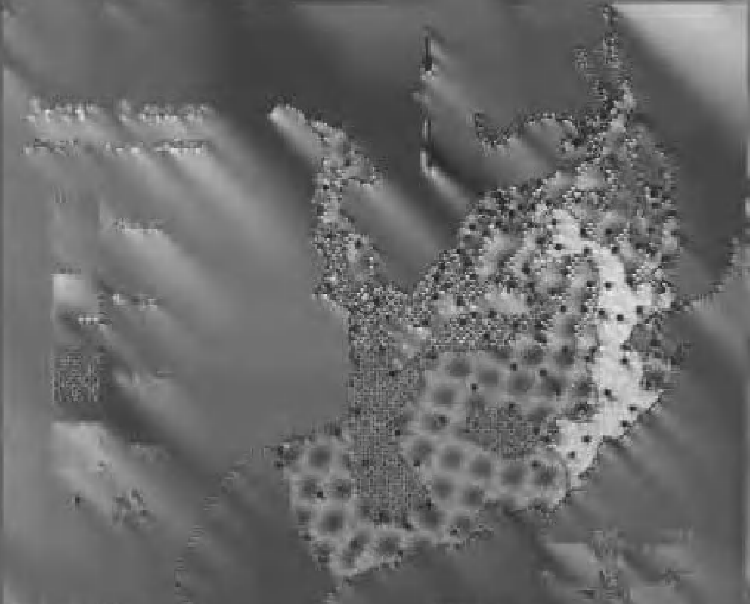
[illegible]

[illegible]



[illegible]

[illegible]



[illegible]

High organic content is associated with finer sediments in deep water (where oxidation is inhibited) and to a lesser degree with areas receiving such rapid sedimentation that organic decay is incomplete. Shallow areas have diminished organic content because the relatively buoyant organic matter of the agitated sediment was either removed to deeper water or pulverized and then oxidized. This distribution of organic material should greatly affect oxygen and nutrients available for life on, in, and above the delta sediments and should be a major factor in the ecological system.

Figure 8 shows trends of organic content ver-

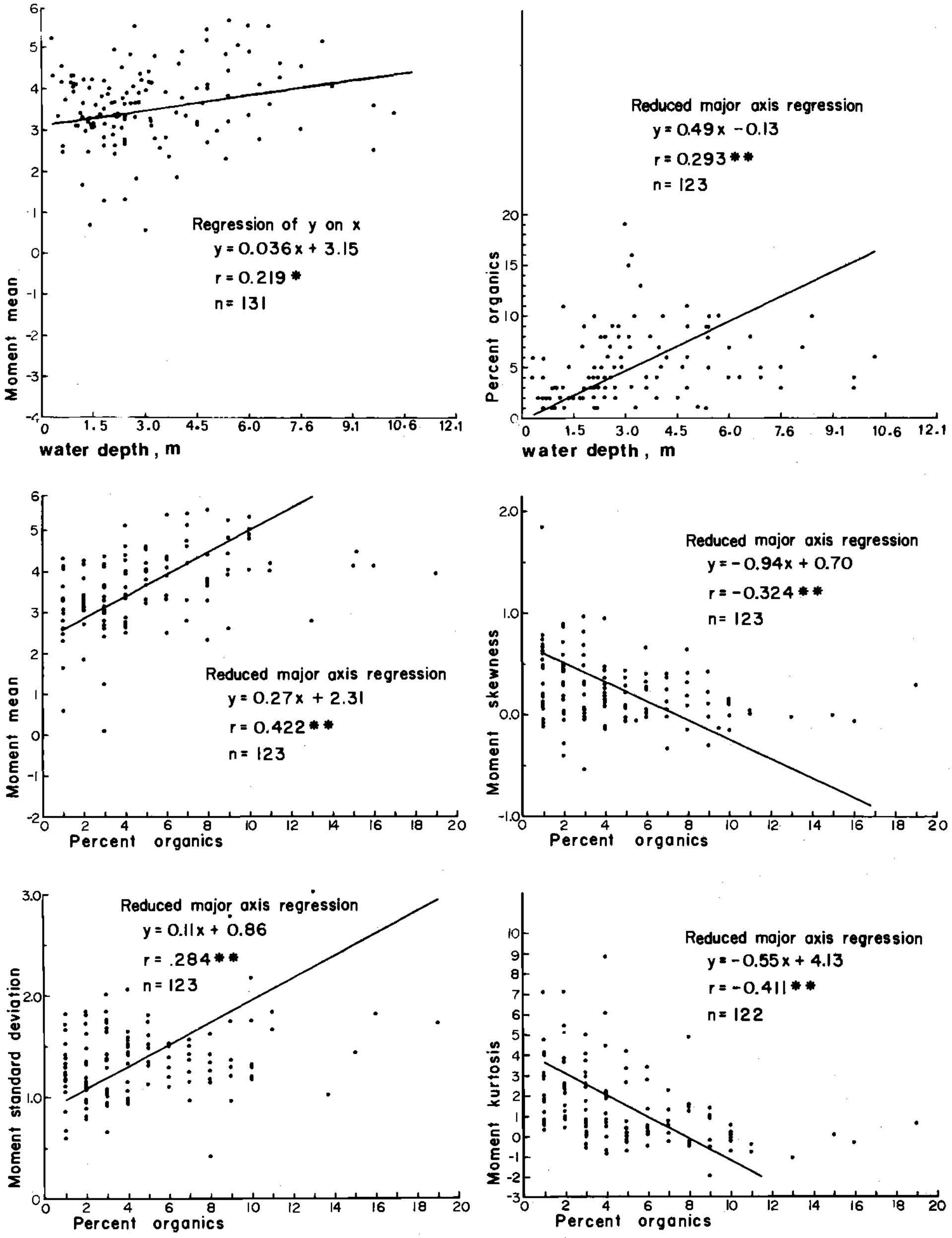
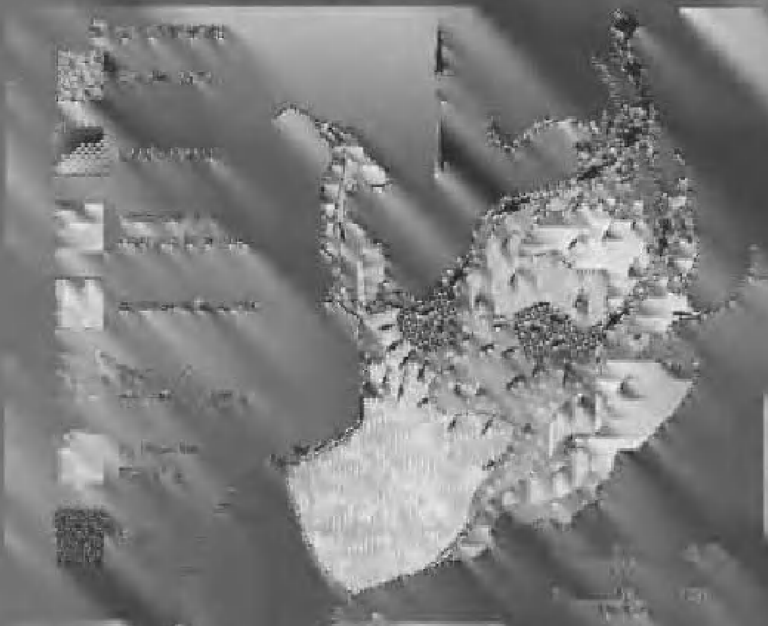


Fig. 8. Statistical trends among parameters. The single asterisk indicates correlation significant at 95% confidence level, and the double asterisk indicates 99% confidence level.



cumulating sediments are fine suspended muds. These would be analogous to distal prodelta muds of marine deltas.

The large inlet on the west side of the Whites Creek embayment is not supplied by many clastics, so that inlet is affected by the annual winnowing process but not by active delta sedimentation. The inlet is well suited for its present use as a marina. The small stream entering the east side of Whites Creek delta produces a minor imprint on the sediment pattern.

Although it is geologically rapid, the growth of Whites Creek delta is slow enough not to endanger the navigation channel of the Tennessee River even after the passage of several centuries. Sediments deposited by the delta do alter the lake substratum and turbidity characteristics in this area of Watts Bar Lake. The ecological relationships of these sedimentary patterns to the biota should be studied.

Acknowledgments. Helen Worsley and Melvin Phipps assisted with the field sampling. William Frank, David Best, and James Hu gave generously of their time with computer problems. Robert W., Johnson, Jr., geologist with the Tennessee Valley Authority, made available lake level and rainfall data and historical background of Watts Bar Lake. The study was partially financed by the University of North Carolina Research Council and the Quaternary Research Center at the University of Washington.

REFERENCES

Bouyoucos, G. J., A sensitive hydrometer for determining small amounts of clay or colloids in soils, *Soil Sci., 44,* 245–246, 1937.

Folk, R. L., and W. C. Ward, Brazos River bar: A study in the significance of grain size parameters, *J. Sediment. Petrology, 27,* 3–26, 1957.

Gilbert, G. K., *Lake Bonneville, Monogr. 1,* 438 pp., U.S. Geological Survey, Washington, D. C., 1890.

Imbrie, J., Biometrical methods in the study of invertebrate fossils, *Bull. Amer. Mus. Natur. Hist., 108,* 213–252, 1956.

Krumbein, W. C., Size frequency distributions of sediments, *J. Sediment. Petrology, 4,* 65–77, 1934.

Krumbein, W. C., and F. J. Pettijohn, *Manual of Sedimentary Petrography,* 549 pp., Appleton-Century-Crofts, New York, 1938.

Worsley, T. W., The sedimentology of Whites Creek delta in Watts Bar Lake, Tennessee, M.S. thesis, Univ. of Tenn., Knoxville, 1967.

Worsley, T. W., and J. M. Dennison, Sedimentology of Whites Creek delta in Watts Bar Lake, Tennessee, *Geol. Soc. Amer. Spec. Pap., 121,* 476, 1969.

Sediment Studies Pertaining to Small-Reservoir Design

JOHN W. ROEHL AND JOHN N. HOLEMAN
USDA Soil Conservation Service, Washington, D. C. 20250

Sediment has been a problem to man since he first began to alter natural conditions. When European man settled in eastern North America, he cleared forest land to grow crops. Since no concern was given to protection of the soil, these fields produced increasing amounts of sediment to downstream areas along with the crops. Where dams were erected across streams (such as for water supply and hydraulic power reserves for mills), sediment accumulated along with the water. In time the water was used or moved on, but the sediment remained. Thus storage space for water supplies was depleted, and without the water reserves the mill wheels became entirely dependent on streamflow for the energy to turn the machinery.

For many years, engineers have recognized sediment problems in certain water supply reservoirs as well as in reservoirs constructed for power, flood control, irrigation, recreation, and other uses. In general, however, the important problem of loss of storage capacity by sediment deposition received little consideration in the development and maintenance of impounding reservoirs in the United States before 1930.

Agricultural specialists, on the other hand, have long recognized that deforestation, forest fires, overgrazing, cultivation of oversteep slopes, improper methods of tillage, and other unwise agricultural practices greatly accelerate soil erosion and result in large increases in the sediment load of many streams.

The relation of accelerated soil erosion to high rates of sediment accumulation in reservoirs has long been recognized by some, but not until about 1935 was the damage to our reservoirs perceived to be sufficiently critical to initiate government studies and programs. In 1935 the U.S. Congress created the Soil Conservation Service (SCS) as a permanent agency of the U.S. Department of Agriculture in order 'to provide permanently for the control and prevention of soil erosion and thereby to preserve natural resources, control floods, prevent impairment of reservoirs,' and so on. To conduct the research provided for in this act, the SCS established a sedimentation division to determine the character and extent of downstream damages resulting from soil washed from upland slopes and the nature and location of control measures required to ameliorate these damages. Reservoir sedimentation was one of the principal problems investigated by this division. The study of this problem included making an inventory of the reservoir resources of the United States, determining by surveys of representative reservoirs the amount and rate of sediment accumulation, establishing the relation of sediment deposition to soil erosion and to the transportation of sediment within the watershed, and considering the methods available for combating sediment damage [*Brown*, 1941].

Sedimentation surveys of lakes and reservoirs have been made by the SCS through the years in conjunction with municipalities, cooperators, and various organizations. A benefit of these surveys has been to obtain more accurate sediment yield data for use in the design of small reservoirs.

In November 1953 the U.S. Department of Agriculture was reorganized, and all soil conservation research administered by the SCS except investigations required for national soil survey was transferred from the SCS to the Agricultural Research Service (ARS). Since then, SCS investigations, studies, and collection and analysis of basic sedimentation data have been undertaken or continued only if they were considered a necessary part of active SCS programs.

Periodically, the sedimentation committee of the Water Resources Council has published summaries of the reservoir sedimentation surveys made in the United States. The latest summary [*U.S. Department of Agriculture*, 1969] lists 1200 reservoirs reported by nine federal and state agencies. Two-thirds of these reservoirs were reported by the SCS. Valuable data listed include reservoir location, drainage area, capacity at various times, volume-weight ratio of sediment, and average annual sediment accumulation rate. All these items need consideration in reservoir design.

The expanding and accelerating programs of watershed protection and flood prevention administered by the SCS have required the collection of basic data and special studies to improve sediment design criteria for small reservoirs. Since 1944 the SCS has designed and constructed some 5255 small floodwater-retarding and multiple-purpose reservoirs and is continuing this construction at the rate of about 260 such structures a year.

PROBLEMS OF RESERVOIR DESIGN

Small reservoirs, as defined for this paper, are those not exceeding 30,850,000 m^3 (25,000 acre-feet) in capacity. This size is also the maximum capacity specified in the Watershed Protection and Flood Prevention Act [*U.S. Congress*, 1954] as amended [*U.S. Congress*, 1956]. Those reservoirs designed and built by the SCS in its watershed protection and flood prevention programs have varied from several thousand cubic meters to nearly the maximum of 30,850,000 m^3 (25,000 acre-feet). An analysis of watershed work plans developed under the Watershed Protection and Flood Prevention Act, approved through June 1969, indicates an average fill per structure of 111,325 m^3 (145,600 yd^3) and a capacity of about 1,604,200 m^3 (1300 acre-feet).

A typical floodwater-retarding structure consists of an earth-fill dam designed to create a reservoir that will temporarily store flood flows. The stored water is released at a relatively uniform predetermined rate through a closed pressure conduit principal spillway. Rare flood events that may exceed the combined capacities of the reservoir and the principal spillway are passed through a vegetated emergency spillway. The reservoir is designed to be fully effective over a selected period; additional storage must be provided for the estimated accumulation of sediment.

Whenever a dam is planned for construction on a natural waterway, the sediment normally carried in the stream immediately creates problems. Among these are the loss of capacity, the quality of the water impounded, the effect of less sediment in the reservoir outflow, and many others.

Among the effects of sediment that concern the designer of a reservoir are (1) the sediment yield (which may be highly variable in a small watershed, i.e., from 2.6 to 65 km^2, or 1 to 20 or 25 mi^2), (2) the expected volume weight of the deposited sediment (which varies by grain size distribution of the sediment as well as the environment of deposition, i.e., submerged or aerated), (3) the locations in the reservoir basin where the sediment will deposit (dependent on particle size, magnitude of the sediment yield, shape of the reservoir basin, topography of the reservoir flood, and others), and (4) the trap efficiency of the reservoir (dependent on factors discussed later in this paper).

CURRENT STUDIES

Being cognizant of these problems, several agencies have carried or are currently carrying out studies. Several sediment studies relating to small reservoir design are under way in the ARS. For example, much has been learned about the measurement of the volume-weight ratio of reservoir sediment with gamma probes by R. McHenry and others at the U. S. Department of Agriculture Sedimentation Laboratory, Oxford, Mississippi. At Columbia, Missouri, *Rausch and Heinemann* [1969] are studying small reservoirs in terms of sediment distribution, density currents, thermal stratification, eutrophication, trap efficiency, sediment yield, volume-weight ratio of sediment, and improved instrumentation.

In June 1969 the SCS instituted a program for the systematic sedimentation surveys of structures designed by the SCS. Reservoirs have been selected to be representative of groups of major land resource areas or, in effect, the various physiographic sections. This long-term study will attempt to correlate the watershed conditions with the quantity and quality of sediment deposited in the reservoir. It is anticipated that information will be obtained to show the value of land treatment, land stabilization, and structural measures in reducing sediment yield and to provide data for improving structural design for small earth-fill dams.

TRAP EFFICIENCY STUDY

Of particular interest here is the cooperative study concerning reservoir trap efficiency. Realiz-

TABLE 1. Summary of Information for Trap Efficiency Study

Reservoir	State	Land Resource Area	Drainage Area		Total Original Capacity		Trap Efficiency, %		Years of Record	Remarks
			km^2	mi^2	10^3 m^3	ac ft	Range	For the Period of Record		
Salem Fork 11A	W. Va.	central Allegheny plateau	0.75	0.288	65.4	53.00	77.6 to 92.7	87.8	7.75	
Double Creek 5	Okla.	Cherokee plains	6.19	2.39	922.3	747.4	93.6 to 93.8	93.7	13.6	
Brownell 1	Nebr.	Nebraska and Kansas loess drift hills	1.99	0.77	153.8	124.6	91.6 to 95.5	93.2	12.25	
Brownell 1A	Nebr.	Nebraska and Kansas loess drift hills	0.51	0.195	4.8	3.90	34.1 to 73.2	57.8	12.5	
Escondido 1	Tex.	Rio Grande plain	7.80	3.01	1141.1	924.7	...	98.6	9.75	
Third Creek 7A	N. C.	southern piedmont	12.54	4.84	1186.4	961.4	96.6 to 84.9	81.7	11.08	
North Fork, Broad River 14	Ga.	southern piedmont	3.11	1.20	346.9	281.1	78.9 to 85.5	82.5	9.08	
Kiowa Creek K-79	Colo.	central high plains	8.29	3.20	159.9	129.6	65.5 to 96.6	81.9	9.17	dry reservoir
Plum Creek 4	Ky.	Kentucky bluegrass	3.88	1.50	493.7	400.1	90.4 to 99.5	92.8	8.17	
Upper Hocking 1	Ohio	western Allegheny plateau	2.75	1.06	537.4	435.5	...	87.7	5.75	
Bernalillo 1	N. Mex.	Arizona and New Mexico Mountains	10.62	4.10	383.3	310.6	...	94.4	8.00	dry reservoir
Six Mile Creek 6	Ark.	Cherokee prairies	10.72	4.14	1609.0	1303.9	...	93.1	7.25	
Upper Peavine	Nev.	Carson basin and mountains	7.02	2.71	372.3	301.7	...	88.2	4.00	dry reservoir
Mill Canyon-Sage Flat	Utah	Wasatch and Uinta mountains	55.94	21.6	249.3	202.0	...	65.3	2.00	dry reservoir

TABLE 1. (continued)

Reservoir	State	Land Resource Area	Drainage Area		Total Original Capacity		Trap Efficiency, %		Years of Record	Remarks
			km^2	mi^2	10^3 m^3	ac ft	Range	For the Period of Record		
Tortugas Arroyo 1	N. Mex.	southern desertic basins, plains, and mountains	53.61	20.7	1634.3	1324.4	...	...	...	no outflow data, established 1963
Frye Creek 3	Ariz.	southeastern Arizona basin and range	67.34	26.0	2700.0	2187.7	...	90.9	3.42	dry reservoir
Highland Creek	Calif.	central California valleys	35.22	13.6	3994.7	3237.2	...	...	...	established 1965
Rock Creek 1	Md.	northern piedmont	31.68	12.23	5217.4	4228	...	...	...	established 1965

ing the need for basic information helpful in the design of small floodwater-retarding reservoirs, the SCS in 1954 initiated a study to obtain basic data on trap efficiency until more exhaustive studies could be completed by research agencies. The U.S. Geological Survey and the ARS agreed to cooperate with the SCS in the study, and this paper will briefly outline the type of study initiated, how it is being carried out, and some preliminary results.

In reservoir design the volume of the sediment expected to accumulate in the reservoir will depend on what portion of the sediment yield will be stored. Thus an estimate of the trap efficiency of the reservoir is essential for design considerations.

Trap efficiency is defined as the percentage of the sediment yield reaching a reservoir that is retained there. The cooperative study was designed to measure the amount of sediment accumulated in a reservoir and the amount of sediment passed through it during the same period of time. The sum of these two items is the total sediment yield, and it is then a simple matter to calculate trap efficiency. Some of the factors that were felt to have an influence on the trap efficiency were also made a part of the data collection program. These other factors include the nature and character of inflow, detention storage time, character of the sediment, physical dimensions of the reservoir, reservoir operation, and perhaps others.

Although it was realized at the outset that natural events require a long time period for meaningful data collection, it was felt that the simplest way of measuring the effects of the parameters thought to influence trap efficiency was through the selection of sites in diverse sections of the country. Different conditions of runoff, sediment, water quality, and other relevant factors were thus represented by the sampling sites.

Twenty reservoirs have been included in the study since its inception. Measurements at several of the structures were discontinued shortly after installation due to a variety of reasons. The collection of data on 11 of the reservoirs has been terminated, as it is believed that the information to be gathered is reasonably complete. Seven stations are still active, and it is anticipated that measurements will continue for some time in the future.

The U.S. Geological Survey measures the sediment discharged through the structures and reports the information in tons per day. In addition to this determination of amounts of sediment, information concerning particle size distribution of the sediment and chemical analysis of the native water are determined. Periodically, samples of the inflow are obtained for information concerning the character of the inflow water and sediment.

The ARS or SCS makes the measurement of sediment deposited in the reservoirs. These surveys are made periodically, and in addition to this measurement of sediment volume the specific weight and particle size distribution of the sediment are determined.

With these data, trap efficiency of a reservoir for a given period is computed by dividing the tons of sediment deposited in the reservoir by the sum of the tons of sediment deposited and the tons discharged during the same period. More than one deposition survey has been made on most of the reservoirs. Thus it has been possible to determine the trap efficiency of each reservoir for several different time periods.

There have been variations in the trap efficiency of a given reservoir for different time periods (see Table 1). Five of the 15 reservoirs listed in the table are dry reservoirs; i.e., they have outlets at the base of the dam so that water is not held permanently. Since all of the water is released in a matter of days, it has been expected that less sediment would be trapped in dry reservoirs than in reservoirs with permanent pools. The short record of these five reservoirs shows a higher trap efficiency than might be expected for dry conditions, ranging from 65 to 94% with an average of 84%.

The normally ponded reservoirs in the table have had a short-term trap efficiency ranging from 34.1% at Brownell 1A for a 3-year period up to 99.5% at Plum Creek 4 during 1 year. The reasons for the variations are not clearly understood as yet but are the object of further analysis.

The SCS has long used the capacity-inflow ratio as an indicator of trap efficiency. The concept of this relationship apparently is still valid, although the variation is such that factors other than the capacity-inflow ratio exert considerable influence. The ARS currently is analyzing the data collected, and, hopefully, additional definitive factors will emerge from the study.

REFERENCES

Brown, C. B., Factors in the control of reservoir silting, *J. Amer. Water Works Ass., 33*(6), 1022–1040, 1941.

Rausch, D. L., and H. G. Heinemann, Sedimentation and eutrophication research on three small reservoirs, *Publ. ARS-41-158,* 11 pp., U.S. Dep. of Agr., Agr. Res. Serv., Washington, D. C., 1969.

U.S. Congress, Watershed Protection and Flood Prevention Act, *Public Law 83-566* (68 Statute 66), 83rd Congress, 2nd Session, August 4, 1954.

U.S. Congress, Watershed Protection and Flood Prevention Act Amendment, *Public Law 84-1018* (70 Statute 1088), 84th Congress, 2nd Session, August 7, 1956.

U.S. Department of Agriculture, Summary of reservoir sediment deposition surveys made in the United States through 1965, *U.S. Dep. Agr. Misc. Publ., 1143*, 64 pp., 1969.

Sediment and Nutrient Research on Selected Corn Belt Reservoirs

H. G. HEINEMANN

USDA North Central Watershed Research Center, Columbia, Missouri 65201

R. F. HOLT

USDA North Central Soil Conservation Research Center, Morris, Minnesota 56267

D. L. RAUSCH

USDA North Central Watershed Research Center, Columbia, Missouri 65201

The U.S. Department of Agriculture conducts research to reduce pollution and to protect our environment. As a part of this research the department is vitally interested in agriculture's effect on the quality of water in reservoirs. Reservoirs are collecting points for water and sediment and are therefore logical places at which to obtain the data needed to evaluate the quality of water that moves downstream. We are studying the sediment and nutrient characteristics in several Missouri and Minnesota reservoirs. These two states are located in the corn belt area, which uses approximately one-half of the fertilizer applied in the United States.

This report gives the results of our research to date. The first section presents data on the disposition of sediment and plant nutrients in two small Missouri reservoirs below cultivated watersheds. The second part presents complementary data on the source and disposition of nutrients in several Minnesota lakes surrounded by agricultural watersheds. In the second part we also give an example of the maximum ratio of watershed area to reservoir water volume required to keep the soluble phosphorus concentration below the threshold value for prolific algae growth.

MISSOURI RESERVOIRS

Physical data. The Missouri reservoirs are on watersheds with cultivated crops and will continue to fill with sediment. A continuation of this study will enable us to obtain information on how reservoirs function for a range of remaining capacities. Data on the two small reservoirs near Columbia, Missouri, that have been studied since 1968 are given in Table 1. We consider the characteristics of these reservoirs to be typical of those constructed in the area. Both reservoirs have watershed soil texture classified as clay loam to silt loam.

Instrumentation. Instruments were installed to obtain the following:

1. On the main tributary flowing into the reservoirs, runoff stage and velocity measurements were made to obtain stream inflow, samples of inflow were collected to determine sediment concentration, and samples of inflow were also collected to quantify and characterize nutrient content.
2. On the reservoirs, samples of the water were collected to determine nutrient forms and concentrations. During sedimentation surveys of the reservoirs, volume and volume-weight of sediment deposits were calculated, samples were collected to obtain particle size distribution and characterization of deposited sediment, and samples were collected to obtain form and concentration of nutrients.
3. At the spillways, water stages were recorded to compute outflow, samples of outflow were collected to determine sediment concentration, and samples of outflow were also collected to quantify and characterize nutrient outflow.

The water stages and the sampling equipment on the main tributaries and at the spillways were automatic and were designed to function un-

TABLE 1. Physical Data of Bailey and Callahan Reservoirs and Their Watersheds

	Bailey	Callahan
Surface area, hectares	4 (5)	9 (28)
Capacity, m^3	69,000 (114,700)	228,200 (1,254,500)
Maximum water depth, meters	4.4 (5.3)	5.7 (11.5)
Average width, meters	88	73
Date of construction, year	1965	1967
Drainage area, hectares	95	1457

Numbers in parentheses apply to the reservoir at emergency spillway elevations.

attended. The sampling rate varied with stage in each case.

The reservoir water was sampled weekly and after each runoff event. The reservoir sediment was sampled at the time of the biennial sedimentation survey of the reservoirs. These samples were used to determine the particle size distribution, volume and weight, and specific gravity of the deposited sediment. The sedimentation surveys were made in accordance with the accepted procedures outlined by *Rausch and Heinemann* [1968].

Trapping of sediment. The trap efficiency of a reservoir is a measure of the reservoir's ability to retain the incoming sediment. It is the difference between sediment yield into the reservoir and sediment discharge from the reservoir, divided by the sediment yield into the reservoir.

Trap efficiency was determined for 18 storms during 1969 and for six storms during 1970 on the Callahan Reservoir and for 10 storms during 1969 on the Bailey Reservoir. The 1969 Callahan trap efficiency values ranged from 75 to 100%, and the 1970 values ranged from 80 to 99%. The 1969 Bailey values ranged from 33 to 99%.

Trap efficiency was inversely related to the volume of storm runoff and varied with season. This variation was due to differences in ground cover and rainfall intensity at different times of the year. Bare land and high-intensity rainfall caused erosion of larger particles of soil, which settled out faster in the reservoirs and increased the trap efficiency. Furthermore, a large suspended sediment load from a storm on October 10 and 11, 1969 (already in the reservoir at the beginning of another runoff event on October 12 and 13), was carried to the spillway. The result was a 33% trap efficiency value for the October 12 and 13, 1969, storm on Bailey Reservoir.

Nutrients. Nutrient data have been analyzed for the Callahan Reservoir only for the period from January 1969 through June 1970. These data show that the highest nutrient inflow occurred during the spring after the application of fertilizer to the contributing area and during high runoff (Figure 1).

In 1969, more than one-half the nitrate (NO_3-N) inflow occurred during the first one-third of the annual runoff. The nitrate inflows in 1970 were greater because of more runoff in April and May and because of a higher concentration of nitrate in the runoff. Ammonium (NH_4-N) in the inflow was more concentrated in July and September 1969. During this period, one-half the ammonium flowed into the reservoir, whereas only one-fourth of the annual runoff occurred. Total (Kjeldahl) nitrogen inflow from the 1214-ha watershed was 33.2 kg/ha for 1969.

Phosphorus inflows (that attached to sediment plus that in the solution) were also highest in the spring, one-third of the total phosphorus in 1969 occurring during the first storm in April (1.98 cm of runoff). The rate of total phosphorus inflow to Callahan Reservoir during 1969 increased with stream discharge and is shown in Figure 2. The concentrations were lower in the fall than in the spring and summer. Total phosphorus inflow during 1969 was 2.7 kg/ha.

Nitrate and ammonium discharges from the Callahan Reservoir were approximately equal to their respective inflows. Total nitrogen discharge from the reservoir was approximately 80% of its inflow, since some of the nitrogen in organic matter was deposited in the reservoir. Total phosphorus discharged from the reservoir was 44% of the total phosphorus inflow, and the remaining 56% was deposited with sediment in the reservoir.

The average trap efficiency of sediment for 1969 was 84%; in other words, 16% of the sediment passed through the reservoir and was associated with 44% of the total phosphorus, which was also discharged. These percentages were not equal, because the sediment passing through the reservoir was finer than the average incoming sediment and therefore could adsorb more phosphorus per unit weight of sediment.

More nutrients remained in the reservoir after each storm than are normally required for algae growth. Nitrate averaged 0.94 ppm, and the orthophosphate averaged 0.07 ppm for the year. Nitrate had decreased to 0.01 ppm by September 3, and orthophosphate had decreased to 0.01

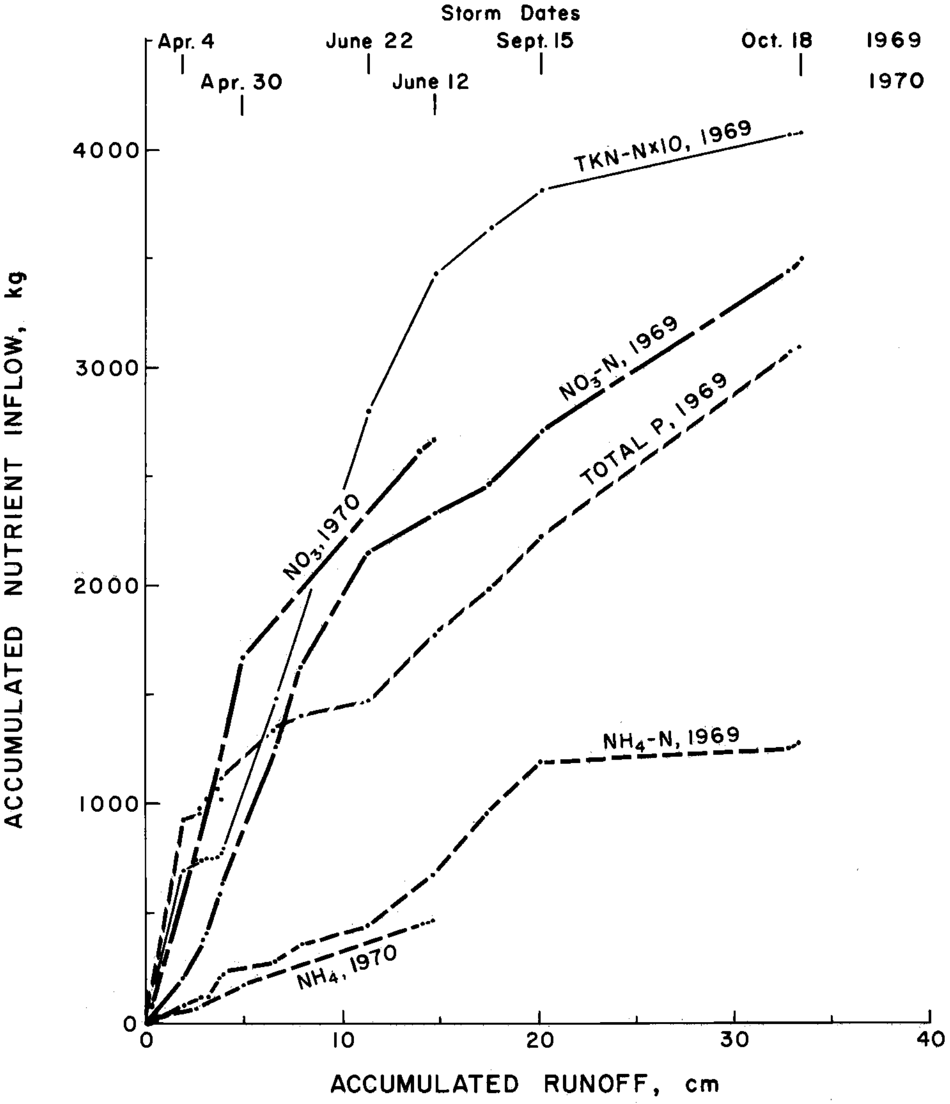


Fig. 1. Comparison of yearly accumulations of nutrient inflow with runoff volume.

ppm by June 25. These decreases were probably due to adsorption of orthophosphate by the sediment and use of these nutrients by algae, although no algae growth was visible. Algae 'blooms' were probably prevented by the high turbidity caused by suspended sediment. Data were insufficient to detect changes in the forms of the nitrogen and phosphorus when they were in the reservoir.

SEDIMENTS: MINNESOTA RESERVOIRS

Surface drainage from agricultural lands is a major source of the water found in natural lakes and man-made reservoirs throughout the uplands of the corn belt. The land use practices on the upland runoff-contributing areas significantly influence the sediment yield and the quality of water that enters these reservoirs.

For a better understanding of the nutrient content of small lakes and reservoirs, we present data on the effect of crop management on the nutrient content of runoff waters and on the influence of sediment on the nutrient content of some lakes in Minnesota. The list below [*Mutchler*, 1970] exemplifies the well-known benefits of a vegetative

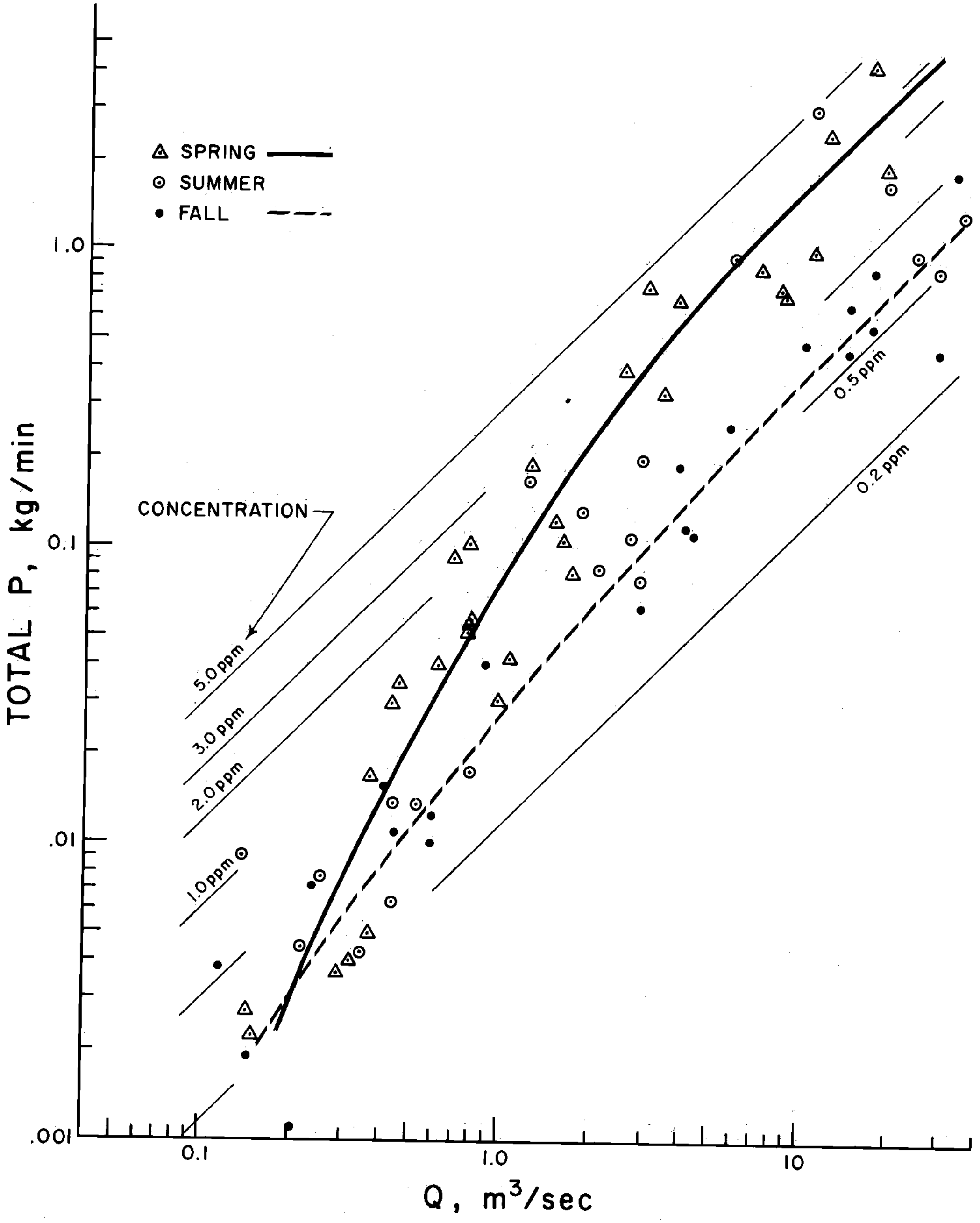


Fig. 2. Effect of stream discharge Q on the rate of total phosphorus inflow into Callahan Reservoir, 1969.

cover in controlling sediment yield to surface-water supplies. Eight-year averages for the soil loss from small plots (Barnes loam soil with 6% slope) under natural rainfall ranged from 38 metric tons/ha/yr for continuous fallow to no loss for the hay plots in a corn-oats-hay rotation:

Cropping Treatment	Soil Loss, metric tons/ha
Continuous fallow	38
Continuous corn	16
Rotation corn	7
Rotation oats	4
Rotation hay	0

Total nitrogen, fluoride-extractable phosphorus, and exchangeable potassium decreased in the sediment carried off the fallow plots over the 8-year period; these nutrients remained at a higher level in sediment from rotation plots. However, the high sediment yield from land unprotected by vegetative cover brings a larger quantity of nutrients than the generally high concentration of nutrients in solids and in water coming from plots under better management.

NUTRIENTS: MINNESOTA RESERVOIRS

Consideration of the influence of sediment in surface waters on the nutrient status of the receiving body prompted a laboratory study of the equilibrium between orthophosphate ions and lake bottom sediments in two eutrophic lakes in the area (Table 2) [*Latterell et al.*, 1971]. The adsorption capacity of sediment from two Minnesota lakes was determined by adding two known concentrations of soluble orthophosphate in solution to a given amount of sediment. The mixture was gently shaken for 2 hours, and the soluble orthophosphate content of the filtered solution was determined. The initial concentrations of added orthophosphate were 8.2 and 42.0 ppm; after equilibration the total orthophosphate in solution was in the range of 0.02–0.05 ppm, indicating that the sediments had a high capability of removing orthophosphate from solution.

TABLE 2. Orthophosphate Concentrations of Solutions in Equilibrium with Lake Bottom Sediments

Sediment Source	Concentration of Solution in Equilibrium with Sediment, ppm P	
	Orthophosphate	Total
	C = 8.2 ppm*	
Norway Lake	0.01	0.10
Big Stone Lake		
Location HB	0.03	0.07
Location O	0.01	0.02
	C = 42.0 ppm*	
Norway Lake	0.02	0.11
Big Stone Lake		
Location HB	0.05	0.07
Location O	0.03	0.05

**C*, concentration of the added orthophosphate solution.

On the basis of this information and the characteristics of the soils in the corn belt, we determined that sediment delivered to reservoirs or lakes is not a major contributor to the soluble orthophosphate content of these waters. In fact, in some instances, it may reduce the dissolved orthophosphate levels. However, there is a rapid equilibrium between water and sediment, and this system could supply phosphorus to a living organism capable of extracting the phosphorus below the equilibrium value. Any mechanism that will suspend deposited sediment in water may therefore increase the availability of dissolved orthophosphate, particularly if reduced iron phosphates in the deposited sediments are suspended.

Surface runoff contained small but measurable amounts of dissolved nutrients. The quantity of nutrients transported to surface water supplies (computed from the total volume of runoff and the concentration of nutrients in the water) varied with the cropping practice on the land (Table 3). Hay land supplied the greatest amounts of total soluble nitrogen to the runoff waters, and fallow land contributed the most nitrate-nitrogen. It is significant that the fallow land did not receive fertilizer during the study period and that the hay plots received no fertilizer during the year they were cropped to alfalfa. The other plots were fertilized the year the measurements were made. The large contribution of soluble nitrogen and orthophosphate by snowmelt runoff from hay fields was due to leaching from plant tissue damaged by freezing. This finding was substantiated by laboratory leaching of frozen vegetation [*Timmons et al.*, 1970].

The maximum phosphorus level of a reservoir is a function of the concentration of inflow, the watershed contributing area, the volume of the lake or reservoir, the evaporation, and the detention time in the reservoir. On the basis of several years of field studies, agricultural land in 50% corn, 25% small grain, and 25% hay (under conditions negating any fertilizer effect) contributed to a lake or reservoir an average of 0.08 kg of soluble orthophosphate per hectare per year. If evaporation is ignored and if (1) a 1-year detention time in the reservoir is used and (2) a dissolved orthophosphate level of 0.03 ppm is the point at which an algae bloom is promoted, then the ratio of watershed area to the volume of water in the reservoir needed to stay below the

TABLE 3. Nitrogen and Orthophosphate Losses in Runoff from Plots in Different Crops

Cropping Treatment	Applied Fertilizer, kg/ha/yr		Nitrogen, kg/ha/yr		Orthophosphate, kg/ha/yr	
	Nitrogen	Phosphorus	Snowmelt	Rainfall	Snowmelt	Rainfall
Continuous fallow	0	0	1.80	0.74	0.02	0.02
Continuous corn	112	29	0.66	0.35	0.02	0.04
Rotation corn	56	29	0.64	0.18	0.03	0.02
Rotation oats	18	29	1.56	0.10	0.04	0.01
Rotation hay	0	0	3.81	0.01	0.19	0.01

minimum level of orthophosphate can be obtained as follows:

$$\frac{\text{hectares of watershed} \times 0.08}{\text{cubic meters of water} \times 0.001} = 0.03$$

or

$$\frac{\text{hectares of watershed}}{\text{cubic meters of water}} \leq 0.0004$$

Therefore, if we deliver 0.08 kg of soluble orthophosphate per hectare per year to a 4-ha reservoir with a 3-meter average depth, we could anticipate soluble orthophosphate levels to be <0.03 ppm with a watershed of <50 ha. However, if the detention time in the reservoir exceeds 1 year, a higher potential orthophosphate level can be anticipated.

Nutrient enrichment of man-made lakes and natural lakes is a natural process, and it would be difficult to alter its course. However, it is imperative that we develop practices that will not unduly accelerate this natural process.

Acknowledgments. This paper is a contribution from the North Central Watershed Research Center, Columbia, Missouri, and the North Central Soil Conservation Research Center, Morris, Minnesota, Corn Belt Branch, Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Missouri and Minnesota Agricultural Experiment Stations.

REFERENCES

Latterell, J. J., R. F. Holt, and D. R. Timmons, Phosphate availability in lake sediment, *J. Soil Water Conserv.*, *26*(1), 21-24, 1971.

Mutchler, C. K., Average erosion losses computed, *Newslett. 3*, Barnes Aastad Corp., Morris, Minn., Feb. 1970.

Rausch, D. L., and H. G. Heinemann, Reservoir sedimentation survey methods, *Res. Bull. 939*, Univ. of Mo., Columbia, May 1968.

Timmons, D. R., R. F. Holt, and J. J. Latterell, Leaching of crop residues as a source of nutrients in surface runoff waters, *Water Resour. Res.*, *6*(5), 1367-1375, 1970.

A Unique Sediment Depositional Pattern

JOE M. LARA

Engineering and Research Center, Bureau of Reclamation, Denver, Colorado 80225

Guernsey Dam, owned and operated by the United States government, was constructed in 1927 and formed a reservoir having a capacity of 91 million m³ (73,810 acre-feet) at a spillway crest elevation of 1347 meters (4420 feet). It is located in Wyoming on the North Platte River, 3 km (2 miles) northwest of a community bearing the same name.

A unique depositional pattern was indicated for the sediments that have accumulated in Guernsey Reservoir, as was evidenced by the survey run in 1966 [*Lara*, 1970]. This pattern is illustrated graphically by the reservoir longitudinal profiles and reservoir range cross sections plotted for the various surveys run. Survey data were used to prepare a table of comparative reservoir surface areas and capacities to record the progressive development of the sediment depositional pattern.

The reason for the uniqueness of the sediment depositional pattern is attributed to the influence of a reservoir sediment withdrawal program [*Jarecki and Murphy*, 1963] operating for several years before the 1966 survey. The purpose of the program was to withdraw sediment-laden reservoir waters for use in sealing downstream canals that had been subject to excessive seepage since the dam was originally built. Special hydraulic and sediment data were collected during the 1960–1962 withdrawal period. The program was essentially a large-scale sluicing process that caused substantial longitudinal and lateral shifting of the deposited sediments in a critical area of the reservoir.

FIELD SURVEY TECHNIQUES AND SAMPLING PROCEDURES

Field surveys of the reservoir, including both land and hydrographic surveys, were begun in August 1966 and were completed in December 1966. Standard land-surveying procedures and equipment were used to run levels along each range line down to water's edge from each side of the reservoir. The hydrographic survey used sonic depth-recording equipment to sound the submerged portion of the ranges. The equipment was installed in a sounding boat. A distance-measuring machine was used to measure horizontal distances of the ranges across the reservoir. The machine provided a way of noting the 'fix' lines on the sonar chart. The gage at the dam was used as a reference for vertical control.

A gravity core sampler was used to collect samples of the underwater reservoir sediment deposits. The sampler was raised and lowered with a power-operated winch having a 6.4-mm (0.25-inch) cable. It was allowed to fall free into the sediment deposits to the greatest possible penetration. When the sampler was raised, it was hauled manually over the side and into the boat where the cutting shoe at the bottom was removed and the inner plastic tube containing the sample was withdrawn. A hacksaw was used to cut that part of the tube holding the sample, and the tube was capped at each end and identified for analysis.

A probe encapsulating a radioisotope (cobalt 60) was used to measure in situ bulk densities of some underwater reservoir deposits. The probe is 3.3 meters (10 feet) long, is operated from a boat, and is raised and lowered by a power-operated reel and cable. It was also operated on a free fall principle. A probe component, the rate meter, recorded the count rate of the radioactivity when the probe was submerged in the sediment deposits.

DESCRIPTION OF THE RESERVOIR

The surface area of Guernsey Reservoir in 1966 was 9.62 km² (2377 acres) compared with

TABLE 1. Guernsey Reservoir

Elevation, meters	1927		1947						
					1927 to 1947				
	Total Capacity	Δ Capacity	Total Capacity	Δ Capacity	Loss in Δ Capacity	Percent Loss	Average Annual Loss	Total Capacity	Δ Capacity
1347	910		606					553	
		142		140	2	0.7	0.1		139
1346	768		466					414	
		130		125	5	1.6	0.25		122
1344	638		341					292	
		117		100	17	5.6	0.85		97
1343	521		241					195	
		105		71	34	11.2	1.7		68
1341	416		170					127	
		94		46	48	15.8	2.4		41.8
1340	322		124					85.2	
		77		30.4	46.6	15.3	2.33		26.0
1338	245		93.6					59.2	
		61		23.9	37.1	12.2	1.86		17.8
1337	184		69.7					41.4	
		48		19.7	28.3	9.3	1.42		14.1
1335	136		50.0					27.3	
		36.5		16.4	20.1	6.6	1.00		11.0
1333	99.5		33.6					16.3	
		28.4		13.3	15.1	5.0	0.76		8.16
1332	71.1		20.3					8.14	
		20.9		10.4	10.5	3.5	0.53		5.67
1330	50.2		9.89					2.47	
		15.2		7.56	7.64	2.5	0.38		2.45
1329	35.0		2.33					0.025	
		11.4		2.32	9.08	3.0	0.45		0.025
1327	23.6		0.012					0	
		8.9		0.012	8.89	2.9	0.44		0
1326	14.7		0						
		6.82			6.82	2.2	0.34		
1324	7.88								
		4.45			4.45	1.5	0.22		
1323	3.43								
		2.30			2.30	0.8	0.12		
1321	1.13								
		0.896			0.896	0.3	0.04		
1320	0.234								
		0.185			0.185	0.1	0.01		
1319	0.049								
		0.049			0.049	0.0	0.002		

Capacity units are in 10^5 m^3.

the original area in 1927 of 9.73 km^2 (2405 acres) at an elevation of 1347 meters (4420 feet). Its 1966 capacity was 55.8 million m^3 (45,228 acre-feet); thus there has been a loss of 35.2 million m^3 (28, 582 acre-feet) since the dam was built. The reservoir is 23.5 km (14.6 miles) long from the dam to the head of the reservoir.

Reservoir widths range from <152 to 402 meters (<500 to 1320 feet) from the dam to about 8 km (5 miles) upstream. Along this portion of the reservoir, both sides of the valley are generally canyonlike. Above this reach the reservoir widens out for a 6.4-km (4-mile) stretch and ranges from 0.8 km (½ mile) to almost 1.6 km (1 mile) wide. Reservoir widths 14.5 km (9 miles) above the dam are 91–396 meters (300–1300 feet) through a canyon about 4.8 km (3 miles) long. Upstream from this point the reservoir remains narrow to its headwaters that terminate near Wendover, Wyoming.

RESERVOIR SEDIMENT DISTRIBUTION

Both the longitudinal and lateral distribution of sediments accumulating in Guernsey Reservoir were substantially affected by the reservoir drawdowns associated with a special operational program. The purpose of this program was to withdraw sediment-laden reservoir waters to be used in sealing downstream canals that were subject to excessive seepage. It was found that lateral and longitudinal disposition of the reservoir sediments varied as a function of the programed withdrawals.

Eleven surveys of Guernsey Reservoir have been run beginning in 1931. Results of the 1947, 1957, and 1966 surveys were compiled in Table 1 to show the progressive changes in the capacity and area data. From this tabulation it is noted that there has been a loss of 35.2 million m^3 (28,582 acre-feet) (1927 capacity minus 1966 capacity) in storage at an elevation of 1347

Capacity and Area Data

1957			1966								
1947 to 1957					1957 to 1966			Area, 10^4 m^2			
Loss in Δ Capacity	Percent Loss	Average Annual Loss	Total Capacity	Δ Capacity	Loss in Δ Capacity	Percent Loss	Average Annual Loss	1927	1947	1957	1966
			558					973	966	964	962
1	1.9	0.19		138	1	5.7	0.11				
			420					894	874	859	853
3	5.7	0.57		122	-0	0	0				
			298					807	758	737	745
3	5.7	0.57		101	-4	-17.7	-0.44				
			197					727	557	542	577
3	5.7	0.57		76	-8	-35.4	-0.89				
			121					655	384	342	410
4.2	7.9	0.79		48.6	-6.8	-30.1	-0.76				
			72.4					570	227	210	238
4.4	8.3	0.83		28.9	-2.9	-12.8	-0.32				
			43.5					444	172	130	150
6.1	11.5	1.15		18.7	-0.9	-4.0	-0.10				
			24.8					353	142	103	99.1
5.6	10.6	1.06		11.7	2.4	13.6	0.27				
			13.1					272	117	82.6	56.3
5.4	10.2	1.02		7.22	3.78	21.5	0.42				
			5.88					214	97.9	62.3	40.5
5.14	9.7	0.97		4.58	3.58	20.3	0.40				
			1.30					160	76.9	44.5	19.0
4.73	8.9	0.89		1.30	4.37	24.8	0.49				
			0					116	59.9	29.9	0
5.11	9.6	0.96		0	2.45	13.9	0.27				
								83.8	40.1	2.0	
2.30	4.3	0.43			0.025	0.14	0				
								65.6	0.8	0	
0.012	0.02	0.002			0						
								50.6	0		
	0	0									
								38.9			
								20.2			
								10.1			
								2.4			
								0.4			

meters (4420 feet), or nearly 40% since the dam was built.

The volumes of sediment accumulated between four periods are listed in Table 2. The amounts listed in the 1927–1947, 1927–1957, and 1927–1966 periods represent the usual pattern of sediment accumulation. However, the 1957–1966 period shows an abnormal pattern. Here it is noted that the sediment volume increased from an elevation of 1327 meters (4355 feet) to an elevation of 1337 meters (4385 feet), but an erratic pattern is followed to the top elevation. Negative values begin at an elevation of 1343 meters (4405 feet) and thus indicate increases in capacity in this range. In reference to Table 1 the 1966 surface areas are greater than the 1957 areas in the elevation range of 1338–1344 meters (4390–4410 feet). Thus the erratic sediment volume pattern beginning at the elevation of 1338 meters (4390 feet) (Table 2) as well as the increase in capacity beginning at the elevation of 1343 meters (4405 feet) is accounted for.

The thalweg profiles plotted in Figure 1 give a progressive picture of how the sediments have longitudinally distributed in the reservoir. Profiles for 1927, 1937, 1947, 1957, and 1966 were plotted to show the unique pattern that developed. Ordinarily, the profile will develop in a pattern similar to the 1937 thalweg that shows a definite formation of the topset, foreset, and bottomset beds. An examination of the latest profile (1966, which is plotted as a heavy line) shows that sediments have deposited to depths between 10.6 and 12.2 meters (35 and 40 feet) between the dam and range 19A. Upstream, from range 19A to range 13, the 1966 profile in most places falls below both the 1947 and 1957 profiles. Little change in the depths of sediment deposits since 1957 is noted above range 11A. The development of the unique pattern exhibited by the 1966

TABLE 2. Guernsey Reservoir Sediment Accumulation and Area Loss

Elevation, meters	Sediment Accumulation, 10^5 m^3				Area Loss, 10^4 m^2			
	1927 to 1947	1927 to 1957	1927 to 1966	1957 to 1966	1927 to 1947	1927 to 1957	1927 to 1966	1957 to 1966
1347	304	357	352	-5	7	9	11	2
1346	302	354	348	-6	20	35	41	6
1344	297	346	340	-6	49	70	62	-8
1343	280	326	324	-2	170	185	150	-35
1341	246	289	295	6	271	313	245	-68
1340	198	237	250	12.8	343	360	332	-28
1338	151	186	202	15.7	272	314	294	-20
1337	114	143	159	16.6	211	250	254	4
1335	86.0	109	123	14.2	155	189	216	26
1333	65.9	83.2	93.6	10.4	116	152	174	22
1332	50.8	63.0	69.8	6.84	83	115	141	25
1330	40.3	47.7	50.2	2.47	56	86	116	30
1329	32.7	35.0	35.0	0.025	44	82	84	2
1327	23.6	23.6	23.6		65	65	65	0
1326	14.7	14.7	14.7		51	51	51	
1324	7.88	7.88	7.88		39	39	39	
1323	3.43	3.43	3.43		20	20	20	
1321	1.13	1.13	1.13		10	10	10	
1320	0.234	0.234	0.234		2	2	2	
1319	0.049	0.049	0.049		0.4	0.4	0.4	

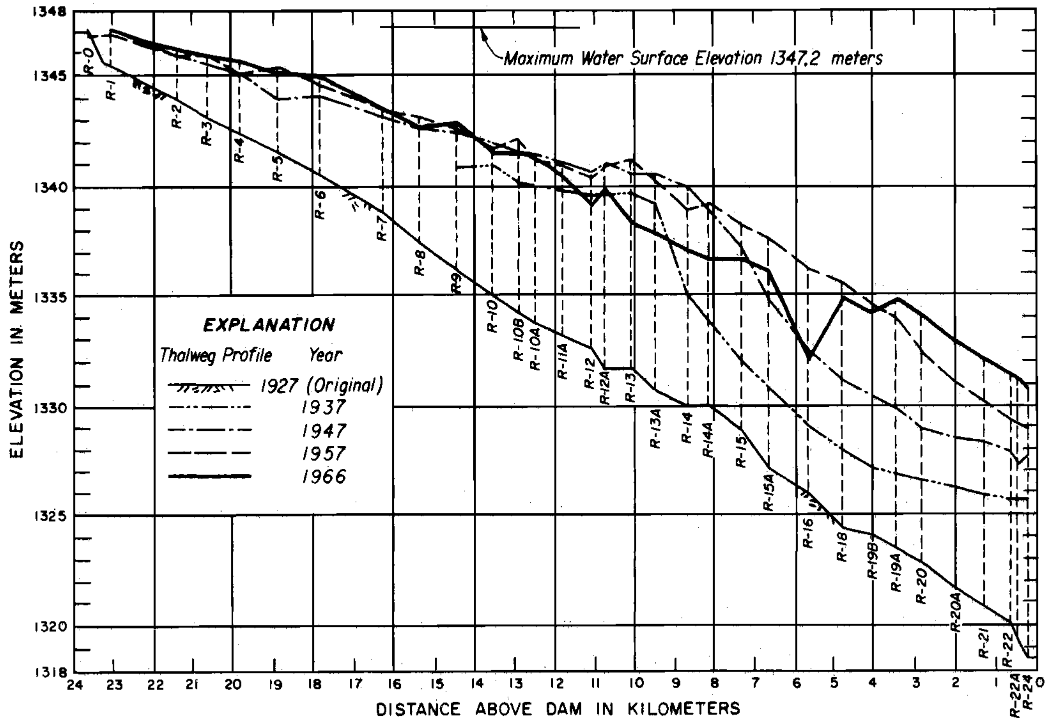


Fig. 1. Longitudinal profiles.

profile is attributable to the effects of the sediment withdrawal program previously mentioned. Thalweg profiles plotted for 1960, 1961, and 1962 withdrawal runs (Figure 2) for the reservoir reach between 3.2 and 11.3 km (2 and 7 miles) above the dam showed a progressive drop in the profiles from 1960 to 1962. The 1962 profile closely followed the 1966 profile except at range 16. Here the 1966 profile dropped about 3 meters (10 feet) below the 1962 profile. These plotted 1960, 1961, and 1962 profiles further substantiate the conclusion that the withdrawal operation had a definite influence on the 1966 profile pattern.

Cross-sectional profiles were plotted of sedimentation ranges 13 and 15 (Figures 3 and 4), selected to represent the lateral distribution of sediments in the reservoir area most affected by the withdrawal program previously cited. Inspecting these graphs shows that the 1966 profile generally fell below the 1957 profile. This pattern indicates an unusual lateral shifting where overall scouring of sediments occurred instead of the usual deposition. The range 13 profiles show unique transitional lateral movement of sediments between survey periods. For example, the 1947 profile shows that the sediments peaked toward the right side of the range (plotted looking downstream) between 900 and 1200 meters, whereas the 1957 profile shows peaking toward the left direction between 420 and 650 meters. The 1966 profile, however, reverted to the general pattern of the 1947 profile except that it dropped considerably lower between 940 and 1100 meters, the actual stream channel area. The graph in Figure 4 of range 15 showed that the 1966 profile fell below the 1957 profile for the entire range width. Again, this pattern indicates scour rather than the usual deposition. The profiles plotted of ranges 5 and 21 (Figure 5) represent typical sediment depositional patterns that develop, respectively, in the headwaters and near the dam areas of reservoirs having this shape.

CONCLUSIONS

Thalweg profiles plotted for the 1937, 1947, 1957, and 1966 surveys indicate a unique development of the longitudinal distribution of sediments accumulating in Guernsey Reservoir particularly between the 1957 and 1966 period. The pattern generally develops in the form

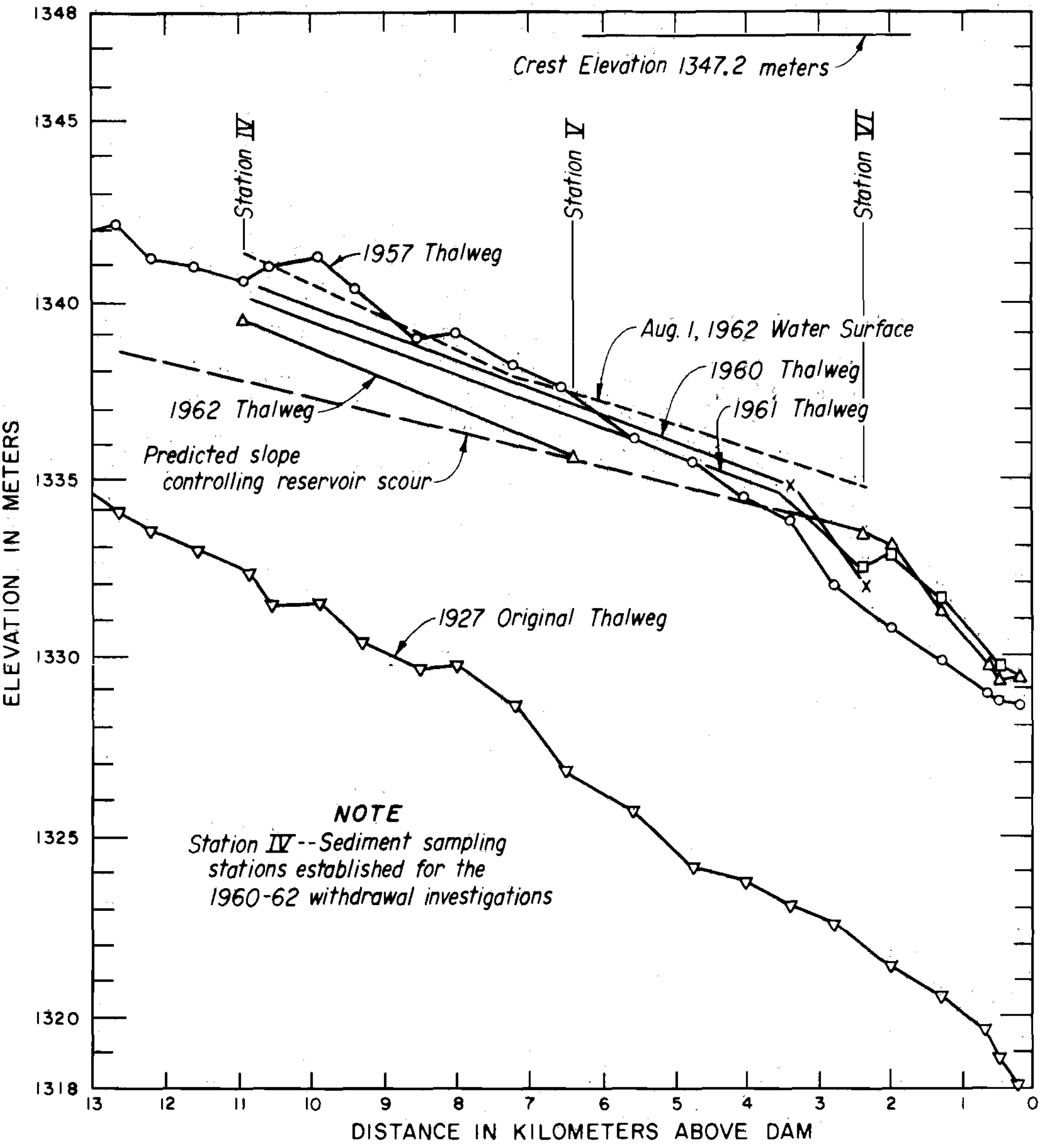


Fig. 2. Longitudinal profiles for 1960–1962 withdrawal investigations.

demarcating topset, foreset, and bottomset beds as indicated by the 1937 profile. The 1966 profile followed a unique pattern in an area of the reservoir about 3.2–12.9 km (2–8 miles) above the dam where it dropped below the profile plotted for the 1957 survey. The 1960, 1961, and 1962 thalweg profiles plotted for the withdrawal runs also showed progressive drops from 1960 to 1962. A study of pre-1966 conditions disclosed that a special plan was implemented to operate the reservoir for the purpose of withdrawing sediment-laden waters. Special hydraulic and sediment data were collected during the 1960–1962 withdrawl period. It was concluded from this study that the reservoir sediment-water withdrawals had a pronounced effect on the manner in which the subsequent (1966) profile was formed.

Cross-sectional profiles of some of the reservoir sedimentation ranges in the reach where the 1966 longitudinal profile was lower than the 1957 profile were plotted for the 1947, 1957, and 1966 surveys. These profiles showed the lateral sediment distribution as an accumulating deposition

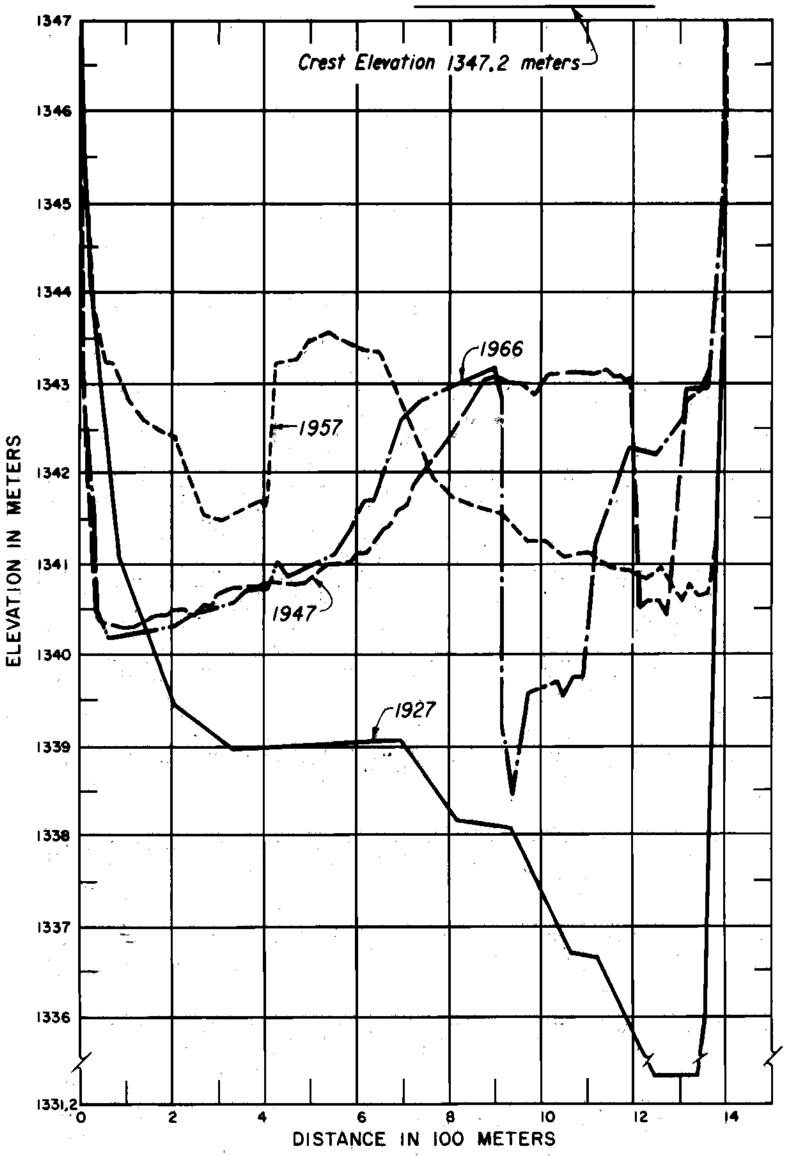


Fig. 3. Cross-sectional profiles for sedimentation range 13.

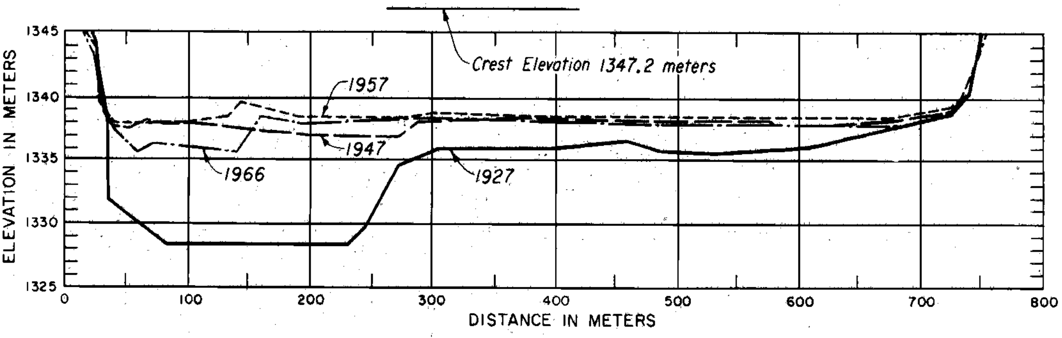


Fig. 4. Cross-sectional profiles for sedimentation range 15.

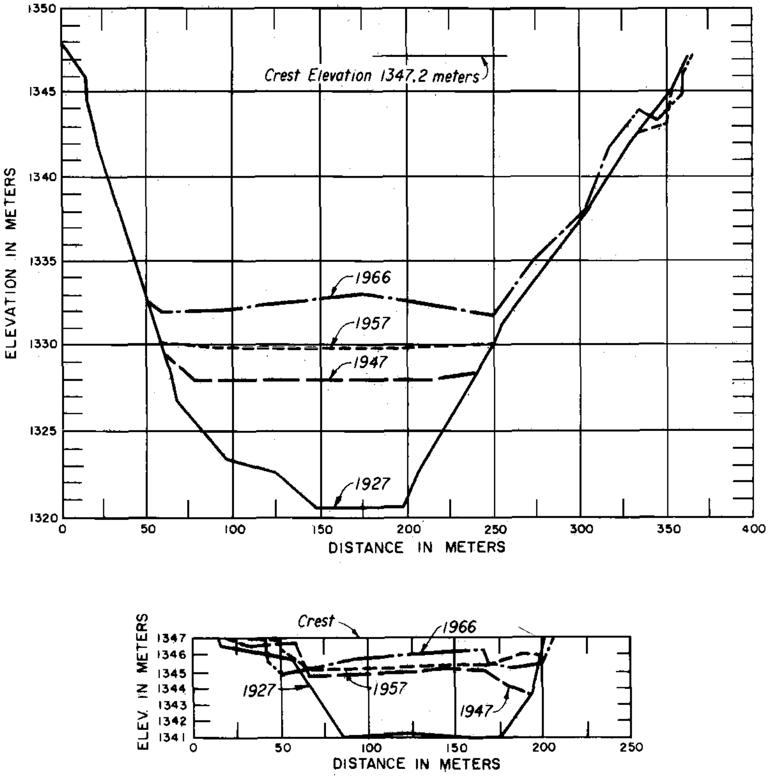


Fig. 5. Cross-sectional profiles for sedimentation ranges 21 (*top*) and 5 (*bottom*).

for the 1947 and 1957 periods. However, the 1966 cross-sectional profile, as in the longitudinal representation, also showed an overall lowering or scouring effect in comparison with the 1957 profile. Here again, it can reasonably be concluded that the withdrawal plan had a definite influence on the lateral distribution of reservoir sediments. Should the withdrawal program continue, further shifting of the deposited sediments can be expected to occur; consequently, both longitudinal and lateral profiles would continue to develop erratic and unpredictable patterns.

REFERENCES

Jarecki, E. A., and T. D. Murphy, Sediment withdrawal investigation—Guernsey Reservoir, Paper no. 91, Proceedings of the Federal Inter-Agency Sedimentation Conference, *U.S. Dep. Agr. Misc. Publ. 970,* 1963.

Lara, J. M., The 1966 Guernsey Reservoir sediment survey, *Rep. REC-OCE-70-22,* Bur. of Reclam., U.S. Dep. of the Interior, Denver, Colo., July 1970.

Sediment Accumulation in Reservoirs of Moderate Size

MELVILLE S. PRIEST

Water Resources Research Institute, Mississippi State University
State College, Mississippi 37962

The *U.S. Department of Agriculture* [1969] has recently released a publication entitled *Supplement to Summary of Reservoir Sediment Deposition Surveys Made in the United States through 1965.* The document is a massive compilation of field data that is likely to serve as a source for numerous future analyses. The coverage of the data is so extensive as to include small farm ponds, reservoirs for containing mud flows, and large reservoir systems, such as those under the Tennessee Valley Authority (TVA). In view of the variety of conditions covered, it seems unlikely that a single, all-inclusive analysis will be forthcoming in the immediate future. However, it does appear that analyses of particular groups of data may yield useful knowledge.

For this paper, only those reservoirs having drainage areas between the approximate limits of 1000 and 182,000 ha were considered. Insofar as the author was able to determine, there was no significant reservoir or sediment trap upstream from any of the reservoirs included in the analysis. That is, the author excluded reservoir systems. Also, those reservoirs for which the primary function appeared to be the containment of mud slides or mudflows were excluded from the analysis. Further, those reservoirs for which the data were incomplete, estimated, adjusted, or, for some reason, dubious were excluded. The foregoing restrictions are not so severe as to preclude a useful analysis. There were a sufficient number of qualified reservoirs to enable a determination of trends within this important set of conditions.

Any analysis of such data is, of course, subject to involuntary restrictions imposed by the nature of the questionnaire through which the data were obtained and the response of the cooperating agency. Of particular significance is the dearth of data describing sediment characteristics. Only one such item was included in the questionnaire: 'average dry weight.' Some respondents provided no data under this item, and many of the data that were provided were assumed or estimated. This shortage seems to preclude the direct use of sediment characteristics in the analysis. Also, the reporting of maximum watershed elevation instead of a more characteristic elevation along the divide makes a three-dimensional description of the watershed a dubious undertaking.

Within the pattern prescribed by the data the rate of accumulation of sediment within the reservoir will be described by the relation

$$S/R = \phi[(a/A)(R/P)] \qquad (1)$$

where S is an average time rate of sediment accumulation, R is an average time rate of runoff, a is reservoir surface area for representative or normal operating conditions, A is projected horizontal area of the watershed, P is an average time rate of precipitation, and ϕ indicates 'function of.' The parameters shown in (1) are dimensionless for purposes of generalization. Units of the quantities in each dimensionless ratio must be compatible. The ratio S/R relates rate of sediment accumulation to rate of stream inflow, a/A relates size of reservoir to size of watershed, and R/P relates rate of runoff to rate of precipitation.

Data from the reservoirs listed in Table 1 are shown in Figure 1 through the parameters of equation 1. Limiting values of the computed, dimensionless parameters are S/R from 0.00010 to 0.016, a/A from 0.0017 to 0.079, and R/P from 0.053 to 0.76. As nothing more than an indication of trends, a curve was fitted by eye to the plotted data. The curve conforms to the knowledge that the quantity S must vanish when the quantity a vanishes. That is, the curve must emerge from the origin. Also, the quantity S must approach 0 as $(a/A)(R/P)$ approaches unity. That is, moving to the right from the origin, the curve must eventually tend to return to the horizontal

TABLE 1. Identification of Reservoirs

Data Sheet No.	Reservoir	State
4-16	Liberty	Maryland
5-7*b*	Triadelphia Lake	Maryland
17-23	Cagles Mill	Indiana
19-16*a*	Grant Lake	Ohio
20-1*b*	South Holston	Tennessee
20-2*b*	Watauga	Tennessee
20-10*a*	Nantahala	North Carolina
20-16*b*	Chatuge	North Carolina
20-17*b*	Nottely	Georgia
20-20*b*	Blue Ridge	Georgia
21-22*b*	Loyalhanna	Pennsylvania
21-23*b*	Mahoning Creek	Pennsylvania
21-24*b*	Crooked Creek	Pennsylvania
24-3*b*	Lake Carlinville	Illinois
24-42*a*	mine pond 4	Illinois
45-37	Waldron Lake	Arkansas
45-38	Howard City Lake	Kansas
57-3*a*	Santa Cruz	New Mexico
70-1*a*	Fullerton flood control basin	California
70-18*b*	Hansen flood control basin	California
70-20*b*	Cogswell flood control basin	California
70-21*b*	San Gabriel flood control basin	California
70-26*b*	Big Dalton flood control basin	California

axis. There is a break in the curve to indicate that the maximum possible value of the ordinate is unknown.

Although data from the reservoirs listed in Table 1 were accepted as reported, there were data from some other reservoirs that were not included because the reservoir surface area *a* was not representative of actual operating conditions or because the time period for which the average rate of runoff *R* was determined did not coincide with the time period for which the average rate of sediment accumulation *S* was determined. The reservoir surface area *a* should relate to the pool elevations at which the sediment accumulation actually occurred, as distinguished from a design pool elevation that is so high that it may never exist. Discrepancies resulting from the determination of *R* and *S* for time periods that do not coincide may or may not be of some consequence. The greater the time periods, the less likelihood of discrepancies of some significance.

Even though some limitations were imposed by the data themselves and by the author, the relation of parameters shown in Figure 1 exhibits orderly trends. Although the data would not permit direct description of sediment characteristics, some of the quantities included in the analysis may have indirectly accounted for these characteristics at least to some extent. Also, the differences in average. deposited sediment characteristics, for the reservoirs of this analysis, may not be sufficiently great to significantly disturb

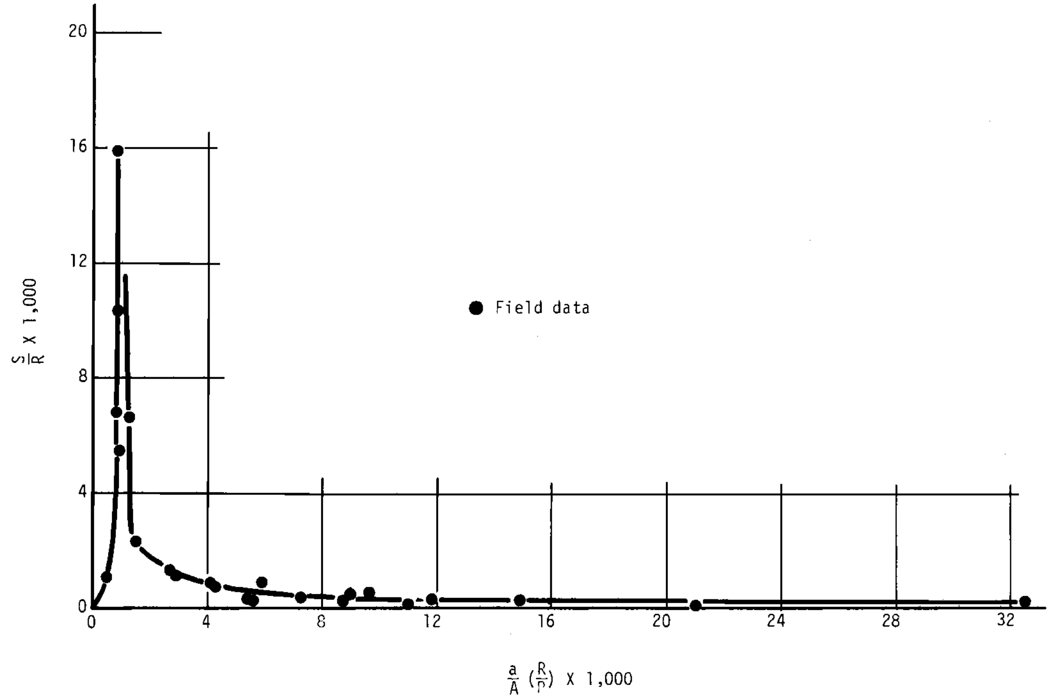


Fig. 1. Relative rate of sediment accumulation in reservoirs.

the trends shown in Figure 1. In any event the author believes that the relation shown in Figure 1 will be informative and useful to those who are concerned with the accumulation of sediment in reservoirs.

REFERENCE

U.S. Department of Agriculture, Supplement to summary of reservoir sediment deposition survevs made in the United States through 1965, *U.S. Dep. Agr. Misc. Publ., 1143*, 1969.

Summary: Interaction between Reservoirs and the Atmosphere and Its Hydrometeorological Elements

J. NEMEC

Hydrology and Water Resources Department, World Meteorological Organization
Geneva, Switzerland

The atmosphere and its meteorological and hydrometeorological factors represent one of the most important physical components of the environment of all water surfaces and bodies. They have an interaction with the water body, be it freshwater or ocean, and influence not only the physical and in particular the hydrologic behavior of the body and its other environmental components but also its biological and ecological systems. It is therefore most difficult to examine in a relatively short paper all the aspects of this interaction, on parts of which books have been written [*Timofeev*, 1963]. Further, it should be noted that the most important intention of this volume is that the problem be considered as a broadly interdisciplinary one, and the paper is not therefore intended for meteorologists or hydrologists but for a broader audience of specialists from all fields concerned with man-made lakes and lakes in general.

It will certainly be appreciated that the paramount interaction between a reservoir and the atmosphere is the process of evaporation. It has in itself warranted many symposiums, and both scientific and operational aspects of this problem attract the attention not only of individual specialists and national agencies but also of international nongovernmental and governmental organizations, particularly the *World Meteorological Organization* [1966; *Hounam*, 1971].

The interaction of a lake and the atmosphere occurs mainly through exchange of mass, heat, and momentum [*Bruce*, 1963]. The evaporation process and some others cut across at least two such exchanges. In addition, environmental changes resulting from man-made lakes necessarily invite a different approach from the one used for natural lakes. In many cases the concrete problems of interaction of a man-made lake with the atmospheric environment must be solved or at least envisaged before the lake exists, and thus the necessary initial data for an empirical solution are completely lacking. A theoretical analysis imposes itself in such cases, and it is often based on data collected on natural lakes under similar environmental conditions.

Thus the first and most important task for further improvement of scientific and operational knowledge of the man-made lakes interaction with the atmosphere will be a systematic collection of data. We will examine this task first, and a detailed example is offered in this direction by the *USSR Hydrometeorological Service* [1957]. The second point, which is examined in some detail, is the theoretical aspect of the problems of the turbulent exchange and vertical distribution of meteorological elements in the air-water interface and the profile above and near the reservoir. Since heat balance is at the base of the meteorological regime above water bodies, elements of this balance are examined.

Practical conclusions from and influence of the interaction of man-made lakes with the atmosphere depend on the size of the water body. A classification of such man-made water bodies from the point of view of practical implication on atmospheric processes, be they in meteorological macroscale, mesoscale, or microscale, is therefore useful.

The interaction may further be considered either as the influence of the water body on the meteorological factors or vice versa. Depending on the size of the body, this problem will be equally examined, and a summary of detailed studies presented in other papers in this section are quoted for this purpose. Furthermore, work undertaken on the North American Great Lakes by United States and Canadian scientists yields significant results in this direction. The instrumentation used for collection of data and in particular for research on the air-water interaction is constantly improving. In addition to routine observations, specially equipped boats, aircraft, radar, radioisotopic tracers, and satellite imagers are used to improve the insight into the processes in space and time.

Because of these instrumental developments, progress in research acquires a rapid pace. It is, however, important that the main direction of future research be oriented toward acute problems of the environment and the urgent necessity of its protection. Some ideas in this direction will be forwarded.

The breakdown of the subject will therefore be as follows: data collection systems, theoretical substance of the problems, influence of the air-water interaction in reservoirs and its practical implications, instrumentation developments for research purposes, and conclusions and future research trends.

DATA COLLECTION SYSTEMS

Although this paper is mainly concerned with the interaction of meteorological and hydrometeorological factors with water bodies, the data collection systems indicated below tend to integrate all observations to be made on such bodies. Indeed, not only for reasons of financial economy but also for the sake of an interdisciplinary consideration of a man-made water body, the integration of all operations should be the rationale behind data collection systems installed at all reservoirs. Thus meteorological, hydrologic, geologic, biological, and all other data should be gathered within one integrated system whenever possible. Examples from the USSR, United States, and Canada demonstrate the usefulness of such an approach.

Although meteorological and hydrologic observations are made in accordance with the principles of such observations at any observing station, special instructions and methods are required and exist for lakes and man-made reservoirs in addition to general principles, which have been put forth on an international level by the *World Meteorological Organization* [1968*a*, *b*, 1970].

An inventory of lakes and reservoirs on a national level is a prerequisite for the installation of comprehensive observational networks. Such an inventory, as initiated, for example, in the USSR [*USSR Hydrometeorological Service*, 1957], is based on the following data for individual lakes: (1) name, (2) type of water body (man-made reservoir, lake, and so on), (3) short description of the hydraulic work (for man-made reservoir), (4) geographical coordinates, (5) area of the catchment, (6) morphometric data (area, widths, lengths, depth, normal levels, and so on), (7) description of the shoreline and of the depression forming the bottom, (8) basic elements of the hydrologic regime, (9) degree of data collection progress (including research campaigns), and (10) use of the reservoir (power production, navigation, and so on).

An inventory of all lakes comprising the above elementary data allows the possibility of rapidly ascertaining the amount of data available not only for any particular reservoir but also for a generalized research program. In addition to the inventory of reservoirs, all permanent observational stations on reservoirs should be listed in a published inventory. (In the USSR, such an inventory is published every fifth year, e.g., 1960, 1965, 1970, and so on.)

Routine basic meteorological observations that should be made on every reservoir are air temperature, absolute values of air moisture, precipitation, cloudiness, wind speed, and frequency of wind speed in different directions of the wind rose. Hydrologic observations involving meteorological elements include records of water levels (particularly during wind setups and seiches), temperatures of the water surface, and the water profile in depth. In addition, the ice and snow conditions; chemical composition (basic components are Ca, Mg, Na+, K, HCO_3, SO_4, and Cl); and height, period, amplitude (length), and velocity of propagation of waves should also be measured and indicated. The wave regime description should include frequency evaluation. In research stations the meteorological elements in the profile above the lake should be indicated. The direction and velocity of currents should also be observed on lakes that are large enough to warrant such observations.

The manual of the *USSR Hydrometeorological Service* [1957], in addition to instructions for all the above observations and their processing, indicates the computation of the water balance of each reservoir or lake. It is, however, considered by the author that methods for the computation of such a balance are rather difficult to standardize and that the instructions included in the manual may serve only as a useful example. Within the USSR Hydrometeorological Service [*Vikulina and Seljuk*, 1966] a specialized observational network on man-made reservoirs has been organized and is operating at present 13 hydrometeorological observatories and 30 lake stations as well as >250 hydrometeorological stations, which provide basic data for man-made reservoir study.

THEORETICAL SUBSTANCE OF THE PROBLEMS

Although macroscale, mesoscale, and microscale processes present different facets of practical implications [*Bruce et al.*, 1968], the theoretical approach may be integrated with the examination of differential equations governing mass and energy transfer between the water body and the atmosphere on one side and the mass and energy transfer between the land (shores) and the atmosphere on the other side. Depending on the boundary conditions, the practical conclusions vary for small and large reservoirs in space and time over the water surface and its land environment.

The basic elements of the heat balance equation must be considered for the air-water interface (the water surface) and for the active air layer above it, which, depending on the size of the water body, may vary considerably. The basic heat balance equation for the active boundary layer of the air on the air-water interface may be written in the following form [*Budyko*, 1956]: $R = LE + P + B$, where R is the difference between the heat energy received in radiation form and that returned to the atmosphere, LE is the loss of heat due to condensation or evaporation, P is the heat exchange between the water surface and the adjacent atmosphere, and B is the heat exchange between the active air layer and adjacent layers.

It is to be noted that in the solution of this equation (and in particular for the estimation of evaporation) an important ratio of two of the above elements has been introduced, namely, the Bowen ratio P/LE, which may be expressed through the values of the saturation deficit and the temperature of the water surface corresponding to the boundary conditions of the active layer of the air. Thus the measurements of air temperature and moisture in the profile above the water surface and the temperature of the latter acquire particular importance among the meteorological and hydrologic elements to be measured on reservoirs and lakes. The above equation and the variations of its elements govern the meteorological regime above the water and the surrounding environment.

The equation of mass transfer (in this case, of water evaporation by diffusion and turbulence) and that of energy transfer are most sensitive to the vertical profile of the wind turbulence and thus to the values of the drag coefficient and surface stress. The logarithmic wind profile approach is probably the most widely known method for estimating these parameters, although other methods are also used [*Bruce et al.*, 1968] for the lower layer of air over the water body. *Timofeev* [1963] indicates the value of the roughness length (coefficient) Z_0 as 10^{-4} meters, which is 2 orders of magnitude less than the value over the land. This difference in order of magnitude applies equally for the coefficient of turbulence of air motion over water and land. Whereas the logarithmic profile applies approximately to conditions of equilibrium (neutral atmospheric stability) in nonequilibrium situations, the vertical profile of meteorological elements (wind, temperature, and humidity) may be expressed by the exponential equations. Such equations have been derived for spring inversion situations and convection by *Laichtman* [1961], *Budyko* [1956], *Monin and Obukhov* [1954], and *Timofeev* [1963]. Direct measurement of the drag coefficients has been undertaken and reported recently by many authors, and results are briefly reported by *Bruce et al.* [1968].

Once the question of exact determination of the drag coefficient either indirectly or by direct measurement (in this latter case the type of instrumentation used represents a problem that requires much further research and study) is satisfactorily terminated, it will help to solve many practical problems of the air-water boundary layer.

On the basis of the analysis of the equations of energy and mass exchange the following classification of reservoirs has been proposed [*Timofeev*, 1963] with respect to the interaction with the atmosphere: (1) large (or unlimited) reservoirs where the dimension along the wind direction axis L is $>10^6$ meters, (2) limited reservoirs where 10^3 meters $< L <$ 5.10^5–10^6 meters, and (3) small reservoirs where $L < 10^3$ meters. However, it is to be noted that, for the purpose of evaporation estimates, this classification is insufficient since the depth of the reservoir is of paramount importance for this process.

The diurnal, seasonal, and annual variations of temperature, moisture, and wind values of the atmosphere over the reservoirs, over their environment, and in the active layer of the water depend largely on the dimensions and classification given above and will be described briefly from observational and experimental results, some of which are reported in this volume. As has already been mentioned, this paper will not discuss the specific problems, either from a theoretical or from a practical aspect, of different methods of evaporation assessment from the free water surface (be it for small and shallow or large and deep man-made reservoirs or natural lakes), since sufficient attention is devoted to such methods in the references indicated, e.g., in the above-mentioned World Meteorological Organization publications.

INFLUENCE OF THE AIR-WATER INTERACTION IN RESERVOIRS AND ITS PRACTICAL IMPLICATIONS

Man-made reservoirs that have an influence in macroscale and mesoscale meteorological processes are rather few, and observations on them are even fewer. The only reported observations are those from reservoirs in the USSR and the United Arab Republic, namely, the Kuybischev Reservoir [*Borushko,* 1965] and Lake Nasser [*National Center for Atmospheric Research*, 1966]. Borushko, investigating the distribution of temperature and absolute humidity of the atmosphere from the meteorological stations at varying distances from the shore, came to the conclusion that the influence of reservoirs on variation of mean monthly temperature and absolute humidity is inversely proportional to the logarithm of the distance of the shoreline. The creation of the Kuybischev Reservoir did not alter the temperature in winter, but its cooling effect appears to be rather substantial in the spring. The possible atmospheric manifestations of the Lake Nasser (area of 4500 km^2) are the subject of rather controversial opinions. It is not, however, anticipated that the moisture entering the atmosphere from the reservoir will, in the absence of uplift to adequately low temperatures, produce even clouds much less precipitation; nor will the lake influence the occurrence or intensity of thunderstorms. Opinion differs on the extent of the influence, if any, of the reservoir on the low-pressure trough trending northeasterly over Lake Nasser to the north of the intertropical convergence.

The macroscale and mesoscale meteorological and hydrometeorological effects of large natural lakes, particularly according to research on the North American Great Lakes, seem to be rather more significant than those observed or predicted on man-made reservoirs. In a complex study of the climate of southern Ontario the influence of Lake Huron, Lake Erie, and Lake Ontario is discussed [*Brown et al.*, 1968]. The effect of differences of temperature over the lakes and the land is most noticeable in the coastal areas immediately to the lee of the lakes but also results in alternating breezes that cause, in these areas, diurnal and temperature regimes that are allied to the lake temperature regime. A very apparent lake effect is the heavy snowfall that occurs in the lee of the Great Lakes on very cold winter days. There is also evidence that the lakes tend to suppress thunderstorm activity in the early summer and that their influence on winds is a factor to be considered in planning the control of air pollution.

Similar studies on Lake Michigan [*Changnon,* 1966] report various effects on mesoscale atmospheric convective systems. Lake influences were found to affect thunderstorm activity in all four seasons, the greatest changes occurring in the summer and fall. The influence both in the increasing and decreasing sense depends on the wind direction and time of day and reaches values of 40–60%. The lake effect also reduces hail frequency throughout lower Michigan. Similar effects are reported for Lake Erie [*Lavoie et al.,* 1970]. The influence of lakes on precipitation have, in general, the main practical implications, as is shown in many studies on the North American Great Lakes [*Changnon*, 1966, 1968; *McVehil and Peace*, 1965; *Lyons*, 1966; *Strong*, 1968] and on Lake Baikal [*Kornienko*, 1969; *Verbolov et al.*, 1965]. As a result of the lake's influence on thunderstorms, hailstorms, and snowfall, the amount of precipitation over Lake Michigan is 6% less than that over the land portion of the basin, which represents 1.85×10^6 fewer cubic meters of water per year in the lake. On the other hand the investigations on Lake Baikal indicate that the evaporation from the lake in periods of low air humidity in the catchment (November and December) increases the precipitation on the southeastern shore of the lake by 10–16%.

It is therefore more difficult to form a general conclusion and in particular to forecast the future influence on precipitation of a man-made reservoir without a most detailed study of mesoscale and macroscale meteorological conditions in the area. Indeed, a statistical study of mesoscale meteorological processes over Lake Balaton in Hungary, which represents a man-controlled natural lake [*Kovacs*, 1965], indicates that this lake is not exerting any significant influence on the temperature and humidity of the air masses passing over the lake.

This conclusion would again not be valid for Lake Victoria, Lake Kyoga, and Lake Albert in Africa. A detailed study of meteorology, hydrometeorology, hydrology, and of other elements influencing the lake's regime is under way [*Krishnamurthy and Ibrahim*, this volume]. The final objective of the project is to establish as exactly as possible the water balance of the lakes and their catchments. The preliminary results already indicate that the water balance equation is highly sensitive to the values of direct rainfall over and evaporation from the lake and to the differential between the two parameters. There is no doubt that it is only at the end of this project that research will be possible on the effects of Lake Victoria on these meteorological parameters, although some of the mesoscale meteorological elements have been studied by aerological methods [*Fraedrich*, 1968]. Although precipitation is the most important element to be considered, other elements such as cloudiness, air temperature, and air moisture [*Davidson*, 1967; *Timofeev and Kirillova*, 1966] are considerably influenced by large water bodies, and *Timofeev* [1963] proposes a theoretical method to forecast the changes of these elements resulting from establishing large man-made reservoirs.

The macroscale and mesoscale effects being the privilege of large lakes and reservoirs, microscale meteorological interaction between water bodies and atmosphere is the subject of many studies in several countries. Local temperature and humidity contrasts around small reservoirs and lakes cause several microclimatic changes and effects, of which the most important is fog formation. A short survey of such studies [*Gregory and Smith*, 1967] and a study of Selset Reservoir (man-made) reveal that here again a generalization may prove dangerous. A study [*Holmes*, this volume] on the effect on the atmospheric boundary layer of three small man-made prairie lakes in Alberta and the downwind consequences indicates that surface radiation temperature differences between dry and moist areas were large and that temperature differences of air cooled by passage over the water were measurable, i.e., amounting up to 3°C. Surface temperature of the surrounding land varied greatly and occasionally was 28°C warmer than the temperature of the lake surface. The cooling of air persisted for 3–4 km at 40 meters after the air passed the shoreline of two of the small reservoirs. In addition to influence on temperature and humidity a larger number of smaller reservoirs in the same region may have some influence on the frequency of summer thunderstorms. Such effects have been reported on the natural Mazury lakes in Poland [*Stopa*, 1967; *Okolowicz*, 1967; *Kossowska*, 1967; *Breier*, 1966].

Although a variety of opposite effects are reported in this respect depending on the actual meteorological situation, a definitely increasing occurrence of fog is reported by a number of studies on smaller lakes [*Pelko*, 1967]. Investigations of the Swedish Meteorological and Hydrological Institute [*Rodhe*, 1968] indicate an increased frequency of fog mainly in winter for this country. Although, in general, the formation of fog may result from cold advection (passage of cold air over warmer surface of the water) or warm advection (passage of warm air over colder water surface), the first case presents a most important point of interest for man-made reservoirs (cooling ponds) of industrial complexes. The paper by *Tsai and De Harpporte* [this volume] on a method for predicting fog produced by cooling ponds proposes a mathematical model for the numerical solution of the heat and moisture diffusion equations for the turbulent atmospheric surface layer over such ponds. Buoyancy considerations are included so that the effect of inversions on the fog may be calculated. The authors indicate good corroboration by observations of predictions made by the model and present an example of its use.

Although the prediction of the fog over cooling ponds represents an important aspect of 'thermal pollution,' the substance of fog is of ever more increasing concern to environmental scientists and authorities. Indeed the thermal pollution of man-made and natural lakes in some cases may create undesirable climatic effects through the modification of near-shore sensible heat exchange [*Bruce et al.*, 1968].

The last but not the least important aspect of the air-water interchange is the qualitative aspect of precipitation washouts polluting man-made and natural lakes. This aspect has been recently indicated by a study concerning the Great Lakes

(W. C. Ackermann, personal communication) in which even limited analyses of precipitation chemistry ascertained a large presence of nitrogen compounds but in which analyses yielded no phosphates. The danger of eutrophication of lakes being as great as it is all over the world, a more detailed chemical analysis of precipitation water is no doubt needed. Furthermore, a washout of heavy metal fallout is a cause of concern. Although most metal concentrations are under the permissible level, cadmium concentration was found in one instance to be almost double the permissible level. A most interesting study of meteorological influence on ecosystems in man-made reservoirs, in particular on the floristic composition of plant communities on the shores of dam reservoirs, is reported by ecologists from Czechoslovakia [*Seda*, 1966].

INSTRUMENTATION DEVELOPMENTS FOR RESEARCH PURPOSES

The air above the water bodies no doubt represents an important environment not only as a subject of observations but also as the carrier of observational instruments, which have a high spatial mobility. Thus the use of specially equipped aircraft is reported by *Holmes* [this volume]. The 'oasis effect' of the small man-made lakes was studied with the help of an airborne system capable of measuring the flux of heat and vapor. Similar arrangements were used on Lake Erie [*Lavoie et al.*, 1970]. Automated combined meteorological and hydrologic lake stations and research ships are reported from several countries [*Bellaire et al.*, 1967; *Okolowicz and Stopa*, 1964; *Richards*, 1967; *Zaitsev and Serova*, 1965; *Bruce et al.*, 1968], and modern methods of isotopic tracing [*Fontes*, 1970] permit estimation of the climatic zone of influence of the lake in the atmosphere, as demonstrated in the example of the Lake Leman (Geneva) in Switzerland. The use of weather radar has become most important for the observation of mesoscale effects of large reservoirs. Probably one of the most important instrumental developments for air-water interface observation is the airborne radiation thermometer technique (ART), which permits complete aerial surveys of water surface temperatures of reservoirs of any magnitude [*Richards*, 1967].

The development of remote sensing space technology via earth satellites is also applied to the instrumental developments for reservoir and lake observations. Already, the Tiros satellite pictures have been used for corroboration of the macroscale influence of great lakes on atmospheric systems [*Lyons*, 1966].

A paper by *Ackermann and Rabchevsky* [this volume] indicates the applications of Nimbus satellite imagery to the monitoring of man-made lakes. Information on gross shoreline configuration, areal extent, and meteorological changes surrounding large man-made lakes provided by Nimbus satellite imagery is specially emphasized for Lake Nasser, Volta Lake, Okavango basin, and Fort Peck Reservoir. It is estimated that further applications might be possible with more sophisticated satellite instrumentation and that a new limnological classification might also develop from such information. In this connection the hydrometeorological and hydrologic applications of the World Weather Watch system developed under the auspices of the World Meteorological Organization must be mentioned, since they include a systematic measurement of the atmospheric moisture flux for hydrologic purposes, including that of water balance of large reservoirs [*Bruce and Nemec*, 1967].

CONCLUSIONS AND FUTURE RESEARCH TRENDS

The general assessment of studies of interaction of man-made lakes with the atmospheric environment indicates that, although research conducted on natural lakes may be extremely helpful, it can be no substitute for theoretical and experimental work designed to clarify and permit forecasts of the effects of man-made reservoirs in their planning and design stage. Thus the installation of an observational network on sites of planned reservoirs that is expanded and completed after reservoir construction is the first prerequisite for successful research in this direction.

The aims of research may be summarized as follows: (1) modification of climate by large and small water bodies; (2) prediction of movement of water including circulation, diffusion, waves, and ice phenomena; (3) assessment of techniques for measuring evaporation and its reduction; (4) water balance of reservoirs; (5) meteorological and hydrometeorological factors affecting the chemical, biological, and thermic composition of water.

It will be noted, for example, that the joint research program of the Canadian and United States scientists, the International Field Year for the Great Lakes [*Richards*, 1967], well expresses such aims, although this program is not concerned with man-made lakes. Thus a rigid line may not and should not be drawn between research on natural and man-made lakes.

Immediate and urgent needs call for studies of evaporation and its suppression, standardization of all observations, development of instruments, and methods for evaluation of drag and stress coefficients in the establishment of wind profiles above water surface. More and more apparent is the need for the control of precipitation washout of pollutants, be they phosphates, nitrates, or toxic metals and gaseous exchanges at the air-lake interface; this control is important for the biological productivity of lakes. There is a need to follow closely the thermal pollution of reservoirs and its possible influence on meteorological and limnological conditions.

First attempts have been made to establish mathematical models of atmospheric circulation over large and small lakes (including man-made lakes as reported in this volume). The refinement of such models [*Strong*, 1968; *Timofeev*, 1963] may represent the most valuable tools of prediction of the interaction of man-made reservoirs and the atmosphere, which for the time being depends largely on observations of existing reservoirs and even more so on observations of natural lakes.

At the University of Pennsylvania a single-layer model simulating the mesoscale lake disturbance and including evaporation from and precipitation to the lake was developed. A vertical cross-section model complemented the single-layer model to eliminate its simplifications. This cross-section model generated a realistic lake storm disturbance [*Lavoie et al.*, 1970].

The World Meteorological Organization through its programs of the World Weather Watch, its efforts within the Global Atmospheric Research and Man and His Environment, its operational hydrology programs, and in particular its commissions for hydrology, climatology, and atmospheric sciences is ready to contribute to research in all the above-mentioned directions as it has in the past. There is no doubt that research on air-lake interaction in general and on man-made reservoirs in particular is gaining momentum.

REFERENCES

Ackermann, H. J., and G. A. Rabchevsky, Applications of Nimbus satellite imagery to the monitoring of man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Bellaire, F. R., F. C. Elder, and A. E. Strong, Lake Michigan meteorological data 1963-1966, *Spec. Rep. 30*, pp. 316-339, Gt. Lakes Res. Div., Univ. of Mich., Ann Arbor, 1967.

Borushko, I. S., Effect of reservoirs on air temperature and humidity of a coast, *Leningrad Gl. Geofiz. Observ. Tr.*, no. 182, 38-49, 1965.

Breier, A., The influence of lakes upon local climatical conditions, *Hidroteh. Gospod. Apelor Meteorol.*, *11*(12), 631-636, 1966.

Brown, D. M., G. A. McKay, and L. J. Chapman, The climate of southern Ontario, *Climatol. Stud. 5*, p. 5, Meteorol. Br., Can. Dep. of Environ., Toronto, Ont., 1968.

Bruce, J. P., Meteorological factors affecting the freshwater environment, *Gt. Lakes Res. Div. Univ. Mich. Publ.*, *10*, 140-148, 1963.

Bruce, J. P., and J. Nemec, World Weather Watch and its implications in hydrology and water resources management, *WMO/IHD Proj. Rep. 4*, World Meteorol. Organ., Geneva, 1967.

Bruce, J. P., R. K. Lane, and H. S. Weiler, Processes at the air-water interface, Proceedings of the 11th Conference on Great Lakes Research, *Gt. Lakes Res. Div. Univ. Mich. Publ.*, *17*, 268-284, 1968.

Budyko, M. O., *Thermal Balance of the Earth Surface*, Gidrometeoizdat, Leningrad, 1956.

Changnon, S. A., Effect of Lake Michigan on severe weather, Proceedings of the 9th Conference on Great Lakes Research, *Gt. Lakes Div. Univ. Mich. Publ.*, *15*, 220-234, 1966.

Changnon, S. A., Precipitation climatology of Lake Michigan basin, *Ill. State Water Surv. Bull.*, *52*, 46 pp., 1968.

Davidson, K. L., Influence of stability on cloud cover and incident solar radiation over Lake Michigan, *Spec. Rep. 30*, pp. 271-295, Gt. Lakes Res. Div., Univ. of Mich., Ann Arbor, 1967.

Fontes, J. C., Isotopic composition and origin of atmospheric water vapor in the region of Lake Leman, *Earth Planet. Sci. Lett.*, *7*(4), 325-329, 1970.

Fraedrich, K., Land and sea breeze system of Lake Victoria from aerological data, *Arch. Meteorol. Geophys. Bioklimatol., Ser. A*, *17*(2/3), 186-206, 1968.

Gregory, S., and K. Smith, Local temperature and humidity contrasts around small lakes and reservoirs, *Weather*, *22*(12), 497-506, 1967.

Holmes, R. M., Effect on the atmospheric boundary layer of three small man-made prairie lakes in Alberta, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Hounam, C. E., Problems of evaporation assessment in the water balance, *WMO/IHD Rep. 13*, World Meteorol. Organ., Geneva, 1967.

Kornienko, V. I., The effect of evaporation from Lake Baikal on precipitation in adjacent regions, *Leningrad Gl. Geofiz. Observ. Tr.*, no. 247, 122-126, 1969.

Kossowska, U., Effects of the water surface on temperature and humidity conditions from observations in the Lake District in the summer of 1962, *Pr. Stud. 2,* pp. 32–61, Inst. Geogr. Katedra Klim., Warsaw Univ., Warsaw, 1967.

Kovacs, Z., Influence of Lake Balaton on the temperature and vapor pressure of air flowing over it, *Idojaras, 69*(1), 49–51, 1965.

Krishnamurthy, K. V., and A. M. Ibrahim, Hydrometeorological studies of Lakes Victoria, Kyoga, and Albert, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Laichtman, D. L., *Physics of the Earth Boundary Layer of the Atmosphere,* Gidrometeoizdat, Leningrad, 1961.

Lavoie, R. L., W. R. Cotton, and J. B. Hovermale, Investigations of lake-effect storms, report, contract E22-103-68(N), 127 pp., Dep. of Meteorol., Pa. State Univ., University Park, 1970.

Lyons, W. A., Some effects of Lake Michigan upon squall lines and summertime convection, *Res. Proj. Res. Pap. 57,* 22 pp., Dep. of Geophys. Sci., Satell., and Mesometeorol., Univ. of Chicago, Chicago, Ill., 1966.

McVehil, G. E., and R. L. Peace, Some studies of lake effect snowfall from Lake Erie, *Gt. Lakes Res. Div. Univ. Mich. Publ., 13,* 262–272, 1965.

Monin, A. S., and A. M. Obukhov, Basic laws of the turbulent mixing in the earth boundary layer of the atmosphere, *Tr. Geophys. Inst.,* no. 24, 1954.

National Center for Atmospheric Research, Assessment of atmospheric effects of Lake Nasser, *Int. Ass. Sci. Hydrol. Publ., 71,* 865–880, 1966.

Okolowicz, W., Cloud cover and precipitation of certain summer months of 1962–1963 in the region of the large Masurian lakes, *Pr. Stud. 2,* pp. 113–137, Inst. Geogr. Katedra Klim., Warsaw Univ., Warsaw, 1967.

Okolowicz, W., and M. Stopa, Results of field research in the Mazury lakes area in July and August 1961, *Pr. Stud. 1,* pp. 104–119, Inst. Geogr. Katedra Klim., Warsaw Univ., Warsaw, 1964.

Pelko, I. R., Dew, mist and fog in the region of the large Mazurian lakes during the summer months of 1961–1963, *Pr. Stud. 2,* pp. 109–112, Inst. Geogr. Katedra Klim., Warsaw Univ., Warsaw, 1967.

Richards, T. L., An introduction to the International Field Year for the Great Lakes, Proceedings of the 10th Conference on Great Lakes Research, *Gt. Lakes Res. Div. Univ. Mich. Publ., 16,* 441–446, 1967.

Rodhe, B., Studies on the effect of lake regulation on local climate, *Swed. Meteorol. Hydrol. Inst. Medd., Ser. B, 28,* 61–77, 1968.

Seda, Z., Hydrological and meteorological influences on sodding of shores of reservoirs, *Wetter Leben, 18*(11/12), 230–236, 1966.

Stopa, M., Frequency of storm occurrence in the region of the large Masurian lakes, *Pr. Stud. 2,* pp. 138–144, Inst. Geogr. Katedra Klim., Warsaw Univ., Warsaw, 1967.

Strong, A. E., Spring lake anticyclone: Its inducement on the atmospheric and water circulations, *Spec. Rep. 34,* 146 pp., Gt. Lakes Res. Div., Univ. of Mich., Ann Arbor, 1968.

Timofeev, M. P., *Meteorological Regime of Reservoirs* (in Russian), 290 pp., Gidrometeoizdat, Leningrad, 1963.

Timofeev, M. P., and T. V. Kirillova, The procedure of complex investigation of reservoirs, Symposium of Garda, *Int. Ass. Sci. Hydrol. Publ., 70,* 1966.

Tsai, Y. J., and D. R. De Harpporte, Cooling pond fog prediction model, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

USSR Hydrometeorological Service, *Manual for Processing of Observational Data on Lakes and Reservoirs,* Gidrometeoizdat, Leningrad, 1957.

Verbolov, V. I., V. M. Sokol'nikov, and M. N. Shimaraev, *Hydrometeorological Regime and Heat Balance of Lake Baikal,* 372 pp., Izdatvo Nauka, Moscow, 1965.

Vikulina, Z. A., and E. M. Seljuk, Study of hydrometeorological regime of large reservoirs of the USSR, Symposium of Garda, *Int. Ass. Sci. Hydrol. Publ., 70,* 1966.

World Meteorological Organization, Measurement and estimation of evaporation and evapotranspiration, *Tech. Note 83*(WMO 201, TP 105), Geneva, 1966.

World Meteorological Organization, Guide to *Meteorological Instrument and Observing Practices, WMO 8, TP 3,* 3rd ed., Geneva, 1968*a*.

World Meteorological Organization, *Technical Regulations, WMO 49,* vol. 1, 3, Geneva. 1968*b*.

World Meteorological Organization, *Guide to Hydrometeorological Practices, WMO 168, TP 82,* 2nd ed., Geneva, 1970.

Zaitsev, A. S., and N. V. Serova, Some results of meteorological observations on Lake Valday from a specially equipped boat, *Sov. Hydrol. Selec. Pap.,* no. 1, 72–79, 1965.

Effect on the Atmospheric Boundary Layer of Three Small Man-Made Prairie Lakes in Alberta

R. M. HOLMES

ERA Sciences Ltd., P.O. Box 3444, Station B, Calgary, Alberta, Canada

This paper describes a study of oases produced by three man-made prairie lakes in southern Alberta. Observations made by using an instrumented aircraft and a mobile ground-based station were taken over and near the lakes, which were surrounded mainly by semiarid prairie land and dryland farms. One lake had an irrigated project near one side. The study was undertaken to show that important and complex climatic modifications, measurable only from an airborne platform, occur in the vicinity of such lakes. The data obtained are insufficient to apply to boundary layer theory, but they do present a three-dimensional picture of observed phenomena near and above such oases.

The effect on climate of large surface features such as islands, mountains, wooded hills, and lakes has been investigated by using surface observations [*Bergeron*, 1960; *Berry et al.*, 1945; *Geiger*, 1957; *Gregory and Smith*, 1967; L. Fritchen, private communication, 1969]. The available data show that air passing over the earth is in a dynamic state and has properties that are continually changing to reach equilibrium with the surface. The effects of some surface features are often noted at great heights and over wide geographic areas. The effects of many of these features on the climate can be difficult to characterize because of the size or nature of the areas involved. As the feature becomes smaller in extent, its effect on the atmosphere becomes less noticeable and is more obscured by the proximity of other features. Nevertheless, it is possible to describe atmospheric processes in and near the boundary layer on a continually reducing space and time scale.

The term 'oasis effect' describes the occasional, abnormally high evaporation rates that occur from an area with a moisture content higher than that of the surrounding terrain. The oases first accurately reported were either irrigated agricultural experimental plots or areas in and near moist lysimeters that were entirely surrounded by hotter and drier agricultural land. In each case the surrounding terrain was a source of large amounts of advectable heat. Use of the term is easily expanded to account for the climatological or meteorological results of discontinuities in the moisture characteristics of the earth-air interface. Discontinuities in interface moisture may result from many things, including vegetation, soil, and free water.

Most studies of the climatic effects of mesoscale oases such as lakes have been carried out entirely on the basis of surface observations. However, the effect on the atmosphere of these features reaches a considerable height above the ground and continues downwind from the area [*Bunker*, 1953; *Geiger*, 1957; *Lorenz*, 1966; *Malkus and Stern*, 1952]. If a complete study of an oasis or other feature and the atmosphere is to be made, an airborne observational platform must be used. With an instrumented aircraft, observations can be made that will permit a complete spatial characterization of the relationship between the surface and the atmosphere. The total three-dimensional effect on the climatology and hydrology of areas of terrain can then be described by using only a few ground stations to provide the observational transition from the ground to the lowest air layers. The aircraft can provide the observational continuity to the atmosphere in the horizontal and vertical directions. The work of *Dutton and Lenschow* [1962], *Lenschow* [1965], *Malkus* [1953, 1954], *Malkus and Stern* [1952], and others suggests this point of view.

STUDY AREAS

To determine the vertical and horizontal extent of the atmospheric influence of strong oases in the prairie, three small man-made lakes were chosen in southern Alberta, Canada. Each of these lakes is at least 15 years old and was created mainly to serve the needs of irrigation. However, each lake is surrounded by arid to semiarid prairie and dry-farm land.

Lake Pakowki was created in the old basin of a large Pleistocene glacial lake situated in southeast Alberta. It is shallow (average depth approximately 3 meters), nearly always turbid, and high in alkali salts, and it has a widely fluctuating annual water level. The surrounding terrain is composed of dry-farm land and rangeland extending to the western edge of the Cypress Hills. One small area of irrigated forage is situated on the southeast side of the lake, but, in general, the surrounding ground surface is flat and dry for most of the summer (spring and summer rainfall comes mostly from convection storms and averages 5 cm).

Lake Newell is a deeper lake (average depth of 12 meters), is roughly oval in shape (13 × 5 km), and is oriented north and south. It lies to the east of an extensive area of dryland farms. East of the lake are two small regions and one large area of irrigation. The nonirrigated land has a mainly undulating topography of uncultivated virgin prairie or rangeland.

St. Mary Reservoir is located near the southwest foothills of Alberta and is surrounded by dryland farms of large acreage. It was created by a dam across the St. Mary River, and the shape follows that of the river coulee and varies in depth up to about 30 meters. The long axis of the lake is oriented northeast-southwest (18 km) and is approximately 3 km at the greatest width. The location and shape of these lakes are shown in Figure 1 in relation to other geographic features in southern Alberta.

INSTRUMENTATION AND EXPERIMENTAL METHOD

Instrumented aircraft have been used for many years to carry out research in cloud physics and weather modification [*Bunker*, 1953; *Malkus*, 1953, 1954; *Malkus and Stern*, 1952; *Simpson and Simpson*, 1966; *Telford and Warner*, 1962]. Published accounts of aircraft use in climatology are also available but are less frequent [*Barry and Chambers*, 1966; *Dutton and Lenschow*, 1962; *Holmes*, 1969*a*, *b*; *Lenschow*, 1965; *McFadden and Ragotzkie*, 1963; *Richards and Massey*, 1966; *National Center for Atmospheric Research*, 1967; *Lenschow and Dutton*, 1964]. In the research described in this paper a light twin-engine and a single-engine aircraft, both described in detail by *Holmes* [1972], were used. Part of the instrumentation in one aircraft is shown in Figure 2. In the final stages of the development of these instrument systems, there was the ability to measure the flux of heat and water vapor. However, the measurements reported here were obtained in the early stages of the development program when only temperature sensors were available. A fast-response electrical resistance element and a temperature-sensitive diode were used as sensors, and the data were recorded on magnetic tape in digital form. The sensors were calibrated and were accurate to 0.1°C. Surface temperature measurements were made with a radiation thermometer corrected for emissivity variations of the surface as described by *Holmes* [1969*b*, *c*]. Measurements of surface temperature are accurate to 1.0°C, and temperature differences are accurate to 0.2°C. Observational height was <300 meters and, consequently, atmospheric water effects were negligible. Air temperature near the surface at 2 meters was measured by using a sensor and indicator-recorder arrangement mounted on a car. The sensor was supported on a 50.8-mm (2-inch) outside diameter aluminum pipe strapped to the roof rack and held about 4½ meters in front of the car. The car was driven to predetermined observational points that coincided as closely as possible to airborne observation points. Measurements were made when the car was in motion.

The general airborne observational procedure required that the aircraft be flown at various altitudes down to 15 meters above the surface. Ground surface and air temperatures were associated with ground fixes for position reference. Transections across the area of interest were flown at various horizontal intervals along north-south lines. Horizontal intervals flown varied depending on wind speed. With this technique, measurements were taken at one level from north to south; then the altitude was increased to the next observational level, and measurements were taken from south to north over the same ground track. The ground track was then horizontally displaced by an appropriate amount, and measurements were made at the higher altitude, observations being made at the lower altitude on the return transect. Height above ground was maintained by use of a radar altimeter.

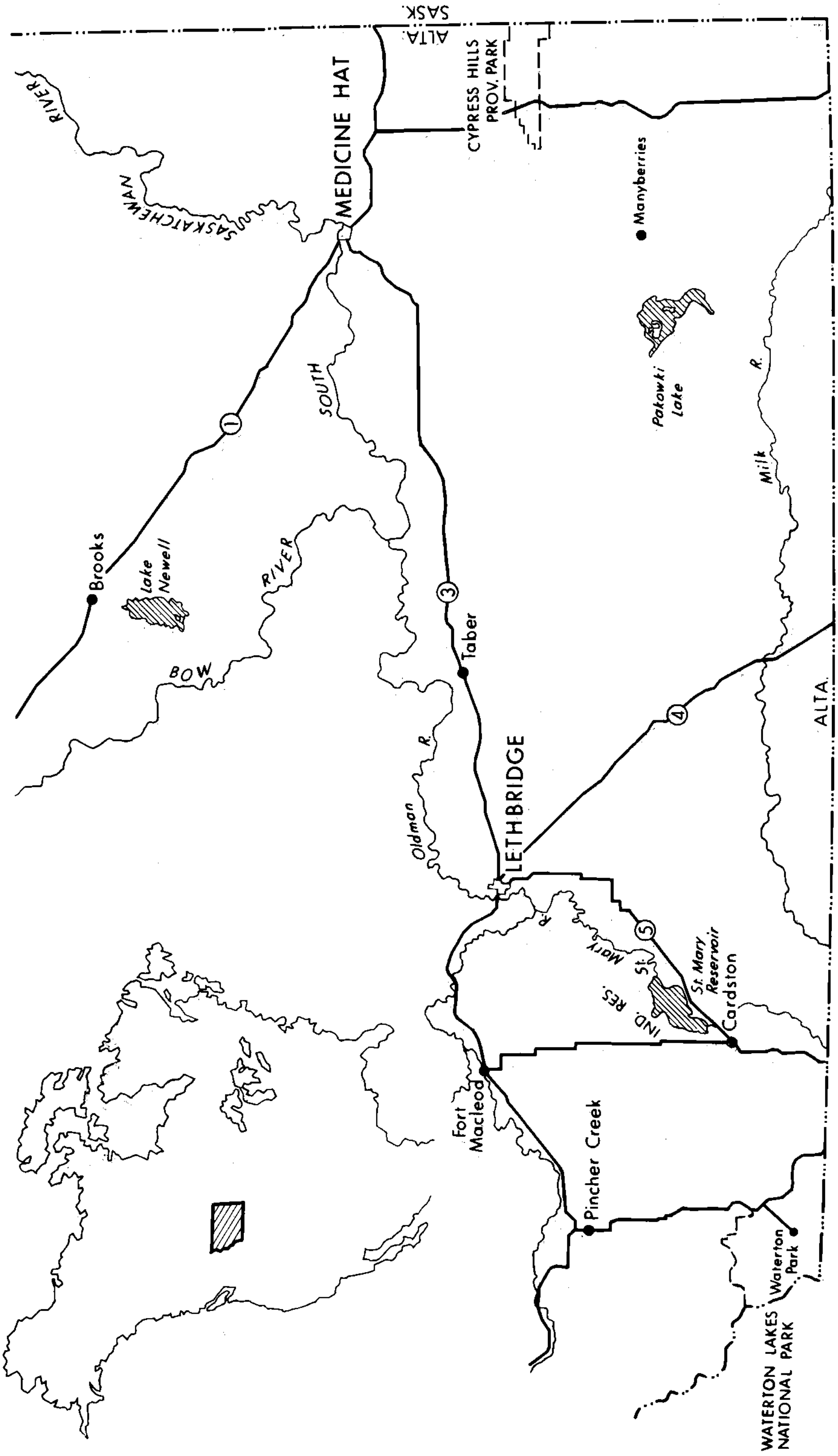
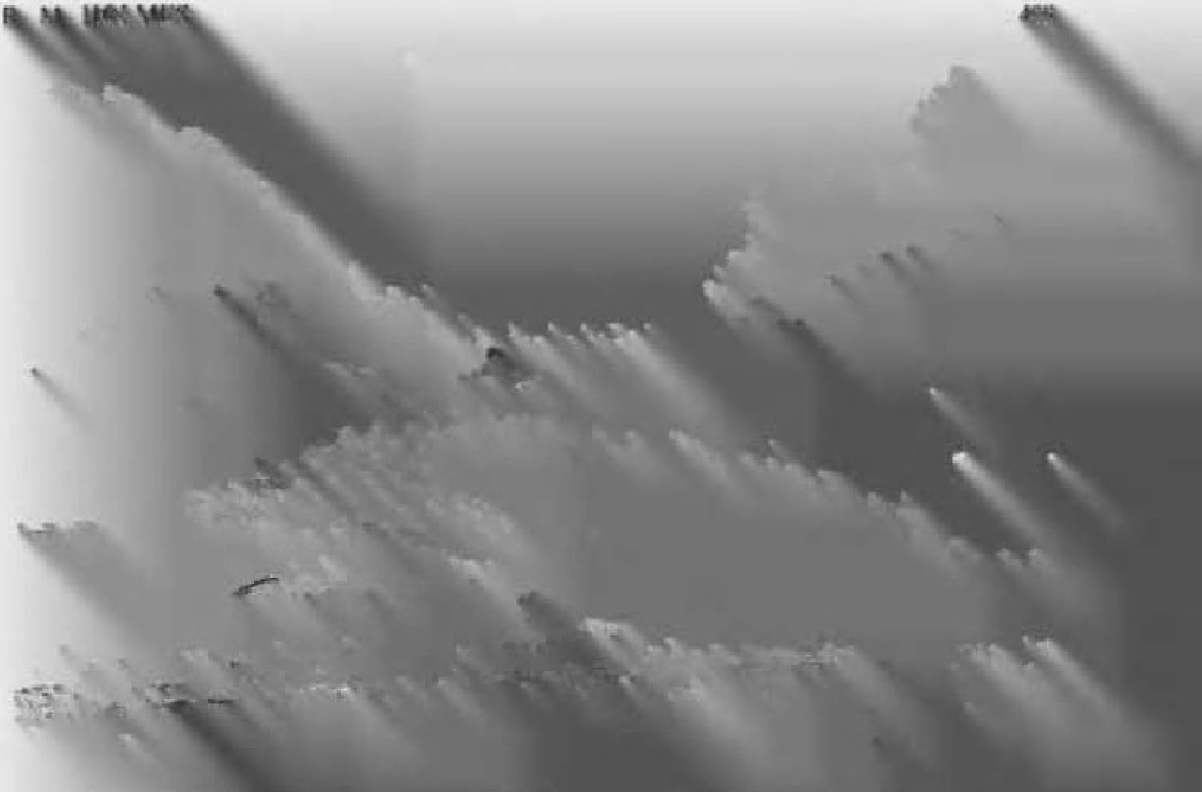
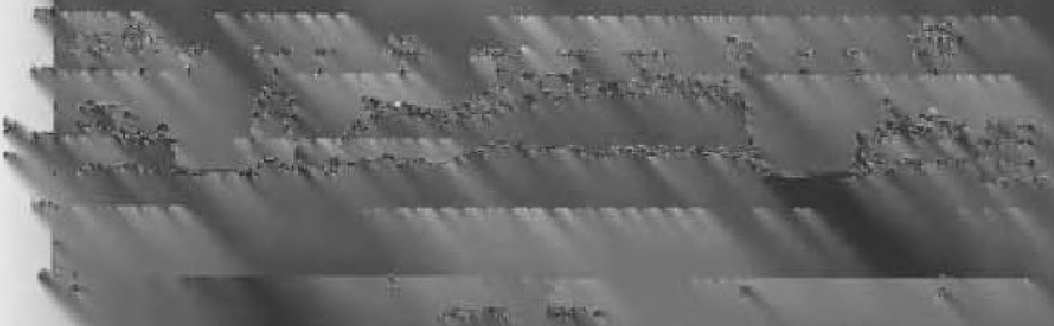


Fig. 1. Lake Pakowki, Lake Newell, and St. Mary Reservoir in southern Alberta in relation to other geographic features.



[illegible]

[illegible]



[illegible]

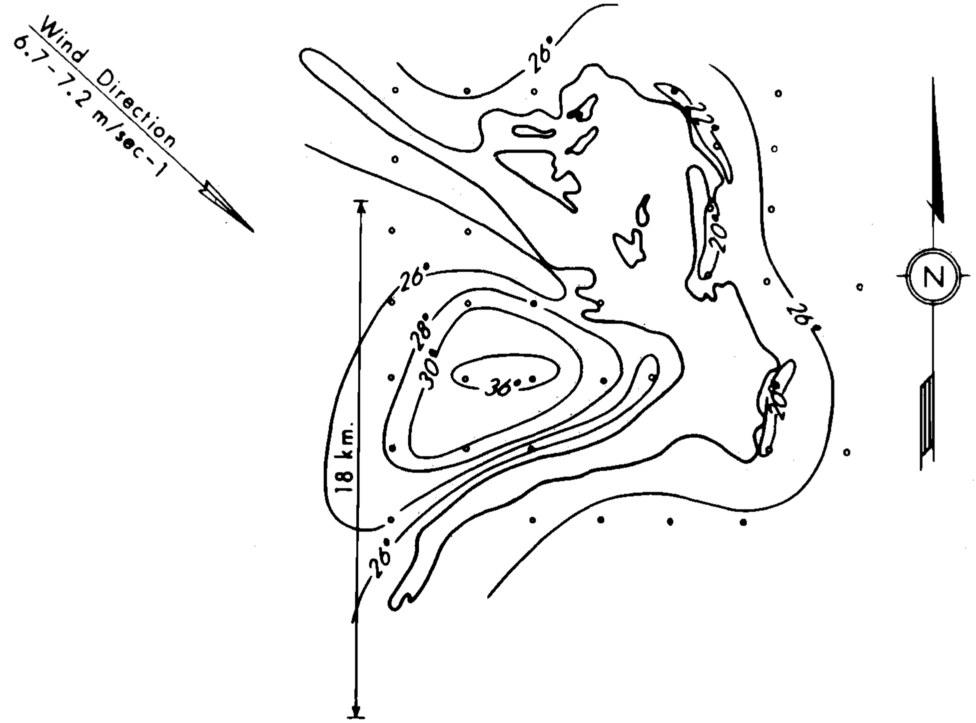


Fig. 4. Isotherms of air temperature and observation grid at 2 meters above the surface near Lake Pakowki (49°20'N, 110°50'W) on August 3, 1967.

temperature are noted, the lake surface temperature being in sharp contrast with the agricultural land surface temperature. Near A (Figure 3) a large community of phreatophytic bush grows, and a drop of approximately 8°C was also noted. A field examination disclosed that the water table was 20–25 cm below the surface whereas the water table was 1.2–1.5 meters below the surface elsewhere on this part of the track. The highest surface temperatures were experienced between B and D, 50°C being exceeded at several points (temperatures of fallow dry land 3 miles upwind averaged 34°–39°C at this time of day). The surface over this part of the track is slightly elevated, and there is very sparse growth of prairie grass. Salt accumulation at the surface was noted in several places with frequent wind-blown depressions (solonetz areas).

The reproduced traces of surface radiation temperature in Figure 3 show temperature variations with time of day. Observations were discontinued after 2100 hours because of darkness. The rapid cooling of the soil surface compared with the cooling of the lake surface was evident as the day progressed. The area of land over the track BCD, which had the highest surface radiation temperatures during the day, also showed the highest temperatures during the evening. These data point to the strong diurnal variation in the character of the oasis around Lake Pakowki.

Figure 4 presents the results of the surface air temperature (2-meter) observations. The isotherms are actual temperature measurements; the small open circles are observation points that coincide closely with the ground position of the airborne observation. The isotherms have the disadvantage of being drawn from single observations at the points indicated. During the observation period it was possible to cover the rather extensive ground track by car in the allotted time (1200–1500 hours) by driving at maximum speeds on country roads. It is to be noted that the highest air temperatures at 2 meters coincide with the highest surface temperatures observed by infrared remote sensing. On the lee of the lake, rather restricted regions of air cooled by the lake are noted. Elsewhere, air temperatures are fairly

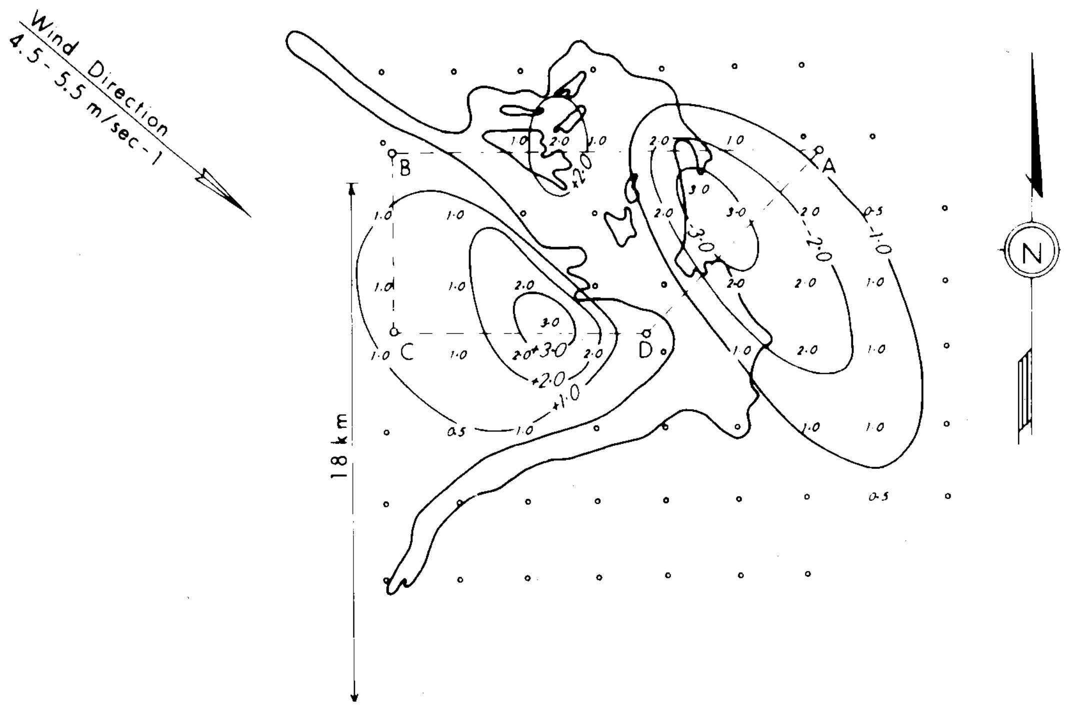


Fig. 5. Isotherms and temperature grid of average air temperature differences (°C) between air temperatures at positions indicated and ambient prairie air temperatures 14–16 km upwind at 15 meters above the surface near Lake Pakowki on August 3, 1967.

constant at 26°C and appear to be relatively unaffected by surface variations. However, it should be noted that the location of heated air parcels at 2 meters was restricted to known heat sources on the surface.

Ten airborne transections were made in the north-south direction at heights of 15 and 45 meters. The horizontal extent of air temperature measurements covered the area shown in Figures 5 and 6. The data presented are the average of 3 hours of observations between 1200 and 1500 hours, August 3, 1967. The isotherms and temperature grid represent temperature differences in degrees Celsius between the air at the indicated position and the ambient prairie air 14–16 km upwind of that position at the same elevation above the surface. Wind speed and direction were measured at a 15-meter height 15 km upwind of the indicated position. Each set of temperatures measured at 15 and 45 meters above the lake was followed by the measurement of the upwind air temperature at 15 and 45 meters above the ground. Generally, it was found that ambient prairie air temperature varied very little with time. A super adiabatic (unstable) lapse existed at all times over the area and during the time indicated. At the upwind measuring point the air temperature near the surface (2 meters) was 31.5°–33.5°C during the study period. On the day shown the variation with time was 24.7°–23.6°C from 1200 to 1500 hours at an altitude of 15 meters and was 23.6°–22.9°C during the same period at an altitude of 45 meters. The student's *t* test was used to determine the significance of the temperature differences shown in the figures. These values are significant only at the 1% level. Where the value is not significant at the 5% level, the small open circle is placed at the position where the measurement was taken (Figures 5 and 6).

The effect of the lake on the temperature of the air passing over it was noted at both levels: there was maximum cooling of 3°C at a height of 15 meters (Figure 5) and 2°C at a height of 45 meters (Figure 6). The isotherms and temperature grid in Figures 5 and 6 show the average position of the cold and warm air 'parcels' for the 3-hour period. Whereas at 75

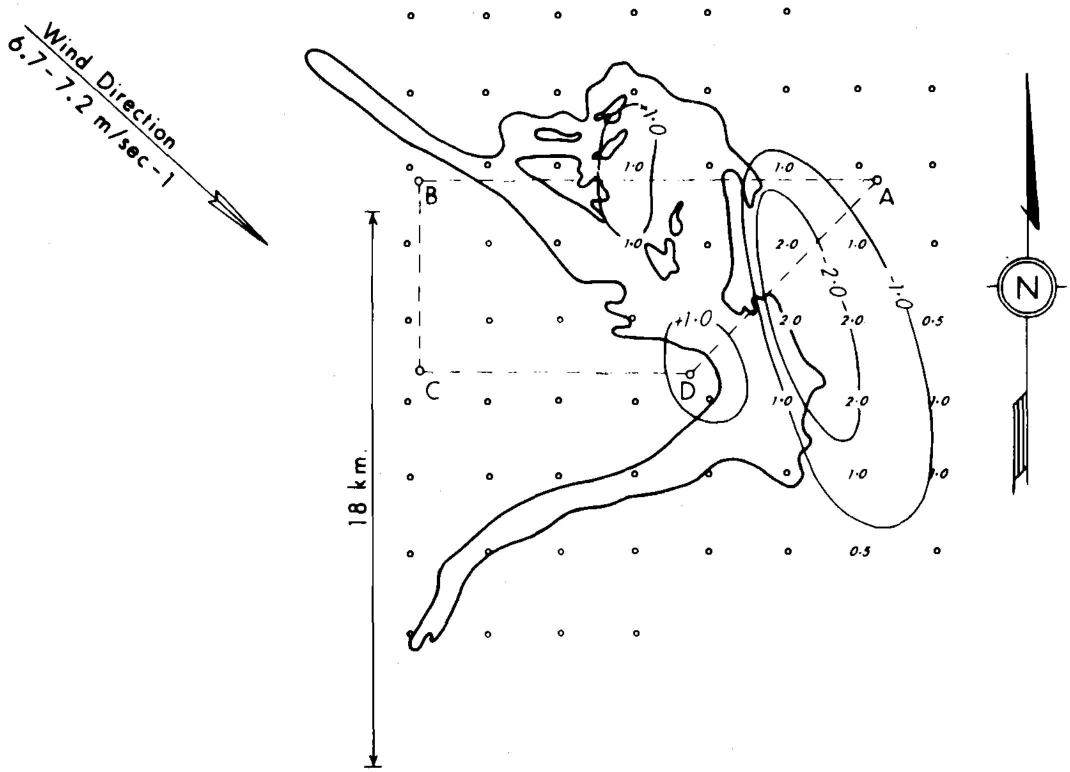


Fig. 6. Isotherms and temperature grid of average air temperature differences (°C) between air temperatures at positions indicated and ambient prairie air temperatures 14–16 km upwind at 45 meters above the surface near Lake Pakowki on August 3, 1967.

meters there was no measurable effect on this particular day, on a calmer day a 3°C cooling was noted up to 120 meters; however, the effect was more restricted horizontally. The radiation temperature traces and air temperatures at 2 meters indicate that warm air rises from the island and from the area between the two easterly arms of the lake, and there is ample reason to believe that momentum conserved downwind and above the oasis may carry aloft air parcels cooled by evaporation.

It is somewhat surprising that the regions of cool temperatures at 15 and 45 meters are almost entirely displaced from the lake; even the region of coolest temperature on the lee shore does not extend over the shore exposed to the largest fetch. Doubtless, lateral mixing from the heated shoreline over this narrow water fetch would tend to place the coolest air to the north of the longest fetch. During the study period and also during August of 1966 and 1967 when transects were flown over the lake, it was discovered that the shape and position of the cooled and heated air were highly variable and largely a function of daytime heating, wind speed, and direction. The data presented show the average position of the heated and cooled air during the study period. The reason for the position of the cooled air being displaced to the lee as much as is shown is not immediately obvious. At no time was cooling noted at altitudes of >120 meters above the terrain, and at no time was cooling measurable farther than 11 km from the lee edge of the lake. There were many days when no air cooling was measurable regardless of height or position. These days were usually cooler and windy.

The airborne observations are in contrast to the observations at 2 meters. It was noted that at ground level the areas of markedly heated air coincided closely with the soil surfaces that provided the energy and that there was very little tendency to locate downwind near the surface. This 'local effect' at ground level was offset by the marked displacement of thermally altered air at

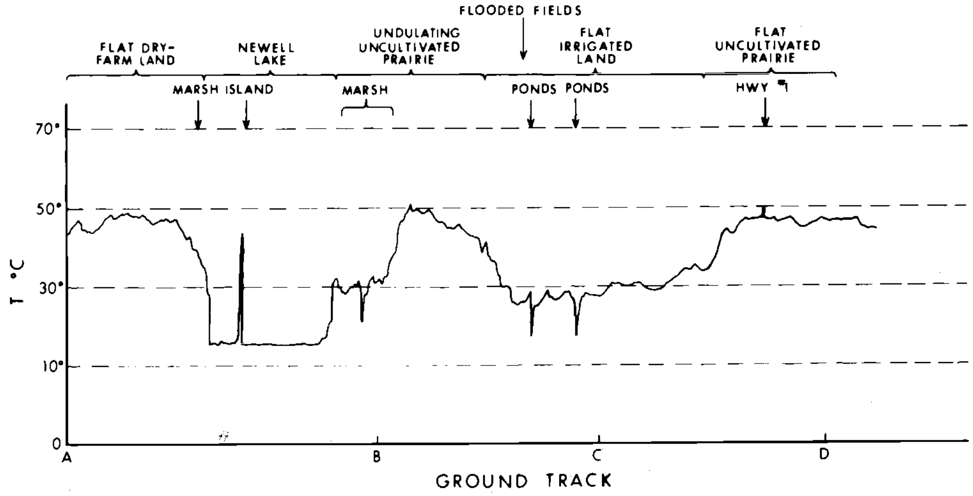


Fig. 7. Surface radiation temperatures (°C) over ground track ABCD near Brooks, Alberta (50°25′N, 111°55′W), shown in Figures 8 and 9.

higher elevations. Obviously, however, warm air is advected at the surface, since the temperature of the air over the irrigated area to the east of the lake, for example, decreases with fetch.

Lake Newell. The area surrounding Lake Newell is a rather diversified surface and was chosen for this reason. Further, the terrain is fairly level and presents an ideal situation for airborne observations. The degree of variation in the surface temperature was obtained with a radiation thermometer. The data (Figure 7) show the strong oasis created by Lake Newell. The ground track is shown in Figure 8.

The general weather during the period was bright sunshine with light and variable surface winds. The surface temperature of Lake Newell contrasted with the heated surrounding land between A and B (Figure 7). The lake has an average depth of 12 meters, and the surface temperature was uniform at 16°C. From observation point B to C the surface temperature exceeded 50°C and then dropped to near 30°C over the irrigated area. The flat prairie approaching D had a surface temperature of approximately 46°C. It should be pointed out that a certain amount of curve smoothing occurs in the process of applying the surface emissivity to the raw data, as is described elsewhere [*Holmes*, 1969*a*]. However, the surface temperature detail that demonstrates the general temperature anomalies at the surface is preserved.

The study area was rather extensive, and it was not possible to cover the region adequately by car in a single day to measure air temperature at 2 meters during the period of maximum daytime heating (1200–1600 hours). A portion of the dry-farm land to the west and part of the large irrigated area to the east of the lake were studied over a 2-day period (August 6 and 7, 1968) when similar conditions prevailed. The data are shown in Figure 8, the small open circles indicating observation points. It can be seen that heated or cooled air is local to the particular surface, cooler conditions existing over the irrigated land and warm air occurring over the surfaces that are heated.

Airborne measurements of air temperature were made over a 1.6-km (1-mile) grid covering the entire area at heights of 20 and 40 meters. The data were obtained and analyzed in a manner similar to that used for Lake Pakowki. Figure 9 shows the temperature differences between air at the positions indicated and air at the same altitude but 10 km upwind from Lake Newell. The student's *t* test was used to determine the significance of the temperature differences, and only those differences significant at the 5% level are shown.

A complex temperature pattern was evident: warm air occurred over several dry-farm land areas, and cooled air occurred over irrigated land and Lake Newell. At 20 meters the maximum significant heating noted was 2.0°C, and the maximum significant cooling was 3.0°C. Warmed air was measured downwind from the westerly dry-farm land and extended over the lake, whereas

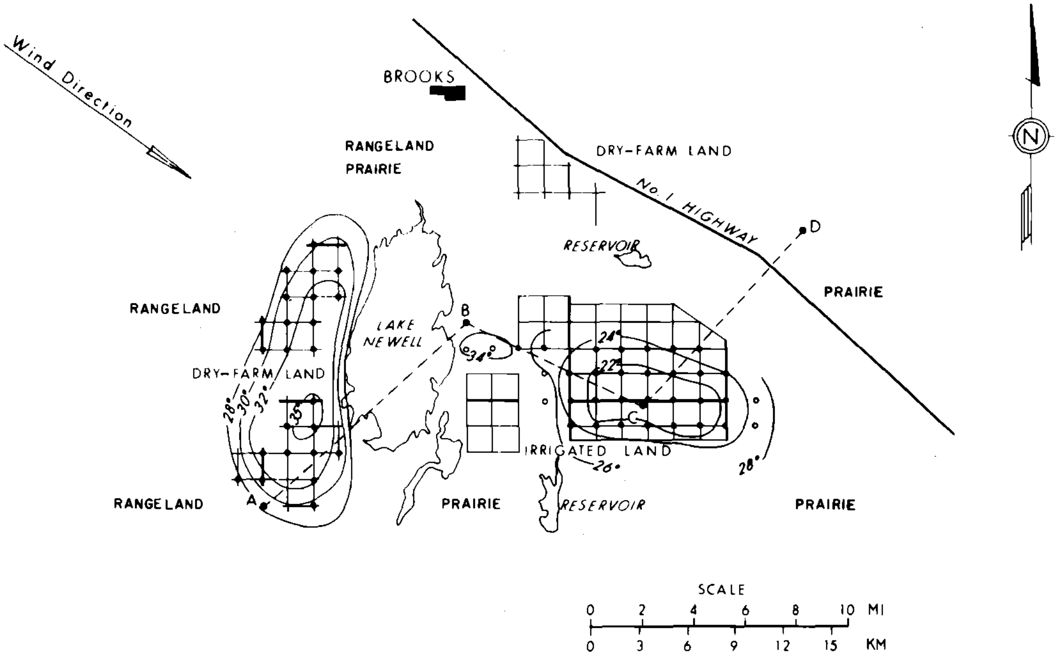


Fig. 8. Isotherms of air temperature and observation grid at 2 meters above the surface of varied agricultural land near Brooks, Alberta, on August 6 and 7, 1968.

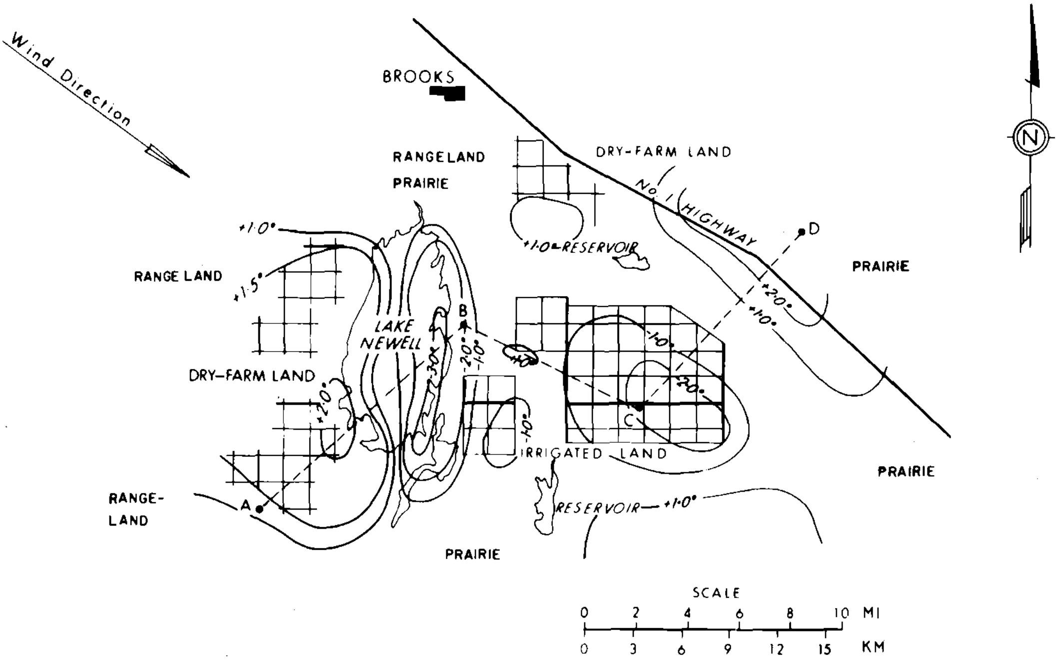


Fig. 9. Isotherms of average air temperature differences (°C) between air temperatures at positions indicated and ambient prairie air temperatures 8 km upwind at 20 meters above the surface near Brooks, Alberta, on August 6, 1968.

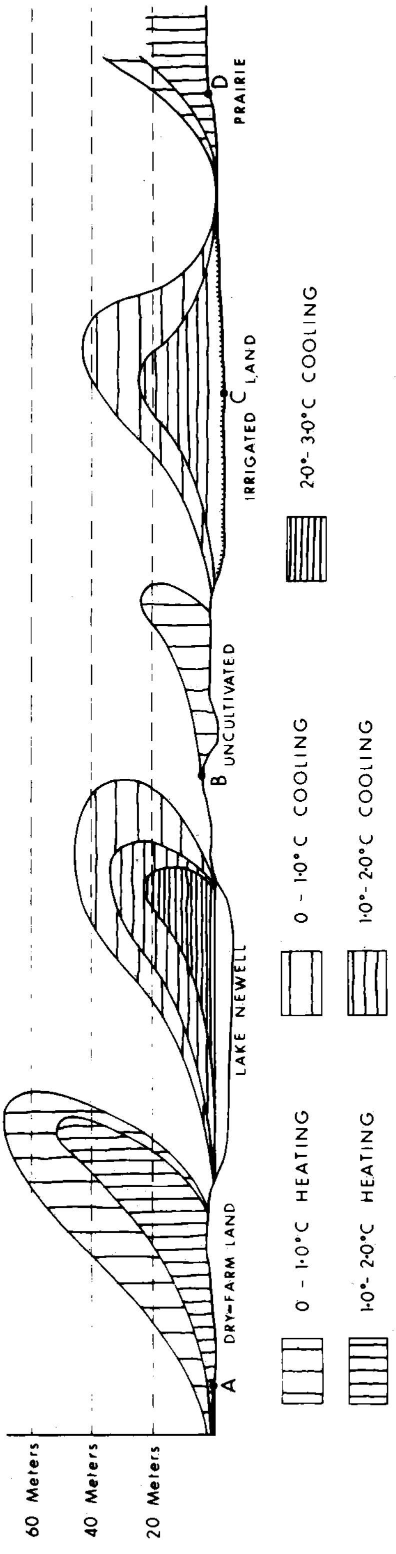
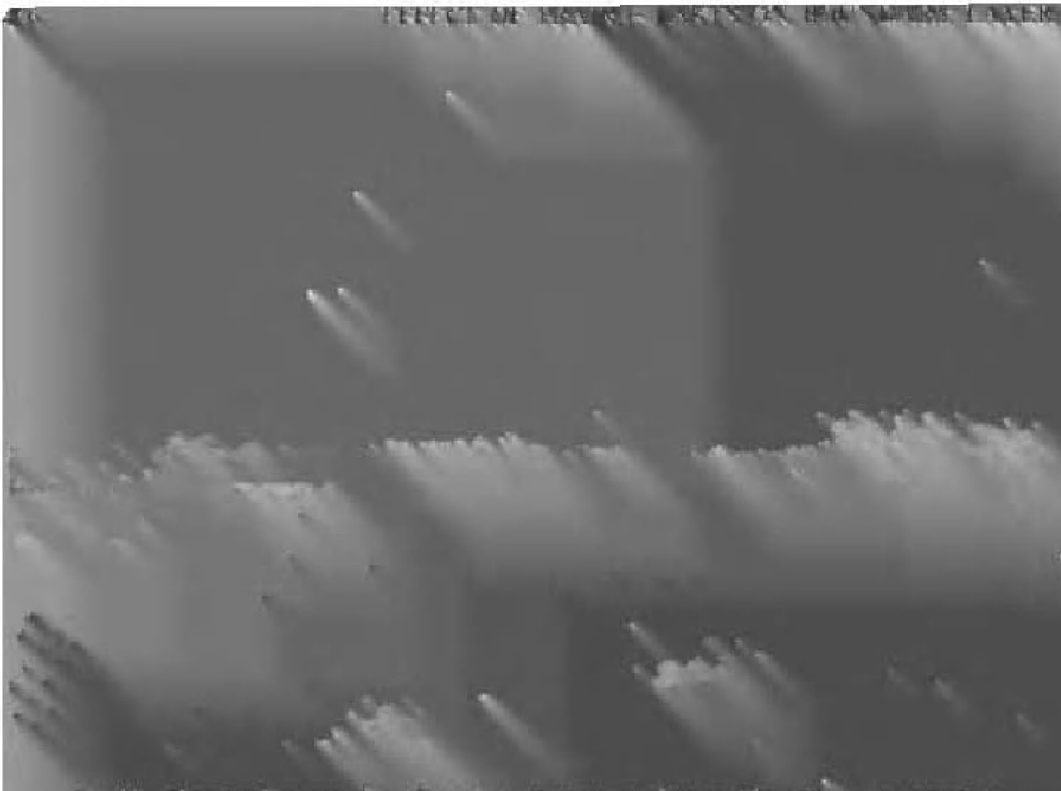


Fig. 10. Temperature profile of air temperatures over ground track ABCD over the area near Brooks, Alberta (shown in Figures 8 and 9), on August 6, 1968.

cooled air from the lake extended over the heated prairie to the east of the lake. Cooled air from the irrigated sections also extended over the heated uncultivated prairie. Heated and cooled air was noted at 40 meters but was not present to the same degree as it was at 20 meters. At 60 meters on this day the air was uniform in temperature over most of the area. The lapse rate was super adiabatic (unstable) to a height of 700 meters. Observations were discontinued at this altitude. It must be remembered that the figures show the average position of heated and cooled air over a 3-hour period. Therefore the true situation at any single moment may be considerably different and much more complex, since the technique used to determine significance of temperature difference is also a smoothing process.

An attempt was made to present the data in a vertical transect (Figure 10). The shapes of the heated and cooled air parcels were deduced from the information obtained at the surface and at heights of 2, 20, 40, and 60 meters above ground on 3 consecutive days. The ground track ABCD is shown in Figure 9. The heated and cooled air rises above and extends over the adjacent land. For example, warm air from near A extends somewhat above and over the lake, and cooled air extends above and over the heated prairie near B. The frequency and positions of observance of heated and cooled air over the 3 days suggest that the shapes of the air parcels are qualitative as indicated. Cooled air remains slightly above but closer to the surface, is more uniform in shape, and is shorter lived than heated air. The heated air rises and seems to break off in parcels that persist to greater heights. The temperature structure of air over this area varied considerably from day to day and was markedly affected by surface heating (radiation) and wind speed and direction.

The effect of advection of warm air on evaporation and evapotranspiration has been studied and is known to greatly increase water losses. The density of measurements in the author's study did not permit a close examination of this phenomenon near the ground where both warm and cold air is seen to advect. The temperature of air at 20 meters over the lake decreases with fetch and indicates that warm air from the dry-farm land is advecting and slowly cooling with fetch. Similarly, air at 2 meters over the irrigated land at C cools with fetch and approaches a minimum temperature downwind;



[illegible]

[illegible]

[illegible]

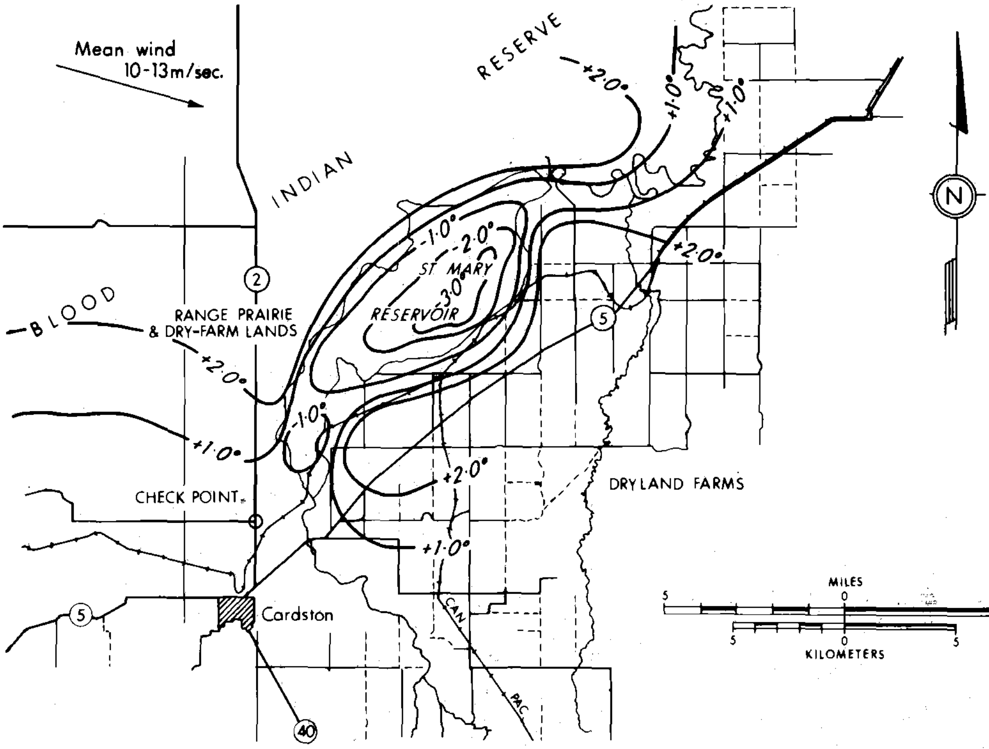


Fig. 12. Isotherms of average temperature differences (°C) between air temperatures at positions indicated and ambient area air temperatures over the checkpoint at 15 meters above the surface of St. Mary Reservoir on August 14, 1969.

cooled air was observed to extend only a distance of about 914.4 meters (1000 yards) beyond the lakeshore. At 30 meters, parcels of cooled air were consistent over the southeasterly half of the lake, but, at 40 meters, cooled air was not measurable. In comparison with the two other lakes studied, cooled air over St. Mary Reservoir on August 10 at 15 meters was more widespread but more restricted in vertical development. It was also noticed that warmed air from the dry land upwind and downwind was also very widespread. Cooling did not occur until near the approach of the mountains. Over the downwind portion of the study area, several small local areas of transient cooled and heated air were noted and were unrelated to identifiable sources or sinks of heat on the ground. These occurrences were possibly parcels of heated or cooled air that had maintained thermal properties obtained upwind.

The flights on August 14 (1300–1500 MST) were made during almost calm conditions, and the vertical development of cooled air extended to 60 meters. Above that altitude, frequent but isolated parcels of cooled air existed in the study area up to 15 km downwind. Figure 13 presents the data taken at 15 meters, and Figure 14 shows that cooled air at 40 meters persisted for up to 4 km downwind. At 60 meters, only a small area showed consistent cooling during the hottest part of the day (Figure 15).

Frequent reference has been made through the discussion pointing to the existence of parcels of heated or cooled air. All the evidence obtained during these studies strongly indicates that such parcels were indeed the case. At no time did the author find evidence of a 'continuous plume' type of structure. Even at 15 meters the atmospheric structure was very much 'parcelized.'

SUMMARY

Two light aircraft instrumented to measure air temperature and radiation temperature of the

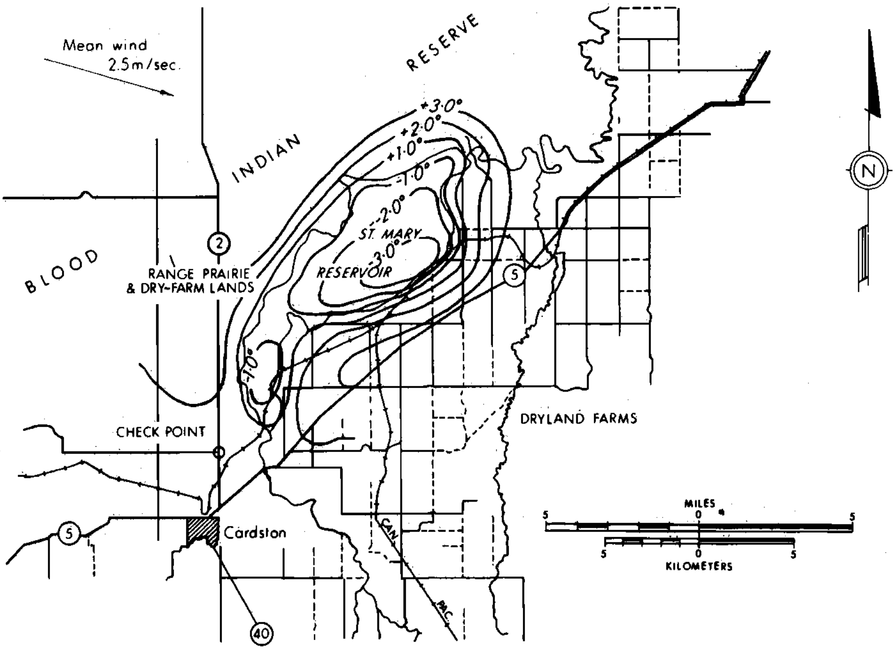


Fig. 13. Isotherms of average air temperature differences (°C) between air temperatures at positions indicated and ambient area air temperatures over the checkpoint at 15 meters above the surface of St. Mary Reservoir on August 14, 1969.

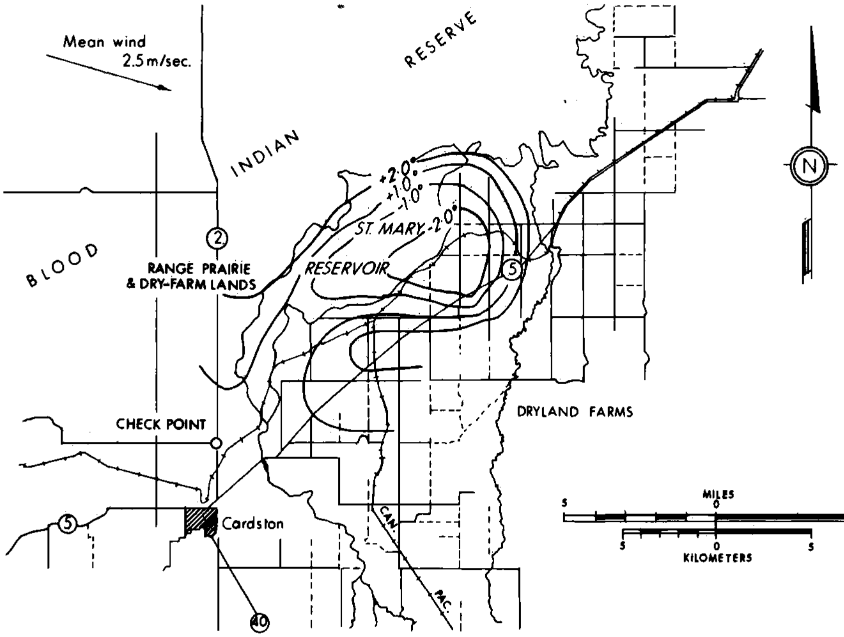


Fig. 14. Isotherms of average air temperature differences (°C) between air temperatures at positions indicated and ambient area air temperatures over the checkpoint at 40 meters above the surface of St. Mary Reservoir on August 14, 1969.

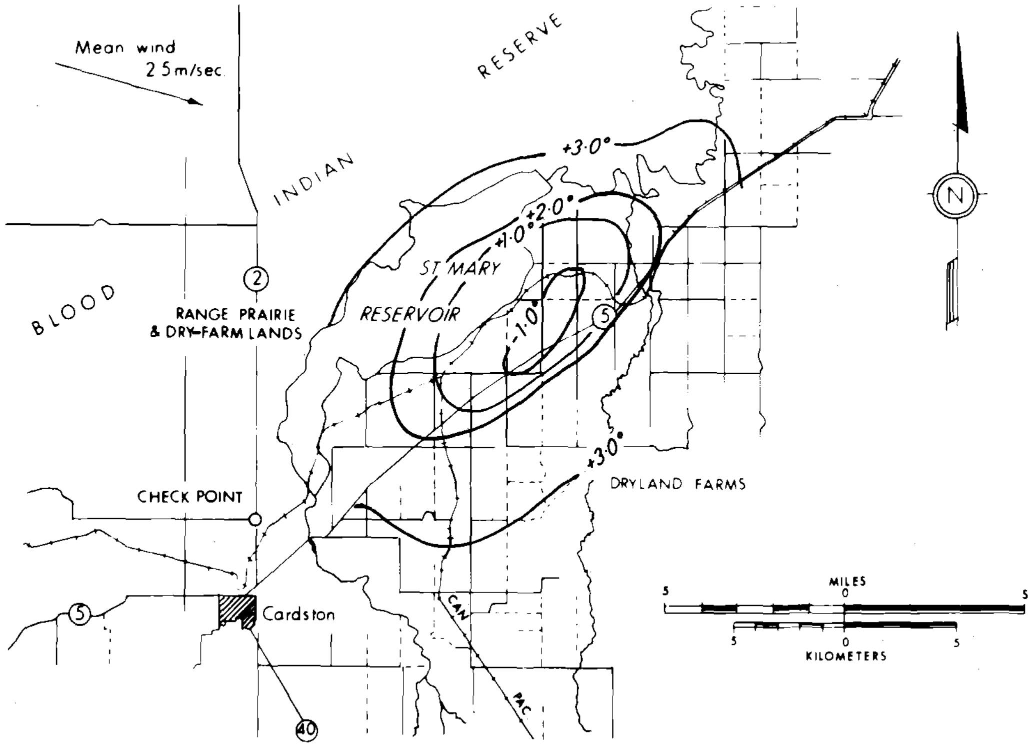


Fig. 15. Isotherms of average air temperature differences (°C) between air temperatures at positions indicated and ambient area air temperatures over the checkpoint at 60 meters above the surface of St. Mary Reservoir on August 14, 1969.

earth's surface were used successfully to identify three prairie oases caused by small man-made lakes. Surface radiation temperature differences between dry and moist areas were large, and temperature differences of air cooled by passage over these areas were measurable. Under the most extreme condition measured, air cooling of 3°C was noted up to 120 meters above Lake Pakowki in southeast Alberta, and this cooled air often persisted as far as 10 km downwind from the lee edge of the lake. Surface temperatures of the surrounding land varied greatly and occasionally were 28°C warmer than the lake surface. Air temperature profiles obtained near Lake Newell and St. Mary Reservoir and their surrounding agricultural area showed the heating and cooling of the atmospheric boundary layer as being due to surface heating and cooling. Up to 3.0°C of heating and 3.0°C of cooling of air near the surface were measured as a result of surface characteristics of agricultural and nonagricultural land and water surfaces. Air cooled by passage over Lake Newell and St. Mary Reservoir persisted for 3–4 km at a height of 40 meters.

Acknowledgment. The work described in this paper was carried out while the author was an employee of Environment Canada, Western Research Section, Calgary, Alberta, Canada.

REFERENCES

Barry, R. G., and R. E. Chambers, A preliminary map of summer albedo over England and Wales, *Quart. J. Roy. Meteorol. Soc.*, *92*(394), 543–548, 1966.

Bergeron, T., Preliminary results of 'Project Pluvious,' *Int. Ass. Sci. Hydrol. Helsinki Publ.*, *53*, 226–237, 1960.

Berry, F. A., Jr., E. Bollay, and R. Beers, *Handbook of Meteorology*, pp. 961–962, McGraw-Hill, New York, 1945.

Bunker, J. W., Investigations into a method of shearing stress determinations from an aircraft in flight, *Ref. 53-52*, Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1953.

Dutton, J. A., and D. H. Lenschow, An airborne measuring system for micrometeorological studies, annual report, contract DA-36-039-SC-90282, Dep. of Meteorol.. Univ. of Wis., Madison, 1962.

Geiger, R., *Climate near the Ground*, 2nd ed., pp. 68–89, Harvard University Press, Cambridge, Mass., 1957.

Gregory, S., and K. Smith, Local temperature and humidity contrasts around small lakes and reservoirs, *Weather, 22*, 497–505, 1967.

Holmes, R. M., Note on low level observations of temperature near prairie oases, *Mon. Weather Rev., 97*(4), 333–338, 1969*a*.

Holmes, R. M., A study of the climate of the Cypress Hills, *Weather, 24*(8), 324–330, 1969*b*.

Holmes, R. M., Oasis effects caused by the Cypress Hills, *Proceedings of the Third Conference on Forest Microclimatology Symposium*, pp. 159–180, Kananaskis Forest Experiment Station, Seebe, Alberta, Canada, 1969*c*.

Holmes, R. M., An airborne instrument system for atmospheric boundary-layer research, *Boundary Layer Meteorol., 5*, 59–76, 1972.

Lenschow, H. H., Airborne measurements of atmospheric boundary layer structure, Studies on the effects of variations in boundary conditions on the atmospheric boundary layer, final report, Dep. of Meteorol., Univ. of Wis., Madison, 1965.

Lenschow, H. H., and J. A. Dutton, Surface temperature variation measured from an aeroplane over several surface types, *J. Appl. Meteorol., 3*, 65–69, 1964.

Lorenz, D., The effect of the long wave reflectivity of natural surfaces on surface temperature measurements, using radiometers, *J. Appl. Meteorol., 5*, 421–430, 1966.

Malkus, J. S., Aeroplane studies of trade-wind meteorology, *Weather, 8*(10), 291–299, 1953.

Malkus, J. S., Some results of a trade-cumulus cloud investigation, *J. Meteorol., 11*, 220–237, 1954.

Malkus, J. S., and M. E. Stern, The flow of a stable atmosphere over a heated island, part 1, *J. Meteorol., 10*, 30–41, 1952.

McFadden, J. D., and R. A. Ragotzkie, Aerial mapping of surface temperature pattern of Lake Michigan, *Gt. Lakes Res. Div. Univ. Mich. Publ., 10*, 1963.

National Center for Atmospheric Research, Proceedings of the atmospheric research aircraft instrumentation workshop and symposium, *Tech. Note NCAR-TN-29*, Boulder, Colo., 1967.

Richards, T. L., and D. G. Massey, An evaluation of the infra-red thermometer as an airborne indicator of surface water temperatures, *Circ. 4354*, Can. Dep. of Transp., Toronto, Ont., 1966.

Simpson, R. H., and J. Simpson, Some aspects of hurricane modification, Project Storm Fury, *Rep. 2-65*, Nat. Oceanogr. and Atmos. Admin., Washington, D. C., 1966.

Telford, J. W., and J. Warner, On the measurement from an aircraft of buoyancy and vertical air velocity in cloud, *J. Atmos. Sci., 19*, 415–423, 1962.

Cooling Pond Fog Prediction Model

Y. J. TSAI AND D. R. DE HARPPORTE

Stone & Webster Engineering Corporation, Boston, Massachusetts 02107

Quantitative evaluation of the effects of the generation of electricity on the environment has recently become a significant factor in power plant site selection and design. Within a certain range of meteorological conditions, evaporation of cooling water from cooling towers or cooling ponds results in fogging, which may reach such a magnitude as to be objectionable to regulatory bodies and/or local communities. Cooling tower plume prediction methods have been given some attention by the engineering community in the past few years, and several sets of predictive equations have been proposed. The prediction of the occurrence and dissipation of fog produced by evaporation from a warmwater surface has been, however, one of the most intractable problems in the environmental sciences. The purpose here is to present a method of predicting the horizontal and vertical extent of fogging produced by cooling ponds.

PHYSICAL BASIS OF MODEL

All bodies of water receive natural heat primarily through short-wave solar radiation and long-wave atmospheric radiation, and they lose heat to the atmosphere by back radiation, conduction, and evaporation. For the case of a cooling pond used for receiving waste heat from a condenser discharge with artificial heat input, the balance of heat transfer will differ from natural conditions by increasing substantially the amount of evaporative heat loss. The water surface temperature in the cooling pond will be raised well above the equilibrium temperature [*Edinger and Geyer*, 1965], and therefore the rate of heat exchange with the atmosphere will be increased.

Fog may form in the surface layer of air when the air becomes saturated because of a drop in temperature to the dew point or because of the enrichment of the air with water vapor. A drop in temperature, an increase of moisture content, or some combination of changing temperature and moisture content is necessary to result in a higher relative humidity, which leads to the reduction in visibility associated with fog. When condensation nuclei are present in the air, the occurrence of fog is facilitated, and smaller changes in the temperature and humidity of the air are necessary to generate fog. One of the principal processes causing changes of the physical characteristics of the air in the surface layer is the heat and moisture exchange between the air and the underlying surface in the case of a cooling pond. The most important factors governing the temperature and moisture distribution and hence the formation of fog in the surface layer of the atmosphere are the vertical eddy diffusion of the substance considered, the horizontal advection, and the latent heat associated with the condensation and evaporation.

The basic mechanism of turbulent diffusion near the ground may be expressed by

$$\partial\phi/\partial t = \nabla \cdot (k\nabla\phi) - \mathbf{V} \cdot \nabla\phi \qquad (1)$$

where ϕ equals the concentration of the diffusing substance, $\partial\phi/\partial t$ equals the local rate of change in the concentration, $\nabla \cdot (k\nabla\phi)$ equals the diffusion term, k equals the turbulent diffusivity of the substance, $\mathbf{V} \cdot \nabla\phi$ equals the advection term, and $\mathbf{V}$ equals the wind velocity. Equation 1 in rectangular coordinates is

$$\frac{\partial\phi}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial\phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial\phi}{\partial z}\right) - u\frac{\partial\phi}{\partial x} - v\frac{\partial\phi}{\partial y} - w\frac{\partial\phi}{\partial z} \qquad (2)$$

The terms of the second-order partial derivatives in (2) are the diffusion of the substances in the x, y, and z directions. The terms of the first-order partial derivatives are the advection of the substance, whereas u, v, and w are the components of the wind velocity **V** in the x, y, and z directions, respectively.

Assume the following:

1. The steady state conditions are that the concentration of the substance is independent of time and that $\partial\phi/\partial t = 0$.
2. The wind direction is coincident with the x axis; i.e., $v = w = 0$.
3. For continuous release along the x axis the longitudinal diffusion is negligible; i.e., $\partial/\partial x\ (k_x\ \partial\phi/\partial x) = 0$.

On the basis of the above assumptions, (2) becomes

$$u\frac{\partial\phi}{\partial x} = \frac{\partial}{\partial y}\left(k_y\frac{\partial\phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial\phi}{\partial z}\right) \tag{3}$$

Equation 3 is the three-dimensional diffusion equation for the lower layers of the atmosphere. In addition to the initial characteristics of the ambient air flowing over the surface of water, the chief characteristics determining the development of fog are the size of the body of water, the temperature difference between water and air, and the turbulent moisture and heat exchange between the surface of the water and the moving air. Neglecting lateral diffusion for the moment and considering the problem of evaporation from a saturated plane surface of finite extent downwind and of infinite extent crosswind, we have

$$u\frac{\partial\phi}{\partial x} = \frac{\partial}{\partial z}\left(k_z\frac{\partial\phi}{\partial z}\right) \tag{4}$$

This problem has been solved by *Sutton* [1943] and *Calder* [1949]. The assumptions and boundary conditions for the solution are the following:

1. The area of the water surface is defined as infinite across wind and finite downwind; i.e., $0 \le x \le x_L$ and $z = 0$, where x_L is the downwind length of the water surface and the origin is the upwind edge of the water.
2. The water surface is on the same level as the surface of the earth, which is assumed to be dry; i.e., $(k_z\ \partial\phi/\partial z)_{z=0} = 0$ for $x < 0$ and $x > x_L$.
3. The mean wind is assumed to be steady and dependent only on the height above ground. The turbulent power law is assumed for the wind speed profile; i.e.,

$$u(z) = \langle u\rangle_1(z/z_1)^p \tag{5}$$

where a value for p is assumed that corresponds to unstable conditions.

4. The vertical turbulent eddy diffusivity is a function of height and is directly related to the wind profile. On the basis of a statistical theory method, *Sutton* [1953] showed that

$$k(z) = \left[\frac{(\frac{1}{2}\pi K^2)^{1-n}(2 - n)n^{1-n}}{(1 - n)(2 - n)^{2(1-n)}}\right] \cdot \langle u\rangle_1{}^{1-n} z_1{}^{-n(1-n)/(2-n)} \lambda^n z^{2(1-n)/(2-n)} \tag{6}$$

which is a function of z only, may be readily inserted into the diffusion equation. In (6), K is the Von Karman constant and $n = 2p/(1 + p)$ (dependent on the wind profile). *Pasquill* [1943] suggested that, for momentum, $\lambda = \nu$ is kinematic viscosity; for vapor, $\lambda = D$ is the molecular coefficient of mass diffusion for the transfer of vapor; and for heat, $\lambda = h$ is the thermometric conductivity.

5. The ambient temperature and the moisture content are constants and can be prescribed as $\phi = \phi_A$ for $x \le 0$ and $z > 0$ and $\phi = \phi_A$ for $x = \infty$ and $z = \infty$.
6. The air at the air-water interface is assumed to be saturated and to be at the temperature of the water; i.e., $\phi = \phi_S$ for $0 \le x \le x_L$ and $z = 0$.
7. Free convection (up to this point) is neglected.

Solution of (4), subject to the prescribed boundary conditions, allows calculation of the vertical heat and moisture flux from the water surface to the atmosphere as well as the heat and moisture distribution downwind from the pond surface. Heat and moisture flux to the atmosphere from a cooling pond is accomplished by vertical diffusion of sensible heat and the water vapor from the water surface. The flux of sensible heat is related directly to the temperature difference between the cooling pond surface and the atmosphere. Since heat accumulates above the water surface with time, replacement of the heated air by cooler air from upwind results in increased heat flux. Therefore the heat flux increases with wind velocity.

Heat flux, as well as moisture flux, also takes place when latent heat is transferred from the pond to the atmosphere during the process of evaporation. The magnitude of this portion of the heat flux is related directly to the moisture content of the air above the water surface in a manner analogous to the relation between sensible heat flux and air temperature. The latent portion of the heat flux and the moisture flux is also directly proportional to the wind velocity.

The change in the vertical distribution of heat and moisture excess over ambient downwind from the cooling pond is shown in Figure 1. At the edge of the pond (profile *a*), there exists a large excess of moisture and temperature near the ground. Downwind from the pond (profiles *b* and *c*) the moisture and temperature excess propagates upwards but decreases in magnitude near the ground until negligible excess moisture and temperature are reached at infinity (profile *d*).

The buoyancy of the plume may be approximated by the following if the difference between the temperature of the plume and the ambient air is known:

$$\int W\,dW = \frac{g}{T}\int (T' - T)\,dz \qquad (7)$$

where W is the upward velocity of the plume, T' is the mean temperature of the air parcel, and T is the temperature of the ambient air above the plume.

Integration of (7) allows modification of the vertical diffusion calculations to include the effects of buoyancy (bottom profile in Figure 1). At distance *b* (Figure 1) downwind from the pond the excess moisture or temperature over ambient conditions reaches a maximum at some height above the ground, as shown by the dotted line. About this point a Gaussian distribution in the vertical of excess temperature or moisture is assumed. When the buoyant plume has spread downward sufficiently to touch the ground, 100% 'reflection' of the excess is assumed (profiles *c* and *d*).

If the topography downwind from the cooling pond is open, lateral diffusion of the plume should be considered. The dilution factor of the diffusing substance along the center line of the plume, generated along a line of finite length in a steady crosscurrent, has been considered by *Brooks* [1960], who treated lateral diffusion separately and assumed that the eddy diffusivity is a function of the width of the diffusing plume.

For the solution of the horizontal diffusion equation,

$$u\frac{\partial \phi}{\partial x} = \frac{\partial}{\partial y}\left(k_y \frac{\partial \phi}{\partial y}\right) \qquad (8)$$

Richardson [1926] developed the relation between

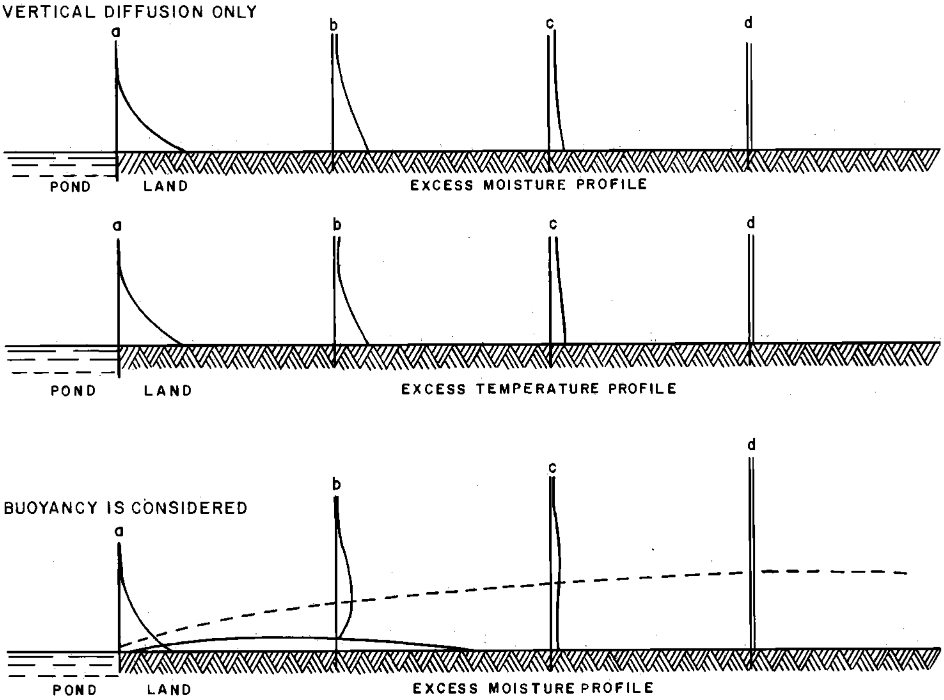


Fig. 1. Fog prediction model.

lateral diffusivity and plume width:

$$k_y = 0.2L^{4/3} \tag{9}$$

where L is the width of the plume in centimeters and k_y is measured in square centimeters per second. The initial lateral diffusivity is determined from (9) by assuming the width of the plume equal to the width of the cooling pond. For cases of restrictions on lateral diffusion due to topography the adopted solution of (8) depends on either a constant value of lateral diffusivity as the initial value or a linear variation of diffusivity with width rather than the four-third law assumption. The dilution factor at any point in the plume is developed from the center line dilution factor by assuming a Gaussian distribution in the horizontal.

After the adjustments due to buoyancy were made and the lateral diffusion on vertical diffusion calculations were included in the mathematical model, a computer program was developed to predict the downwind extent of the fog given the following input: (1) mean water surface temperature of the cooling pond, (2) mean temperature of the ambient air, (3) mean moisture content of the ambient air, (4) mean wind speed; and (5) dimensions of the cooling pond. Output from the computer program is a three-dimensional field of relative humidity calculated from the temperature and moisture content excess downwind from the pond.

The relationship between humidity and restrictions on visibility due to fog is not a direct one and in fact is very complex. The humidity may be 100% for several hours before water droplet growth results in significant fog. Conversely, fog sufficiently dense to sharply restrict visibility may be present under conditions of <100% humidity. Time available for droplet growth sufficient to restrict visibility and the availability of condensation nuclei are two of the factors involved. For this model a value of relative humidity of ≥100% was assumed to constitute fog. For other definitions of fog the model may be adjusted to accept lower relative humidity values.

Figure 2 is an example of the type of computer output that may be derived from the model. A hypothetical fog plume is shown in cross section; the areas where humidity values are >100% are shaded to indicate fog. The plume profile appears realistic; the buoyancy of the plume is clearly evident out to 152 meters (500 feet) downwind from the cooling pond, and the fog extends farthest downwind at the elevation of the plume center line. In an application to surface fogging situations, such output is desirable because it specifies the distance where the fog leaves the ground and becomes a cloud.

ACCURACY OF THE MATHEMATICAL MODEL

The accuracy of the mathematical model was verified by using data taken from a cooling pond in operation (Table 1). All the 14 cases used occurred during the morning when the contrast

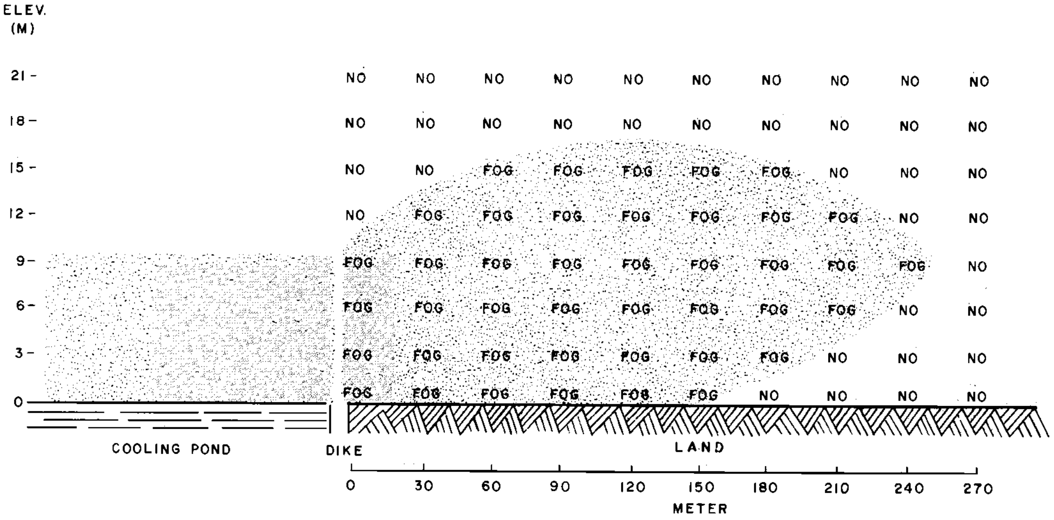


Fig. 2. Computer print-out for a selected set of meteorological conditions in a particular geographic area.

TABLE 1. Cooling Pond Data: Comparison of Observed and Predicted Fog Conditions

Date	Time, A.M.	Temperature, °C		Relative Humidity, %	Wind Speed U, m/sec	Wind Direction	Observed Fog		Fog Predicted by Mathematical Model*	
		Dry Bulb T_A	Pond T_S				Height, meters	Distance of Travel, ±12 meters	Height,† meters	Distance of Travel,§ meters
1-16-69	8:40	2.7	32.8	90	1 to 2	S-SE	6 to 12	100	6	110
1-17-69	8:40	3.9	29.4	92	2 to 3	S-SE	6 to 12	100	4	120
1-21-69	8:45	-0.8	27.2	92	1.5 to 3	west	6 to 9	190	8	190
2-17-69	8:45	1.5	30.0	91	1.5 to 2	west	15 to 20	150	8	180
3-5-69	9:40	3.3	30.0	72	4.5 to 8	west	0 to 2	0	0	0
12-31-69	9:30	-1.5	32.8	85	calm	calm	6 to 12	0	12	0
1-15-69	8:50	1.9	29.4	91	2 to 4.5	south	3 to 6	35	3	120
2-10-69	9:00	6.3	25.6	92	3.5 to 5.5	S-SE	3 to 12	100	4	110
2-20-69	8:40	2.1	25.6	96	0 to 1	south	6 to 12	150	10	150
1-9-69	8:35	5.3	26.7	74	3.5 to 4.5	S-SE	0 to 2	0	0	0
2-12-69	9:55	6.0	32.8	91	0 to 1	S-SW	6 to 12	130	8	90
3-17-69	8:20	10.9	27.8	88	0 to 1.5	S-SE	2 to 9	65	4	60
2-28-69	8:45	6.5	29.4	79	1 to 2	south	3 to 9	80	3	15
3-26-69	8:20	9.5	34.4	72	0 to 1	S-SE	2 to 4	0	2	0

*Average of wind speeds.
†Average error is ±2.7 meters.
§Average error is ±20 meters.

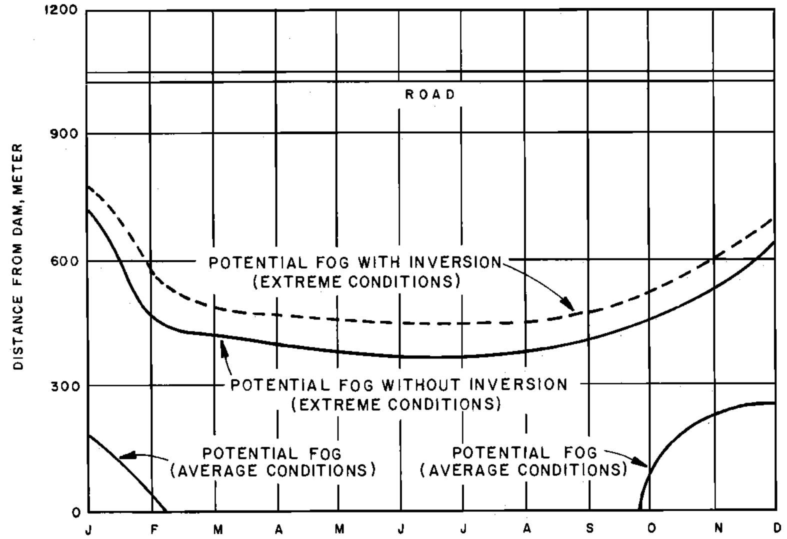


Fig. 3. Extent of potential fog for a selected set of meteorological conditions in a particular geographic area. Extreme conditions are defined as a combination of high relative humidity, moderate wind speed, and low air temperature.

between water and air temperature was at a maximum and when maximum fog extent might be expected. However, during four of the cases, no fog was observed. Fog observations were carried out on the ground by trained observers. The observed distance of travel of fog was assumed to be accurate within 15 meters (±50 feet). All input necessary for prediction is shown, whereas the output from the model is indicated by the maximum distance of travel of the fog downwind and the maximum fog height during its trajectory.

The prediction of the model for distance of fog travel was, on the average, within 20 meters (±66 feet) of observed values. Prediction of fog height was, on the average, within 2.7 meters (±9 feet) of observed fog height. Cases of no fog were also predicted quite satisfactorily, and in none of the four cases was fog observed downwind from the pond when it was not predicted.

APPLICATION OF THE MODEL

The use of the fog prediction model can be anticipated in several different engineering applications under certain meteorological conditions for particular geographic areas. Frequent fogging or icing (if the temperature is below 0°C) of plant equipment could constitute a hazard to equipment operation and a nuisance to plant personnel. Knowledge of cooling pond–induced fogging frequency at residences and business establishments outside plant boundaries during the design stage of the cooling pond could well influence conceptual engineering decisions.

Probably the most familiar potential effect of cooling pond fogging is on nearby roadways where severe fogging might result in poor visibility or icing of the road surface. Figure 3 shows application of the model to prediction of the variability during the year of the extent of fogging toward a road. The lower curves labeled potential fog (average conditions), pertaining to the winter season, indicate the extent of fogging from the ground during weather conditions representative of the long-term average climatological conditions. The upper curve labeled extreme conditions indicates predicted fogging during weather conditions exceptionally conducive to fog formation. The dotted curve indicates fogging during extreme conditions with the additional condition of the presence of an inversion. Such a curve can be derived from the model by limiting vertical diffusion to a specified level. (For Figure 3 the level is 15 meters, or 50 feet.)

CONCLUSIONS

The described mathematical model makes it possible to evaluate fogging induced by cooling ponds during the site selection phase for a new power plant or when expansion of an existing plant is contemplated. This method represents another effort toward better management of our environment and a more thorough evaluation of the effects of cooling facilities on the atmosphere.

Acknowledgment. Credit is due Mr. Bruno Brodfeld, Chief Environmental Engineer, Stone & Webster Engineering Corporation, for many relevant comments and helpful suggestions.

REFERENCES

Brooks, N. H., Diffusion of sewage effluent in an ocean current, in *Waste Disposal in the Marine Environment,* Pergamon, New York, 1960.

Calder, K. L., Eddy diffusion and evaporation and flow over aerodynamically smooth and rough surfaces: A treatment based on laboratory laws of turbulent flow with special reference to conditions in the lower atmosphere, *Quart. J. Mech. Appl. Math.*, *2*(2), 1949.

Edinger, J. E., and J. C. Geyer, Heat exchange in the environment, *Publ. 65-902*, Edison Elect. Inst., New York, June 1965.

Pasquill, F., Evaporation from a plane, free-liquid surface into a turbulent airstream, *Proc. Roy. Soc., Ser. A, 182,* 75, 1943.

Richardson, L. F., Atmospheric diffusion shown on a distance-neighbor graph, *Proc. Roy. Soc., Ser. A, 110,* 709–737, 1926.

Sutton, W. G. L., On the equation of diffusion in a turbulent medium, *Proc. Roy. Soc., Ser. A, 182,* 48, 1943.

Sutton, O. G., *Micrometeorology,* p. 285, McGraw-Hill, New York, 1953.

Applications of Nimbus Satellite Imagery to the Monitoring of Man-Made Lakes

HANS J. ACKERMANN AND GEORGE A. RABCHEVSKY

Allied Research Associates, Inc., Lanham, Maryland 20801

The Nimbus meteorological satellite program is planned by the National Aeronautics and Space Administration (NASA) to provide experimental sensor carriers to measure the earth's cloud cover and atmosphere. Since August 1964, four separate Nimbus satellites have provided valuable sensory data [*Allied Research Associates, Inc.*, 1969*a*, *b*, *c*].

Data from the Nimbus 3 high-resolution infrared radiometer (HRIR) discussed in this paper have been emphasized as being applicable in lake and large watershed studies. Figure 1 presents an example of coverage from the HRIR system. The HRIR experiment has one primary objective: day and night global mapping of cloud and earth surface reflectances (day) and emissions (night) in the 0.7- to 1.3-μ band (day) and the 3.4- to 4.2-μ band (night).

The primary emphasis in this paper will be on the daylight 0.7- to 1.3-μ reflectances over the areas of three man-made lakes, i.e., Lake Nasser, Volta Lake, and Lake Kariba (including the Okavango basin). A Nimbus 1 advanced vidicon camera system (AVCS) view of Fort Peck Lake is also included.

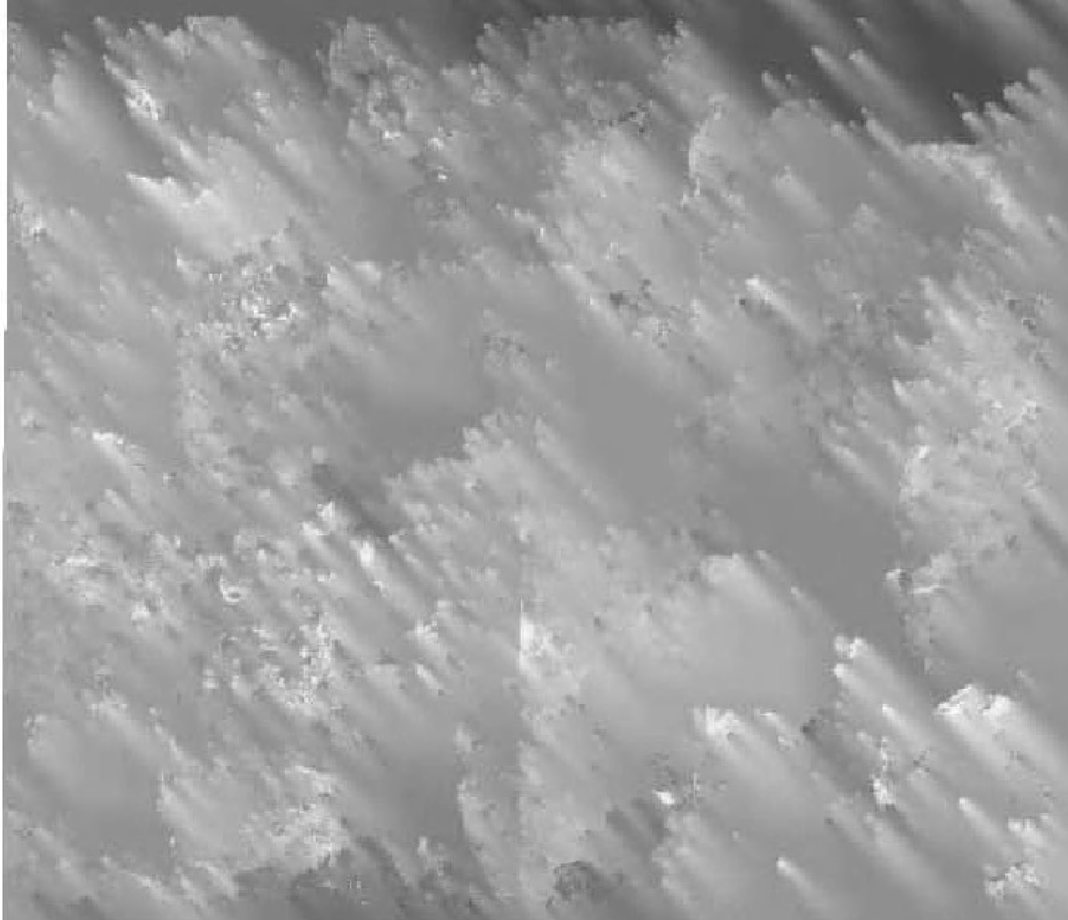
SATELLITE OBSERVATIONS

Satellite observations are often characterized by general cloudiness over land areas and minimum cloudiness over coastal waters and large rivers and lakes (Table 1). Newly developing man-made lakes, which were previously cloud-covered regions, often are observed to have a reduction in cloudiness. This reduction is due to the essentially cooler daytime temperatures over water. No large-scale cloudiness or rainfall changes are evident in the data examined in this study. Case examples from Nimbus 3 for two man-made lakes in moist (cloudy) areas and one desert area are discussed. A view of Fort Peck Lake from Nimbus 1 is also discussed.

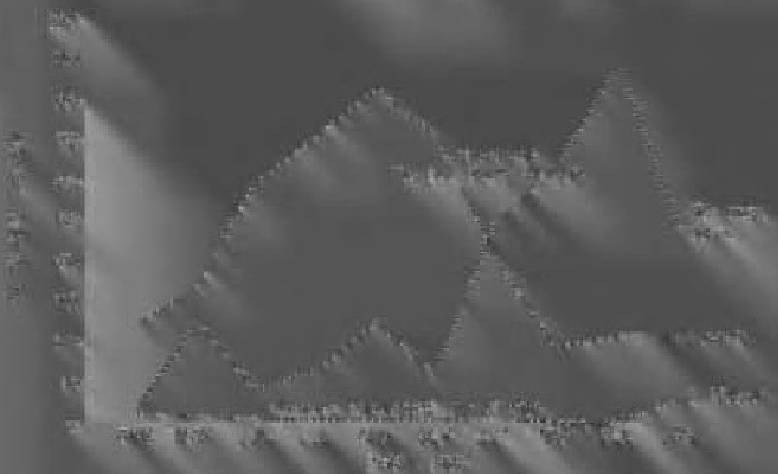
Lake Nasser. Lake Nasser is located in a very dry subtropical desert climate. The domination of warm, dry anticyclonic flow in the area suppresses most convectional shower activity [*Riehl*, 1954]. Even in December and January, when Nimbus-observed cloud cover increases to 10% (Figure 2, and Table 1), convectional showers are suppressed by the still generally dry anticyclonic circulation aloft. Even the moisture added to the air by the development of Lake Nasser does not appear to influence either local convective cloudiness or large-scale cloudiness as observed by Nimbus. It thus appears that Lake Nasser has had little effect on the cloud climatology of the area. Therefore, if the reservoir area is to get any appreciative and accumulative water supply to sustain life in this area, it must receive this water from the June–October floodings of the Upper Nile River, located in a more humid and rainy climate such as the Ethiopian highlands and the equatorial regions of the White Nile.

Nimbus satellite systems have recorded images of the Lake Nasser area since September 1964. The increase in lake size can be seen between 1964 (Figure 3*a*) and 1969 (Figure 3*d*). Nimbus 1 on September 16, 1964 (Figure 3*a*), showed no evidence of the lake, although construction of the Aswan High Dam had been under way for 4 years. In the Nimbus 2 photo (Figure 3*b*) the reservoir seems to be taking shape. Flooding conditions in June can apparently be seen in the Wadi el 'Allagi Valley, as well as all along the Nile, some 2 years before the dam's completion. Nimbus 3 gives us a first good look at the constantly growing reservoir in May 1969 (Figure 3*c*) and in September 1969 (Figure 3*d*), which is 1 year after the dam's completion.

[illegible]



[illegible]

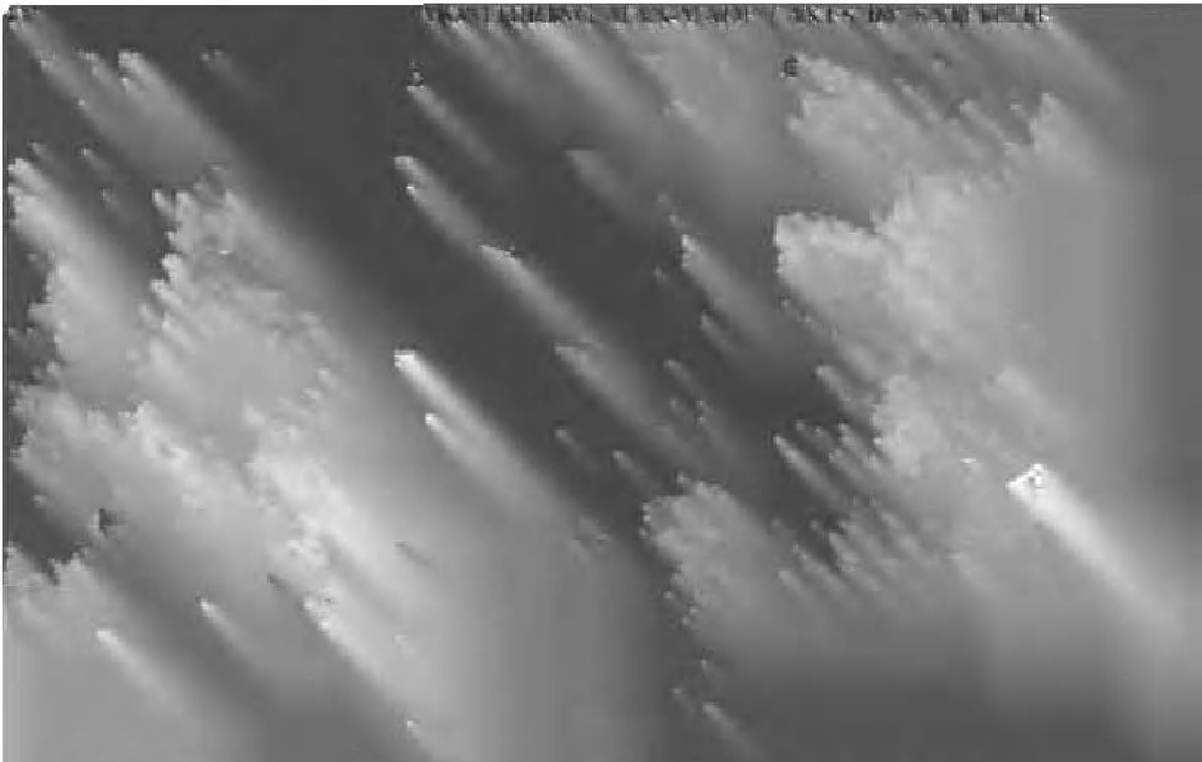


[illegible]

TABLE 1. Daily Noontime Cloud Cover in Tenths of Percent over Volta Lake, Lake Nasser, and Okavango Basin

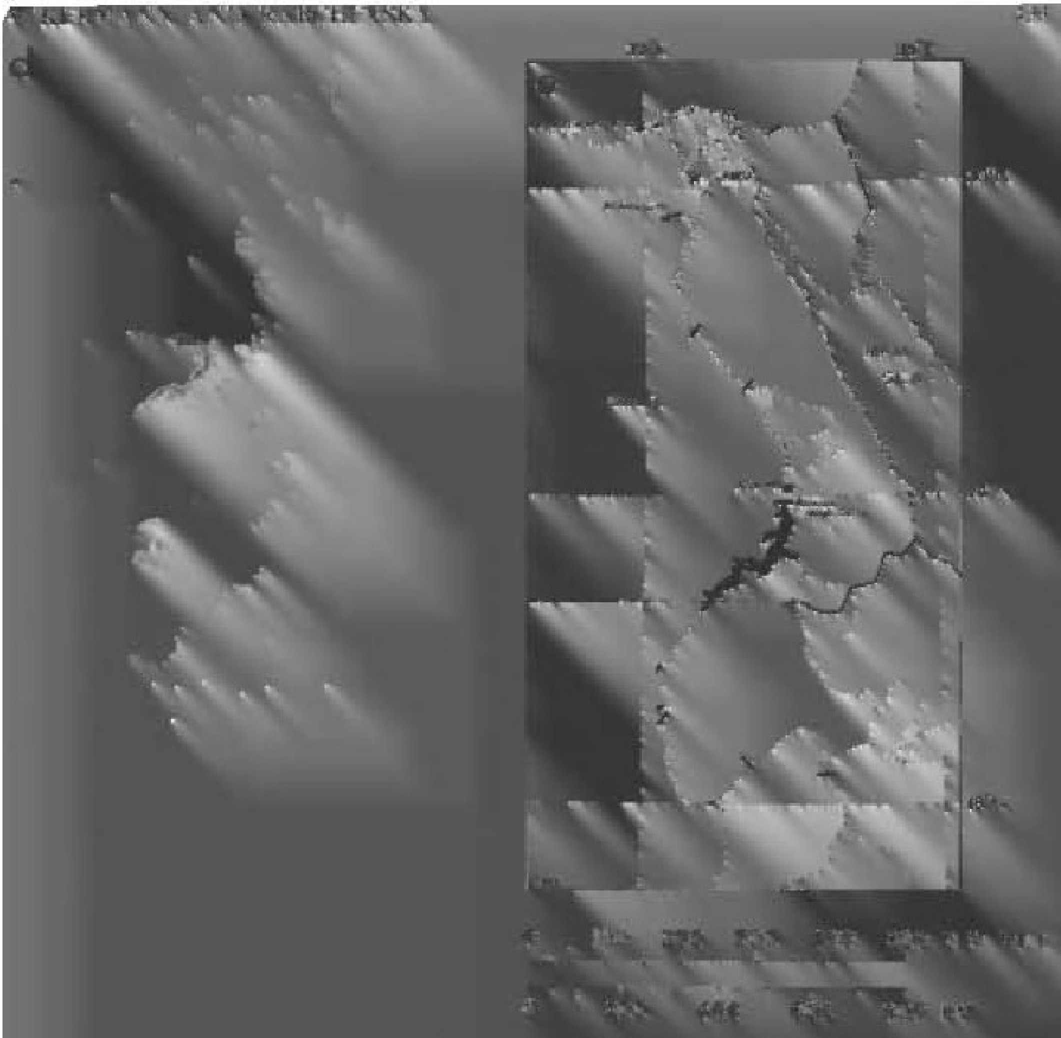
	April			May			June			July			August			September			October			November			December			January		
Day	V	N	O	V	N	O	V	N	O	V	N	O	V	N	O	V	N	O	V	N	O	V	N	O	V	N	O	V	N	O
1				0	0	3	2	0	0	10	0	3	4	0	0	8	0	3	3	0	2	2	0	9	3	0	10		0	6
2				0	0	2	0	0	0	10	0	1	9	0	6	10	0	0	0	0	0	9	0	9	10	0		1		4
3				2	0	0	3	0	0	4	0	0	10	0	7	9	0	0	8	0	0	4	0	6	0					7
4				10	0	0	3	0	0	5	0	0	10	0	0	9	0	0	0	0	8	4	0	3	0	0		0		
5				2	0		0	0	0	6	0	0	9	0	4	8	0	0	2	0	9	4	0	10	0	0			0	
6				0	0	2	2	0	0	10	0	0	9	0	0	9	0	3	9	0	0	7	0	10		0		0		
7				9	0	0	10	0	0		0		10	0	4	7	0	0	7	0	4	8	10	8			10		0	
8				0	0	2	3	0	0	3	0	0	8	0	4	9	0	0	10	0	7	0	0	6		0	10			0
9				8	0	0	10	0	0	7	0	0	7	0	8	10	0	0	3	0	3	3	0	7	6		8		0	2
10				9	0	3	9	0	0	7		5	10	0	6	10	0	0	2	0	5	0	0	10		0	10			0
11				0	0	3	3	0	0	4			8	0	6	10	0	0	0	0	0	2	0	10	2		10		0	0
12				2	1	4		0		5	0		7			5	0	0	0	0	4	0	0	6	8	0		2		0
13				5	0	3	0	0	0	5	0		9	0	0	2	0	0	10	0	6	0	0	10	0					
14				2	9	4	2	0	0	8	0	6	7	0	3	10	0	8	3	0	5	0	0	7		0		0		
15				3	10	6	10		0	8	0	6	10	0	0	5	0	8	3	0	7	0	0	0	0	0		0	0	
16				2	8	4	3	0	0	10	0	4	9	0	3	7	0	0	7	0	2	0	0	3		0		0		
17				1	4	2	10	0	0	10	0	0	9	0	7	10	0	4	2	0	7	3	0	0			10		0	
18				2	0	0	2	0	0	10	0	0	9		4	8	0	3	3	0	6	0	0	3		0		2		
19				0	0	0	9	0	0				3	0	7	9		2	3	0	7	0	0	4			8		10	
20				2	0	0	7	0	0	9	0	0	10	0	2	4	0	0	4	0	6	0	0	4		0	8			10
21		0		0	0		4	0	0	2	0	0	8	0	2	9	0	0	4	0	8	2	0	7	2		7	3	0	9
22	5	0	0	0	0	2	7	0	4	10	0	0	10	0	0	7	0	0	2	0	8	0	0	7			7	4	0	8
23	2			0			9	0	3	3	0	0	7	0	0	7	2	0	5	0	8	0	0	7	2			0		
24	2	0	0			2	9	0	2		0		0	0	0	10	2	0	2	0	8	0	0	6	1	0		8	0	5
25	2	0	1	3	0	0	10	0	0	9	0	0	10	0	0	2	0	0	2	0	9	0	0	6	0			10	0	2
26	2	0	0	9	0	7	7	0	4	10	0	0	8	0	0	4	0	0	4	0	8	0	0	7		0		3	0	4
27	0	2	0		0	3	10	0	4	9	0	0	10	0	0	2	0	0	4	0	8	0	0	7	0			0	0	7
28	9	0	0	2	0	5	9	0	2	2	0	0	9	0	0	8	0	0	10	0	7	0	0	8		0		7	0	8
29	4	0	2	9	0	6	7	0	3	10	0	4	7	0	0	8	0	0	2	0	7	9	0	10	3	0		0	0	7
30	0	0	0	0	0	7	10	0	0	3	0	0	8	0	3	3	0	2	3	0	8	0	0	7		0		0	0	7
31	0	0	0	9	0	0				8	0	3	9	0	2				7	0	6				2		8	0	0	5
Monthly Average	2.6	0.2	0.3	3.3	1.1	2.5	5.9	0	0.8	7.0	0	1.3	8.2	0	2.6	7.1	0.1	1.1	4.0	0	4.9	1.9	0.3	6.3	2.3	0	8.8	2.1	6.4	4.8

The data were derived from Nimbus 3 daytime HRIR radiometer readings (0.7 to 1.3μ) during 1969 and 1970. In the heading, V stands for the Volta Lake region, N stands for the Lake Nasser region, and O stands for Okavango basin and Lake Kariba.



[illegible]

[illegible]

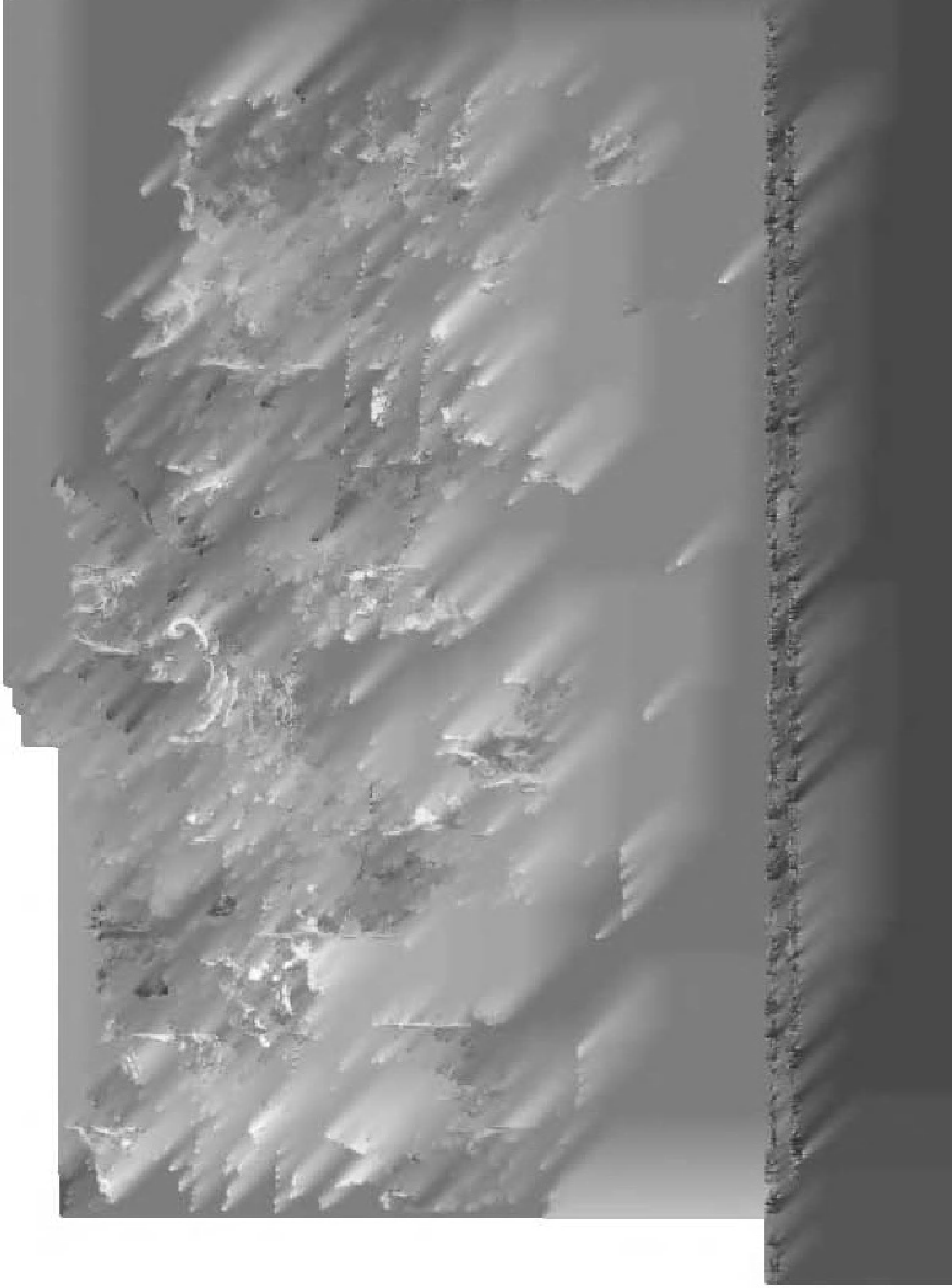


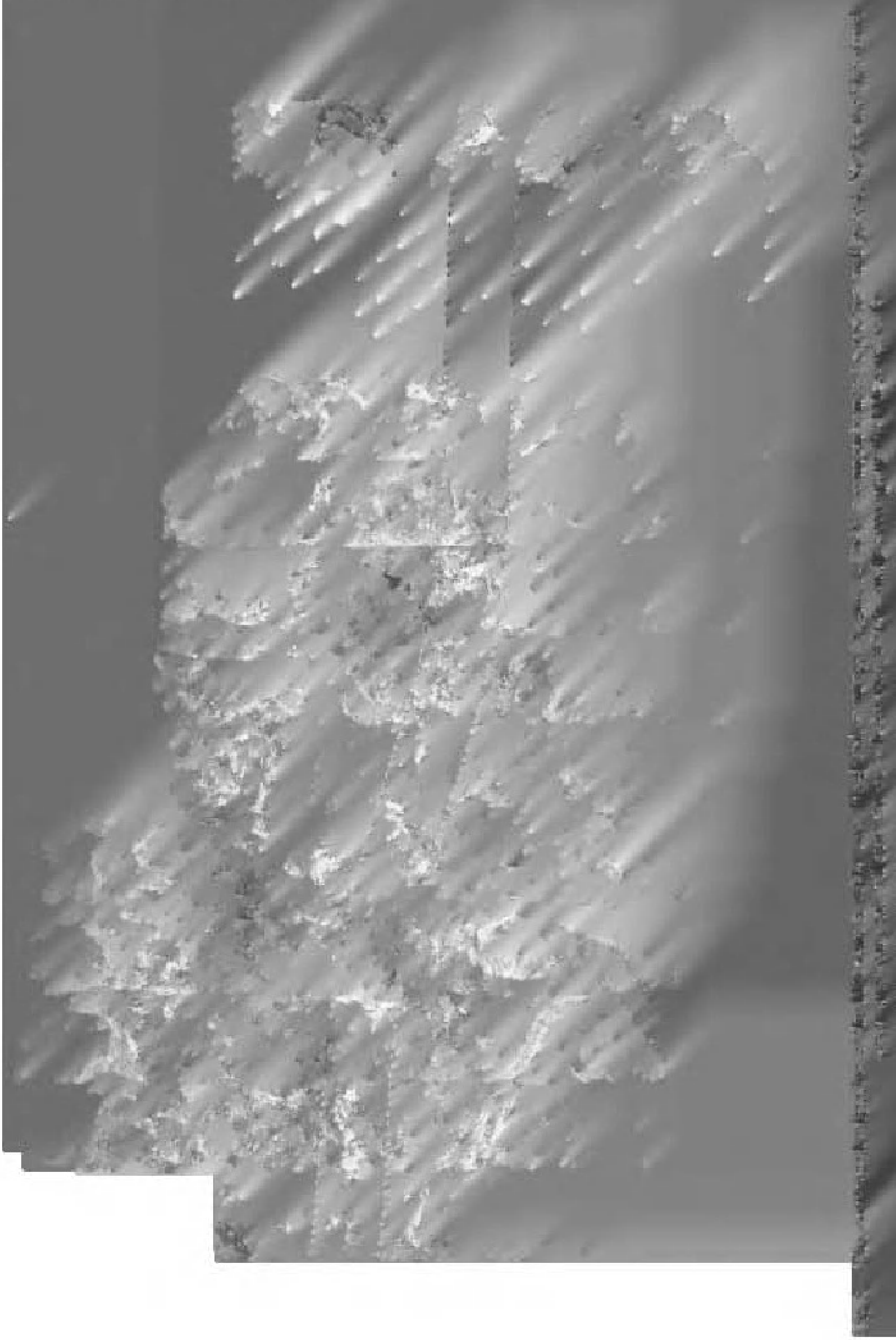
[illegible]

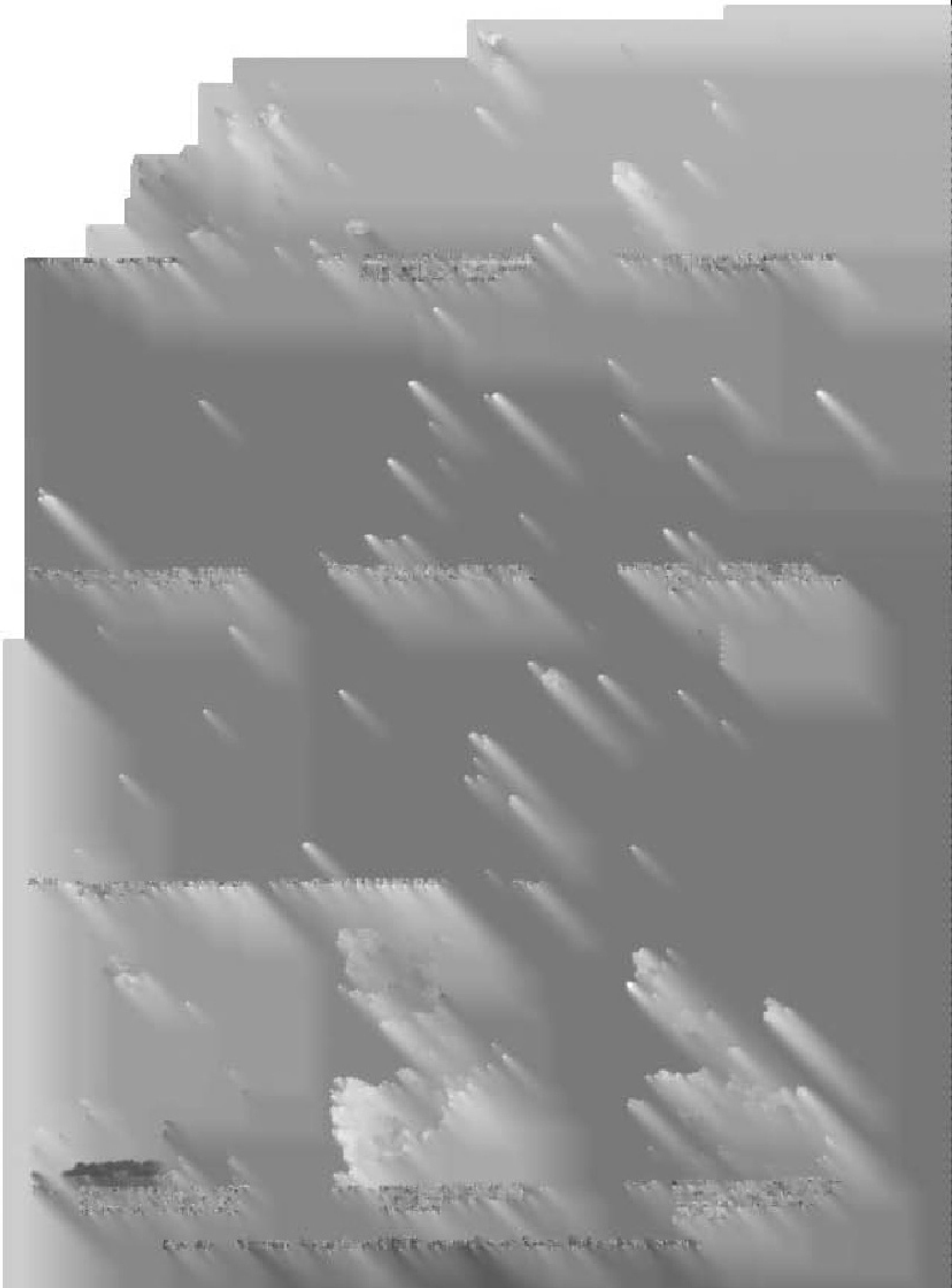
[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]







[illegible]

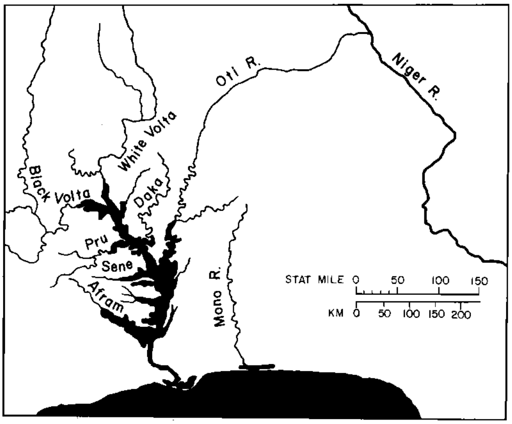


Fig. 6*b*. Map of Volta Lake area.

(stream piracy) the headwaters of the Cuando. Other river systems such as the Luete and Cuando also illustrate this point.

Flood control and irrigation activities have already changed the physical setting of this region. More man-made structures (dams, canals, and so on) may be erected in the basin in the future. The Nimbus observations may provide valuable information on the seasonal behavior of this complex region for future flood control and irrigation projects.

Fort Peck Lake. Nimbus 1 observations of the Fort Peck Lake in Montana (Figure 8) provided an opportunity to test satellite surveying of man-made lake areas. (Nimbus 1, launched on August 28, 1964, had a perigee of 421 km. This accidental orbit provided resolutions from the AVCS camera of ~365 meters.) An area of 871.8 km^2 (336.6 mi^2) was derived from maps of the *U.S. Geological Survey* [1964, 1966] (Figure 9). The same area on the satellite image, enlarged to map scale, was calculated to be 929.0 km^2 (358.7 mi^2), representing a deviation of only 6% from the map derivation.

SUGGESTIONS FOR CLASSIFYING SHORELINES

With the superior resolution of future earth resources technology satellites (ERTS), an immense number of man-made and natural lakes will be observed on a regular basis. The existing limnological classification systems will be unable to uniformly handle such data. To date, many diverse 'personalized' classifications exist that would create a chaos if they were applied indiscriminantly to global coverage. We believe therefore that a new limnological classification system is necessary to cope with this problem. Such a classification system should be automated, devoid of personal bias or degree of training, and based on the electronic, geometric, and computerized approach.

The general problem of automatic lake classification may be formulated as follows: given a pictorial input, isolate a feature (such as a shoreline), and generate a description of it. Classifications applicable to limnology could be based on linear features (shorelines or forms), on textural features of regions adjacent to those linear boundaries (type of vegetative coverages along the shorelines), or on spatial density gradients (contrast ranges between the shore and water surface).

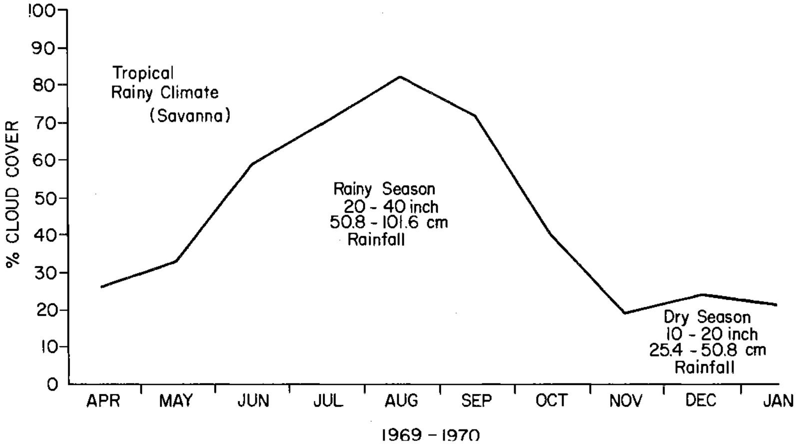
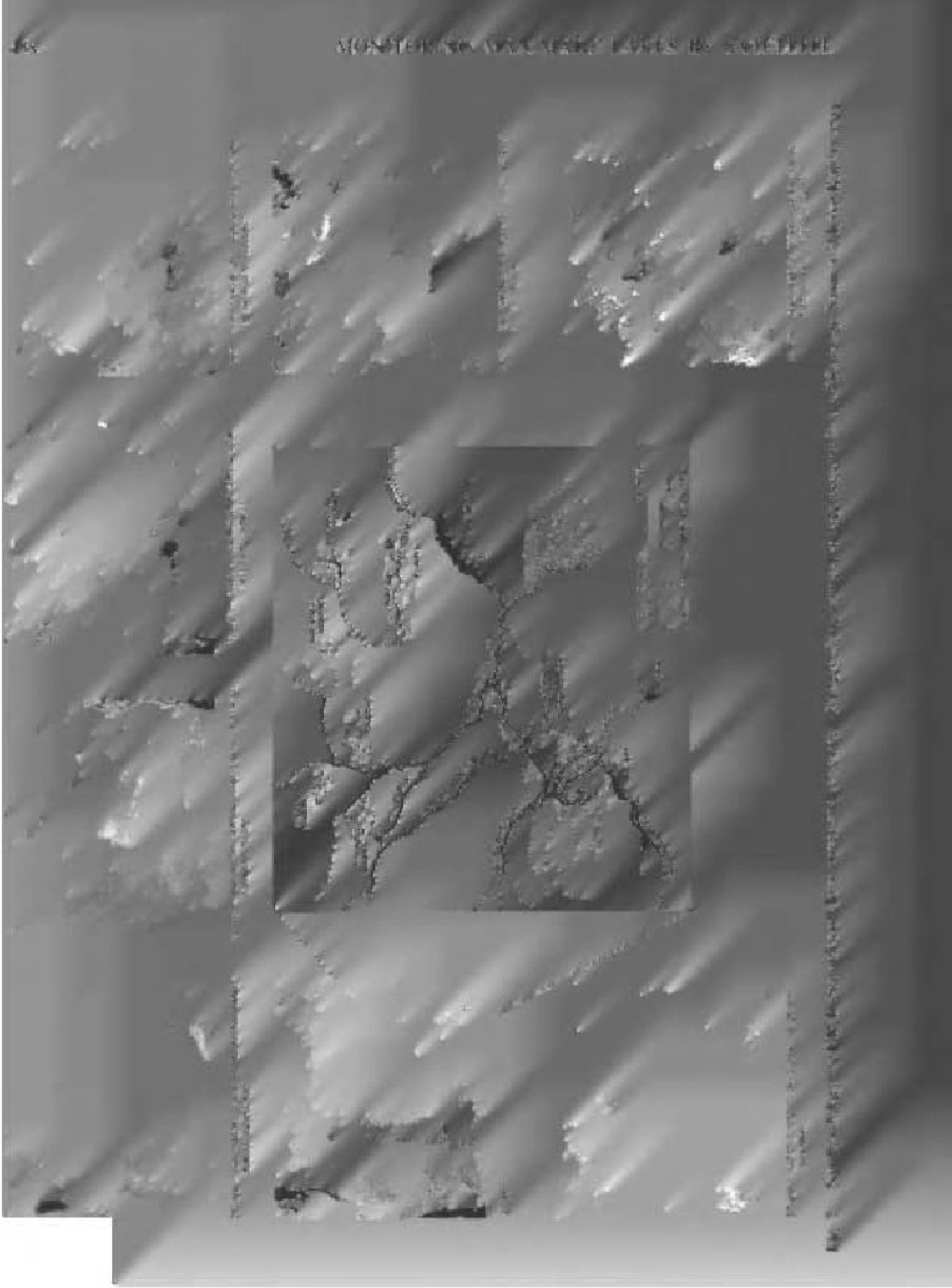
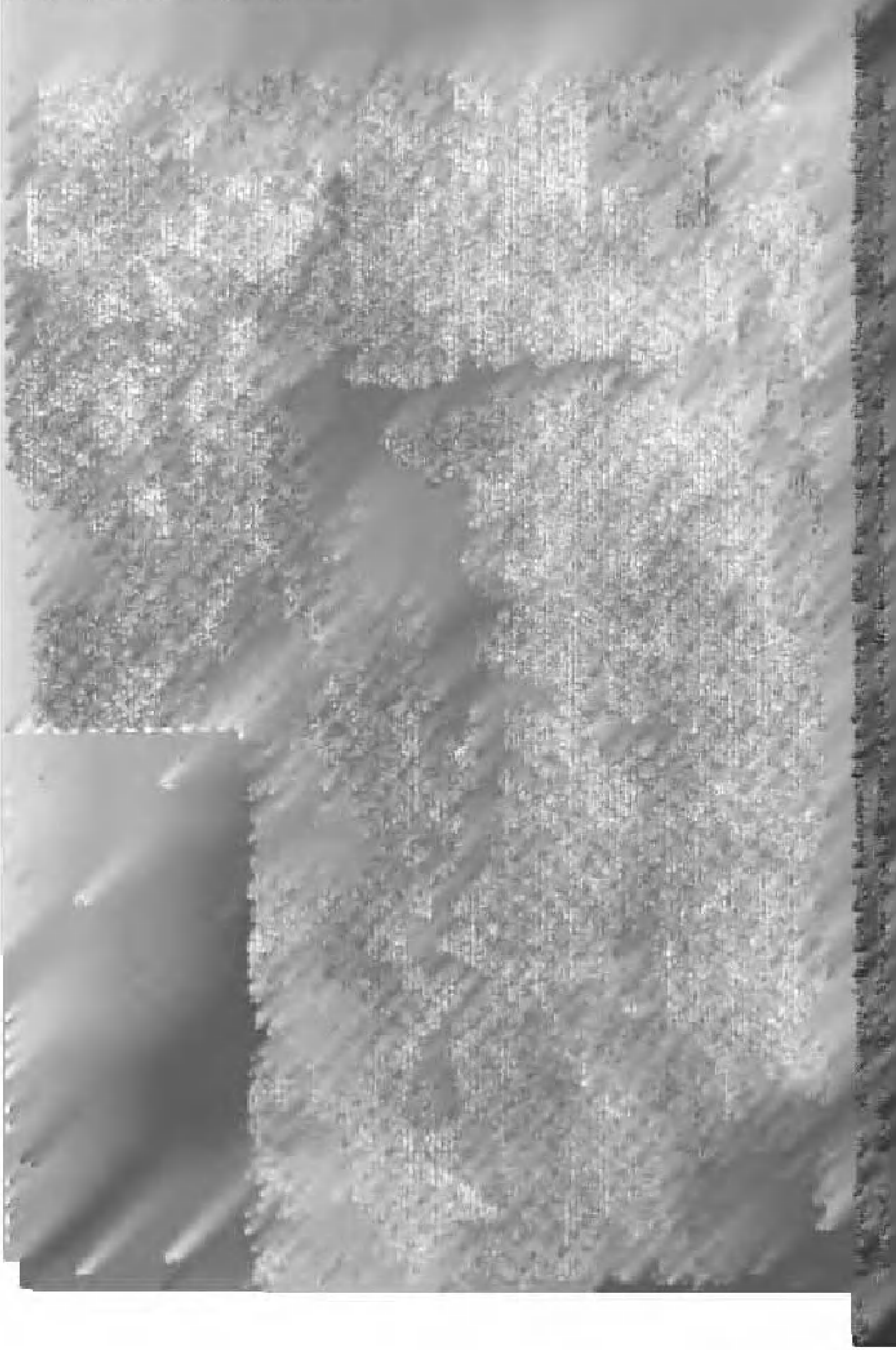


Fig. 6*c*. Monthly cloud cover for Volta Lake area derived from Nimbus 3 HRIR data.





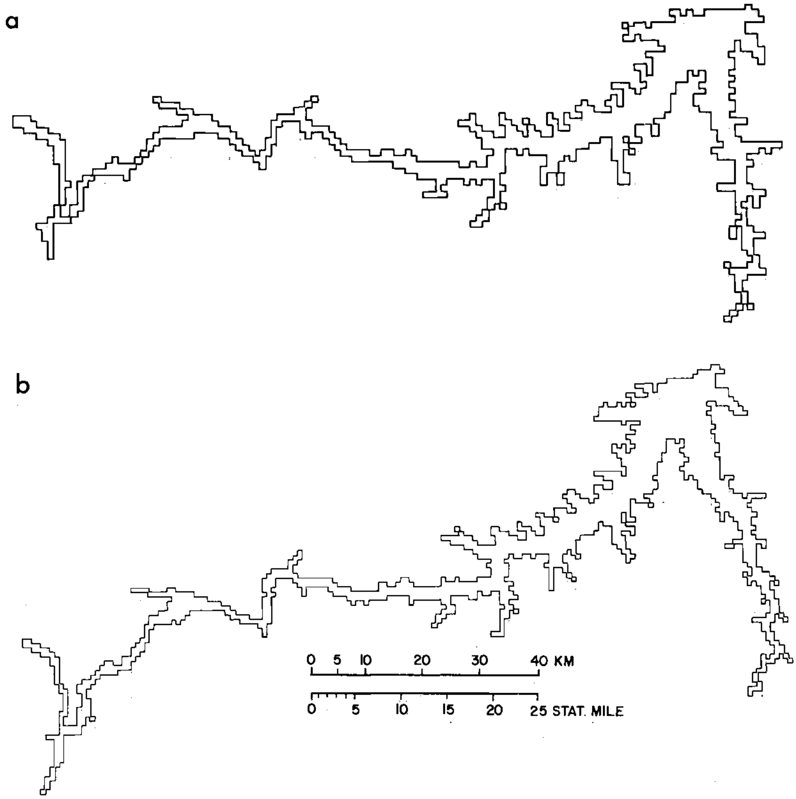


Fig. 9. Fort Peck Lake schematic area representation and calculated area as derived from (*a*) Nimbus 1 AVCS photograph (929.0 km^2, or 358.7 mi^2) and (*b*) maps of the *U.S. Geological Survey* [1964, 1966] (871.8 km^2, or 336.6 mi^2).

CONCLUSIONS

Nimbus satellite imagery has potential application for some man-made lake studies. As new large man-made lakes develop, their local cloud and weather effects can be evaluated. New lake growth can be monitored on a monthly basis. Shape and area values can be extracted from ~800-meter (½-mile) resolution imagery; such values have accuracies within 6 to 10% of the same values derived from maps. Gross soil moisture and vegetation changes adjacent to these lakes can be observed in near-infrared imagery as changes in image tone.

The repetitive, large-area, and multispectral coverage recorded by Nimbus meteorological satellite sensing systems makes this imagery a useful tool for some man-made lake analysis problems. The available satellite data offer a unique learning tool in preparation for the high-resolution multispectral imagery from the earth resources technology satellite launched in 1972.

REFERENCES

Allied Research Associates, Inc., *The Nimbus 3 User's Guide,* National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Md., 1969*a.*

Allied Research Associates, Inc., *The Nimbus 3 Catalog,* vol. 1, parts 1 and 2, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Md., 1969*b.*

Allied Research Associates, Inc., *The Nimbus 3 Data Catalog,* vol. 2 and 3, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Md., 1969*c.*

Bartholomew, J. (Ed.), *The Times Atlas of the World,* vol. 4, Houghton-Mifflin, Boston, Mass., 1956.

Espenshade, E. B., Jr. (Ed.), *Goode's World Atlas,* Rand McNally, Chicago, Ill., 1960.

Odyssey, *The Odyssey World Atlas,* New York, 1966.

Riehl, H., *Tropical Meteorology,* Department of Meteorology, University of Chicago, Chicago, Ill., 1954.

U.S. Geological Survey, Jordan, Montana, *Map NL 13-1,* Washington, D. C., 1964.

U.S. Geological Survey, Glasgow, Montana, *Map NM 13-10,* Washington, D. C., 1966.

Summary: Geophysics Report

J. P. ROTHÉ
University of Strasbourg, Strasbourg, France

Among the problems facing the geophysicist as a result of the more and more frequent creation of artificial lakes, the phenomena of seismicity provoked by the filling of these reservoirs have received particular attention. It is perhaps useful to undertake a brief historical review of the development of the research in this domain.

On December 10, 1967, a destructive earthquake occurred on the Indian peninsula. It brought a heavy loss of human life and caused considerable material damage. The epicenter as confirmed by calculations made at the Bureau Central International de Séismologie in Strasbourg coincided with Koyna Dam, which was seriously damaged by this shock. The earthquake in 1966 in the proximity of the Kremasta Dam in Greece, the seismic activity that had accompanied the filling of Lake Mead formed on the Colorado River by Hoover Dam, and some analogous observations that we made in France immediately made me see a cause and effect relation between the filling of Lake Koynanagar and the earthquake of December 10, 1967.

On December 29, 1967, *Le Monde,* a Paris newspaper, published an article, based on an interview that I had accorded the scientific correspondent, that was entitled 'The Tremors of the Earth May Have Their Origin in the Works of Man' [*Rebeyrol*, 1967]. This article summarized the accounts in my possession of seismic activity in the vicinity of certain large reservoir dams. The next day, on reading this article, the editor in chief of the *New Scientist* asked me by telegram for a more detailed report on this subject. This report [*Rothé*, 1968], translated into English, appeared on July 11, 1968, and was entitled 'Fill a Lake, Start an Earthquake,' a title lacking gradation that overstepped the thoughts that I expressed in the article.

In January 1969 at the Fourth World Conference on Earthquake Engineering in Santiago, Chile, I attempted to establish a detailed comparison of the different cases that had been observed. At that time a good many geologists and geophysicists still remained skeptical about the possibility of earthquakes engendered by the filling of reservoirs formed by dams, undoubtedly because the several known cases were studied individually and because a fortuitous coincidence between the shocks and the filling could be considered reasonable. The latter reason, in particular, was the conclusion formulated in several of the reports published after the earthquake of Koyna. This coincidence, which subsequently was repeated when each case was studied separately, merited a more complete comparative study that today leaves no doubt of the reality of this phenomenon [*Rothé*, 1969].

More and more numerous studies in ever greater detail have been published during the past 2 years, stimulated by the observations made near Denver of seismic activity provoked by the injection of fluids under pressure into a deep well. *Gupta et al.* [this volume] have presented a study of the earthquakes of Koyna and have recounted a comparison of these earthquakes with those produced in different regions of the globe on the occasion of the filling of storage reservoirs behind dams. *Hoffmann* [this volume] has summarized the positive and negative observations made at the time of the filling of reservoirs at San Luis and Oroville in California.

FACTS

I recount here some characteristic examples.

Hoover Dam and Lake Mead. The following information has been obtained regarding Hoover Dam and Lake Mead: type of dam, arch; height of dam, 142 meters; maximum lake volume, 35,000 Mm^3; start of filling, 1935; end of first filling, July 1938; first shock, September 1936; and principal shock, May 4, 1939 (magnitude of 5.0).

This first example has been rendered as being classic through the studies by *Carder* [1945]. Lake Mead, formed on the Colorado River by Hoover Dam, started to fill in 1935; the first shock was experienced at the time when the water level of Lake Mead reached 100 meters. About 100 shocks were observed in 1937 when the lake level attained an altitude of 330 meters above sea level (corresponding to a water height in the lake of 120 meters). The installation in 1938 of seismological stations in the vicinity of the dam permitted the registration of a very great number of shocks (several thousand) that were generally not perceptible by man, as well as the location of the epicenters. The greatest seismic activity occurred in May 1939, about 9–10 months after the normal lake height was attained (355 meters above sea level; water height of 145 meters); the water volume at this height was 35 billion m^3. Once the normal regime was established, the peak seismic activity (in particular in 1940, 1941, and 1942) followed the periods of maximum filling by several weeks.

Around 6000 shocks, distributed over an area of 8000 km^2, were registered during a period of 10 years following the start of filling. These shocks for the most part were of small magnitude (on the order of 2). On May 4, 1939, at the beginning of the period of strongest activity, a single shock attained a magnitude of 5.0. The two shocks of August 11 and September 9, 1942, had magnitudes in the neighborhood of 4 and followed a period when the volume of water stored was near 40 billion m^3.

From the geologic point of view, this region is complex and is composed of granite and gneiss, Precambrian schists, Paleozoic formations, and Tertiary volcanic rocks. Several faults have been mapped, in particular those bordering the Callville basin filled by Lake Mead immediately north of the dam.

Kariba Dam. The following information has been obtained for Kariba Dam: type of dam, arch; height of dam, 125 meters; maximum lake volume, 160,000 Mm^3; surface area of lake, 6649 km^2; start of filling, December 1958; end of filling, August 1963; first notable shocks, July 3, 1961, and September 13, 1961 (magnitude of 4.0); and principal earthquake, September 23, 1963 (magnitude of 6.3).

Lake Kariba, the greatest artificial lake in the world, extends for a length of 250 km and overlies a region formed principally from sediments of the Karoo and of volcanic lava whose age is between upper Carboniferous and Jurassic. These formations are preserved in a graben carved deeply into the middle of the Precambrian substratum. Numerous faults whose first movements must have occurred in Mesozoic time have been identified and mapped; in general, they are oriented southwest-northeast. *Drysdall and Weller* [1966] consider the Zambezi Valley to be an asymmetrical rift valley, bordered on the northwest by a well-characterized fault escarpment (Figure 1). For these authors the existing faults are governed by ancient broken zones resulting from sliding movements in the Precambrian formations.

From the records obtained from the temporary stations established near the lake and from the permanent stations at Bulawayo (Southern Rhodesia), Broken Hill–Kabwe (Zambia), and Chileka (Malawi), *Archer* [1969] has established as complete a record as possible of the shocks originating in the area of Lake Kariba.

The first shocks started in June 1959; 22 shocks were counted in 1959, nine were counted in 1969, and 15 were counted in 1961 (the shock of September 13, 1961, at 1920 hours attained a magnitude of 4). Beginning on March 3, 1962, the activity increased rapidly, and several of these shocks were felt at Kariba; 63 shocks were registered in 1962, and 61 were registered during the first 7 months of 1963. Gradually and in proportion as the lake level rose, the frequency and energy of the shocks increased.

The filling of the reservoir was achieved in August 1963 when the water level for the first time reached an altitude of 480 meters (corresponding to a height of about 120 meters above the base of the valley). Some days later on August 14 the series of strongest shocks began. These shocks were registered by many seismological stations. About 10 epicenters were calculated by the U.S. Coast and Geodetic Survey; all were placed in the part of the lake where the water was deepest. The Bureau Central International de Séismologie in Strasbourg attributed a magnitude of 6.1 to the strongest shock, which occurred on September 23 at 0901 hours, and a magnitude of 6.0 to one of the aftershocks, which occurred on September 25 at 0703 hours.

Several hundred foreshocks and aftershocks were registered between September 23 and 30, 1963 (*Archer*'s [1969] catalog shows magnitude determinations for 368 of these). Thereafter,

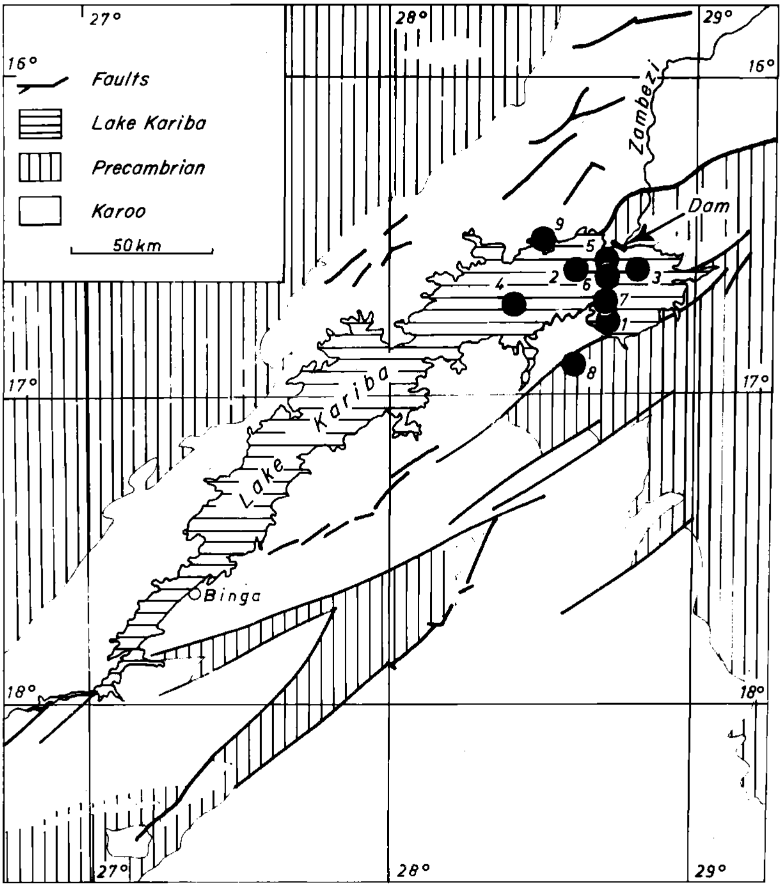


Fig. 1. Schematic geologic map of Lake Kariba showing the epicenters of the principal shocks of September–November 1963 [*Gough and Gough,* 1970*b*; *Rothé,* 1970].

seismic activity decreased, although 50 shocks were recorded in 1967, 39 were recorded in 1968, and several shocks occurred in 1969 and 1970. A very complete report has been published [*Gough and Gough,* 1970*a, b*].

Before the construction of the dam the Zambezi Valley had been considered aseismic; not a single epicenter for this region is shown in the catalog compiled by the United Nations Educational, Scientific and Cultural Organization (Unesco) [*Gorshkov*, 1963]. However, before the filling of the reservoir, several weak shocks were felt by the population of the Binga region upstream of Victoria Falls.

Monteynard Dam. The following information has been obtained regarding Monteynard Dam: type of dam, arch; height of dam, 130 meters; maximum reservoir volume, 275 Mm^3; start of filling, April 19, 1962; end of first filling, April 20, 1963; first shock, April 25, 1963, at 0034 hours; and principal shock, April 25, 1963, at 1336 hours (magnitude of 5.0).

Monteynard Dam (44°57′N, 5°42′E) in the French Alps has been built in the gorge formed by the Drac upstream from Grenoble. It is founded on hard but very diaclastic limestone of the Toarcian (upper Lias) that is underlain by weak schists of the upper Domerian (middle Lias) and by marly limestone interbedded with schists of the lower Domerian [*Gignoux and Barbier*, 1955, plate 6, pp. 32–33]. Filling of the reservoir started in April 1962 and continued until April 20, 1963, when the water level reached an altitude of 490 meters, corresponding to a depth of 130 meters and a total volume of 275 Mm^3. Two shocks were felt at the dam on April 25, 1963, at 0034 hours and 0037 hours and were followed several hours later by a violent shock (magnitude of 5.0) that caused light damage in villages near the dam. The macroseismic epicenter [*Rothé*, 1968, 1970] and the epicenter calculated on basis of records from many seismological stations coincided very exactly with the site of the dam. The small distances between the isoseismals show that the disturbance had a shallow focus (Figure 2).

Some aftershocks were felt during the following days; that of April 27 at 0526 hours caused new damage at Monestier and Sinard. In total, 15 shocks were felt or recorded in 1963, and 10 were recorded in 1964. After a quiet period in 1965 (one single shock), seismic activity resumed in 1966 (23 shocks) and continued in 1967 (16 shocks). The shock of August 24, 1966 (magnitude of 4.3), was felt over a slightly smaller area than that of 1963. The two strongest shocks in 1963 and 1966 occurred when the reservoir was at its maximum height. It is important to note that the Monteynard region is tectonically complex and has a network of faults, fissures, and fractures existing in the substratum, and it is probable that the effective reservoir is more important than the visible lake.

Vaiont Dam. The following information has been obtained regarding Vaiont Dam: type of dam, arch; height of dam, 261 meters; volume of reservoir, 150 Mm^3; start of filling, February 1960; maximum height attained, August 1963; and principal shocks, May 2, 1962, and September 2, 1963.

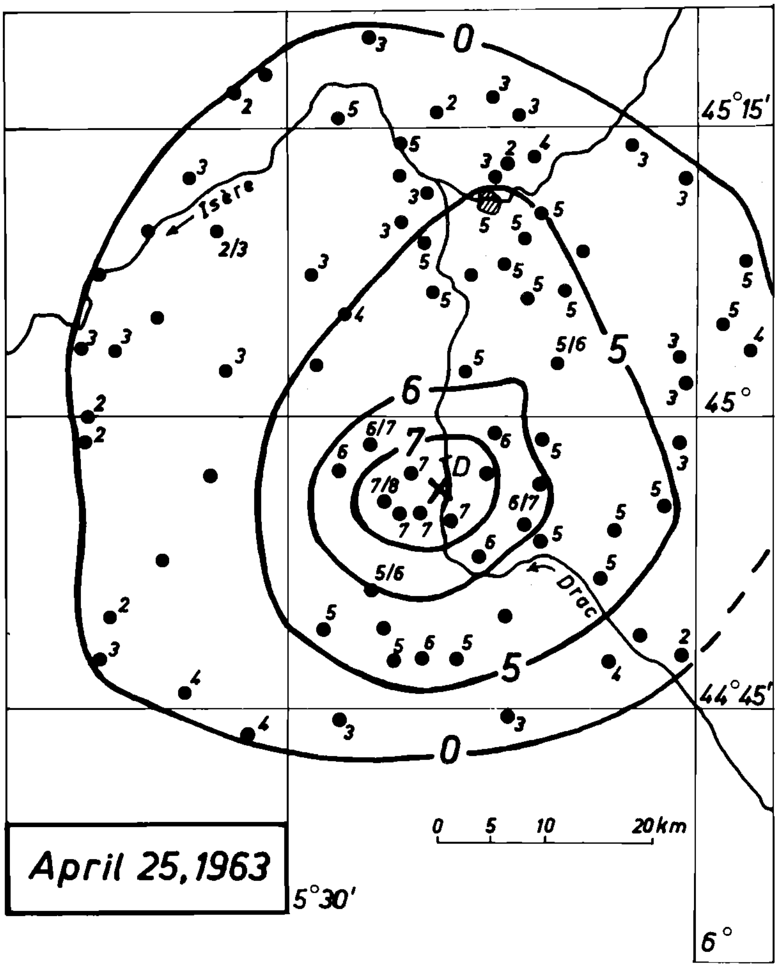


Fig. 2. Map of Monteynard Dam (France) showing isoseismic lines of the earthquake of April 25, 1963 [*Rothé*, 1968]. A cross marks the epicenter, and the letter D marks Monteynard Dam.

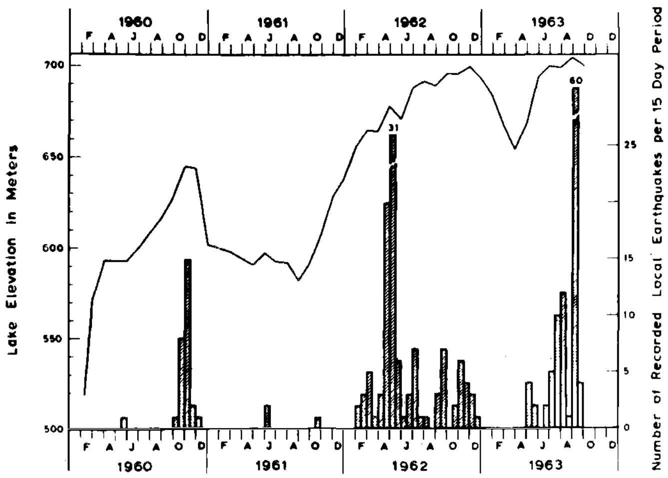


Fig. 3. Seasonal fluctuation of the lake level and number of recorded local shocks per successive 15-day periods at Vaiont Reservoir (Italy) [*Galanopoulos*, 1967; *Caloi*, 1966].

On October 9, 1963, Vaiont Dam, one of the highest in the world, was the scene of a catastrophe that caused the death of more than 2000 persons. The earth movements that caused the catastrophe were preceded by several years of considerable seismic activity characterized by a clear relation between the frequency of shocks and the progress of filling the reservoir. A first maximum of activity (15 shocks in November 1960) corresponded to the first filling to a lake altitude of 650 meters (water depth of about 130 meters). After partial draining in 1961, during which seismic activity was near the zero point, a renewed filling reached an altitude of 675 meters in April 1962; this new height provoked a strong return of seismic activity (50 shocks between April 15 and May 15). The shocks on April 29 at 1658 hours and on May 2 at 1750 hours were sufficiently strong to be registered on several European seismological stations. Finally the lake level surpassed an altitude of 700 meters in September 1963. In the first 15 days of September, 60 shocks were registered, and an earth movement started along the slope of Mont Toc overlooking the lake. The earth movement accelerated at the beginning of October and precipitated a landslide into the lake having a volume evaluated at 350 Mm^3. A giant wave was generated that fell violently into the valley at the foot of the dam and annihilated several villages. To some geologists the terrain of Mont Toc had been in an unstable equilibrium even prior to the filling of the lake. One may suppose then that the effect of numerous shocks caused by the filling of the lake contributed to upsetting the already unstable equilibrium of Mont Toc, the earth slide having started and accelerated in September when the frequency of shocks was highest (Figure 3). It should also be noted that the region of Vaiont belongs to a zone in which natural seismicity is not negligible [*Caloi*, 1964, 1966].

Kremasta Dam. The following information has been obtained regarding Kremasta Dam: type of dam, gravity; height of dam, 147 meters; maximum reservoir volume, 4750 Mm^3; start of filling, July 21, 1965; end of first filling, February 1966; first shock, November 1965; principal shock, February 1966 (magnitude of 6.2); and principal aftershock, May 4, 1966 (magnitude of 5.5).

Kremasta Dam on the Acheloos River in Greece (38°53'N, 21°31'E) started to hold back water in July 1965. In the beginning of November 1965 the water level rose rapidly, and the first shocks were felt (Figure 4). Their frequency accelerated in January, and on February 5, when the lake had nearly reached its maximum altitude (the water depth was about 120 meters), a violent shock (magnitude of 6.2) occurred. There were one dead and 60 injured, and 480 houses were destroyed. Some landslides and surface fractures were visible on the slopes of the Acheloos Valley. The epicenter as calculated (39°03'N, 21°45'E) is located about 25 km northeast of the dam.

The principal earthquake was followed by a large number of aftershocks, of which 2580 were

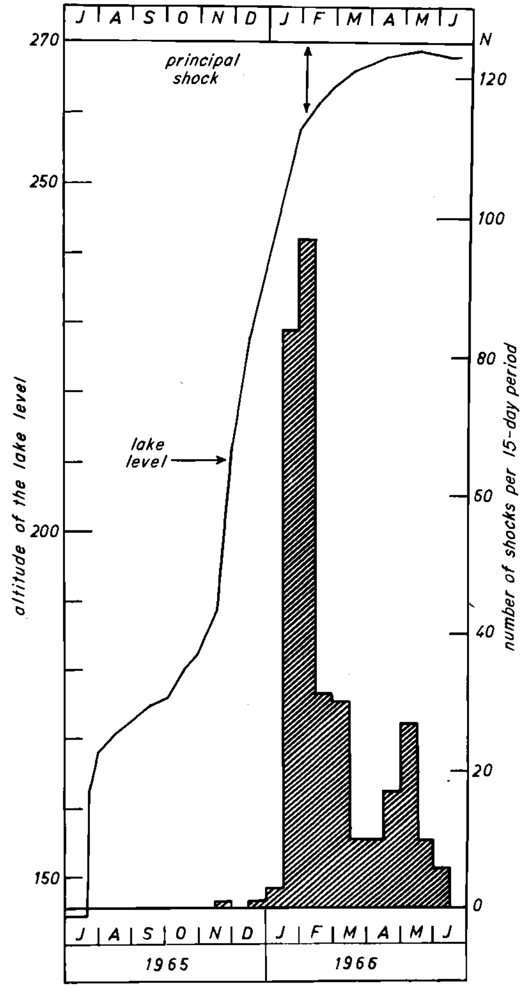


Fig. 4. Seismic activity in number of shocks per 15-day period and curve of lake level rise during filling of Kremasta Reservoir [*Galanopoulos*, 1967].

registered by the station at Valsamata. These aftershocks were located; some were in the neighborhood of the lake, and some were in the mountainous zone northeast of the dam. At least five of the aftershocks exceeded a magnitude of 5. A map of these epicenters was published [*Galanopoulos*, 1967] as well as a detailed study of the foreshocks and aftershocks [*Comninakis et al.*, 1968].

The lake is underlain principally by Eocene-Oligocene flysch. However, about 11 km north of the dam the lake covers a zone where major faults bring the flysch in contact with Jurassic limestones of the Gavrovon formation. This zone produced the strongest foreshocks and aftershocks.

Koyna Dam. The following information has been obtained regarding Koyna Dam: type of dam, gravity; height of dam, 103 meters; maximum lake volume, 2780 Mm^3; start of filling, 1962; end of first filling, 1964 (2000 Mm^3); first shock, 1963; major foreshock, September 13, 1967 (magnitude of 5.0); principal earthquake, December 10, 1967 (magnitude of 6.3); strong aftershock, December 24, 1967 (magnitude of 5.5); and another strong aftershock, October 29, 1968 (magnitude of 5.4).

Koyna Dam (17°23'N, 73°45'E) and the reservoir of Shivajisagar are located in a region uniformly covered by basaltic rocks of the Deccan plateau. This shield is one of the least seismic of the Precambrian areas of the world; a few rare shocks occur here from time to time at isolated points. In fact the basaltic formation is composed of alternate sequences of compact basalt flows and very thin cinder beds, tuffs, and breccias with intercalations of bolar clay. There are no known faults, but there may be slip faults particularly at the contact of the basalts and tuffs (Figure 5).

A few months after the partial filling of the reservoir (860 Mm^3) in 1962, seismic shocks were observed; their frequency increased greatly beginning in the middle of 1963. The epicenters that could be determined were all found either in the neighborhood of the dam or under the reservoir at a distance of 40 km upstream from the dam. As in other regions, these shocks were accompanied by rumbling and by a sort of hollow muffled sound [*Guha et al.*, 1966; *Mane*, 1967].

The volume of the reservoir was progressively brought up to 2000 Mm^3, a value attained in 1964, and since then has varied annually from 850 to 2000 Mm^3. The shocks continued and were attributed to readjustments in response to the heavy overload of water either in the vicinity of the dam or in a zone of particularly weak resistance 40 km upstream. Guha and his collaborators in November 1966 thought that the overload due to the water in the lake had triggered the shocks along a plane of least resistance in the underlying layers and that the elastic energy liberated could perhaps be related to the variation of potential energy of the water mass due to the variation in lake level. In September 1967, *Mane* [1967] wrote, 'It is gathered that such tremors gradually decrease over a period of years and stop com-

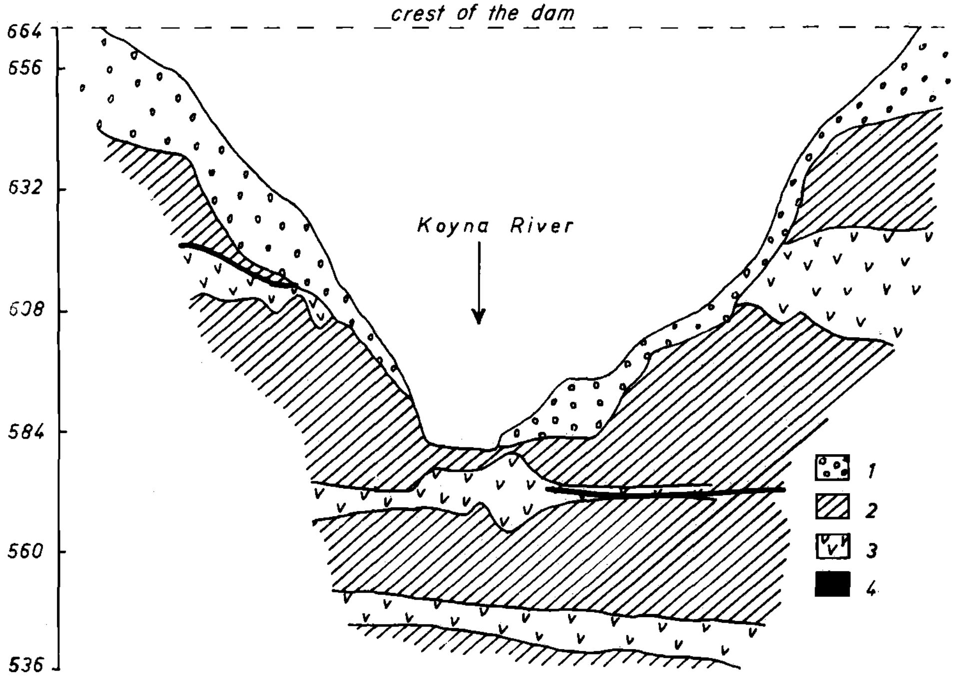


Fig. 5. Simplified geologic cross section of the Koyna Valley: 1, overburden; 2, massive basalt; 3, tuff breccia; and 4, bole; Figure is adapted from a report by *Mane* [1967].

pletely. It is hoped it will be so here also.'

But at the same time, two important shocks occurring on September 13, 1967, caused some light damage; they were followed 3 months later by the destructive shock of December 10, 1967. This earthquake (magnitude of 6.4) caused great damage in the vicinity of the dam (particularly in the village of Koynanagar) and at the dam itself, which was cracked. The dead numbered 177, and the wounded numbered 2300. Numerous aftershocks were felt or registered for several months following; the shock of October 29, 1968, at 1000 hours (17°04N, 73°08E) attained a magnitude of 5.4 and was felt in Poona.

The determination of the epicenter was the object of several studies [*Rothé*, 1968; *Tandon and Chaudhury*, 1968; *Dutta*, 1969]. The different locations calculated all fall either in the vicinity of the dam itself or near the reservoir (Figure 6).

The research into the cause of this earthquake, whose magnitude was unheard of in a region considered to be aseismic according to the Indian paraseismic code [*Indian Standards Institution*, 1962], has led to contradictory positions. Several geologists and geophysicists, those ignoring the very existence of the reservoir, have affirmed that this earthquake was purely tectonic [*Petruchevsky et al.*, 1968; *Auden*, 1969; G. V. Berg et al., unpublished data, 1969]. On their side the committee of experts [*Okamoto et al.*, 1968], made up of members of the Unesco mission, has concluded:

> Since, however, the small shocks were followed by the important shocks of September and December 1967, it would appear more probable that the whole sequence of seismic events is related to a single tectonic cause and the small shocks were foreshocks to the two main ones, which followed. It is the view of the Committee, therefore, that the reservoir was not responsible for the two major shocks of September and December 1967.

Other researchers believed the origin of the great Koyna earthquake to be in small tectonic movements at a depth on the order of 40–70 km [*Bhaskara Rao et al.*, 1969]. As has been noted by *Balakrishna and Gowd* [1970], one may be astonished that the *Geological Survey of India* [1968] and certain other experts [*Guha et al.*, 1968*a*, *b*; *Tandon and Chaudhury*, 1968] could

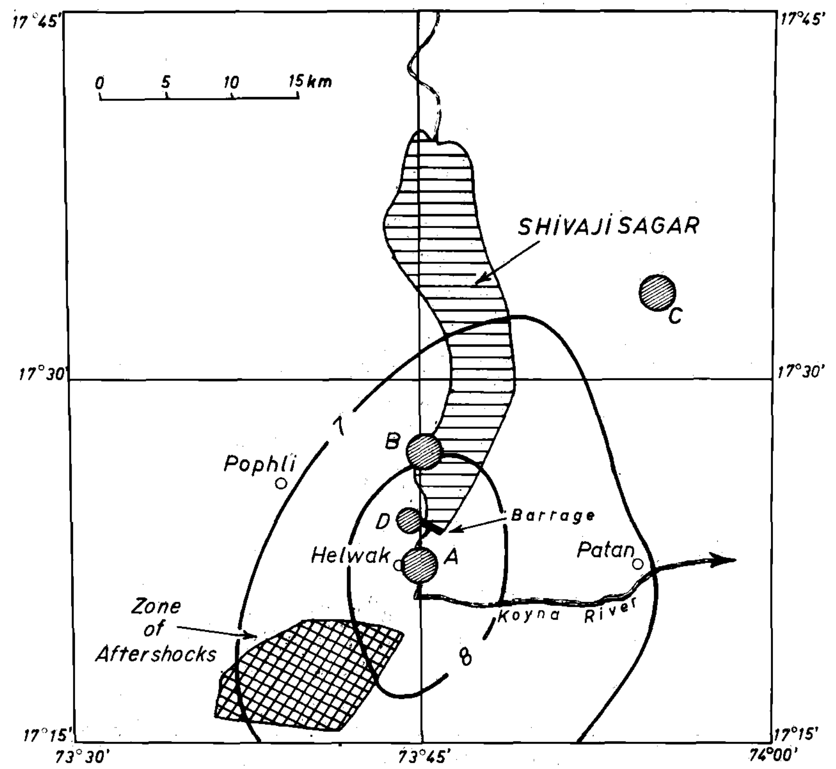


Fig. 6. Zone of greatest intensity (isoseismals of intensity 7 and 8) of the earthquake of December 10, 1967: A, epicenter according to the India Meteorological Department; B, epicenter according to the U.S. Coast and Geodetic Survey (stations at a distance of >20°); C, epicenter according to the U.S. Coast and Geodetic Survey, (109 stations); D, epicenter of the earthquake of September 13, 1967. Figure is adapted from a report by *Dutta* [1969].

believe that the small shocks up until September 13, 1967, were related to the filling of the reservoir but that the two great shocks of September 13, 1967, and of December 10, 1967, were due to tectonic movements in the basement rock under the basalt flows. Thus there would be only a simple coincidence between the small shocks and the great shocks, and consequently there would be two different causes. It is evident that a comparison of the events at Koyna with analogous phenomena that have occurred elsewhere (in particular at Kariba and at Kremasta) permits the rejection of this hypothesis of a dual origin.

In contrast, other authors have seen a direct relation between the series of shocks at Koyna and the filling of the reservoir [*Rothé*, 1968; *Narain and Gupta*, 1968*a*, *b*; *Gupta et al.*, 1969]. The hypothesis that can be drawn on the triggering mechanism for these earthquakes will be discussed below.

Camarillas Dam. The following information has been obtained regarding Camarillas Dam in Spain: type of dam, gravity; height of dam, 36 meters; maximum reservoir volume, 40 Mm^3; start of filling, winter 1960–1961; end of first partial filling (to height of 24 meters), March 1961; first shock, March 16, 1961; and principal shock, December 8, 1961 (magnitude of 3.5?).

In contrast to the previous examples, this dam is small; it was established on Rio Mundo, a tributary of Rio Segura in southeastern Spain. In March 1961, when the first partial filling had reached a stage of 24 meters, numerous subterranean noises were heard. Then more and more numerous shocks occurred. The reservoir was then nearly completely emptied, and the shocks ceased. Another partial filling took place between October and December 1961; the shocks recurred, and the strongest, recorded at several Spanish seismographic stations, occurred on

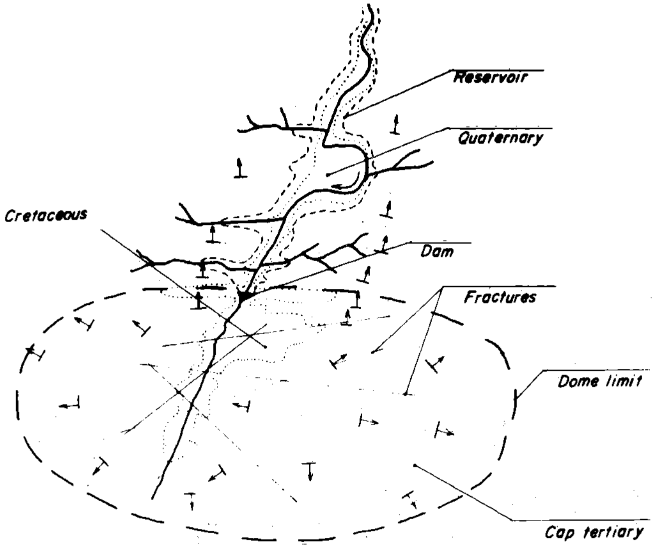


Fig. 7. Sketch map of the location of Camarillas Dam (Spain) with respect to the triassic dome [*Yagüe*, 1969].

December 8, 1961, and caused light damage to dwellings near the dam. The water level was then limited to 24 meters until the seismic phenomena ceased nearly completely (March 1962).

The geologic conditions are very singular: the dam is, in effect, resting on an anticline of Jurassic and Cretaceous limestone that is much fractured by the rise of a dome of Triassic salt (Figures 7 and 8). These geologic conditions explain the seismic activity despite the low height of water in the reservoir [*Yagüe*, 1969].

Oroville Dam and San Luis Dam. Hoffman [this volume] has summarized the observations and the records made prior to and during the filling of two storage reservoirs in California. The geologic conditions at these dams near active geologic faults (San Andreas and Ortigalita) posed some particular problems for the precise location and interpretation of the recorded earthquakes. A surveillance network of seismographs was established in the vicinity of the dams, and the records were studied at the analytic center in Sacramento.

Concerning San Luis Dam (30 km northeast of Hollister) the study concentrated on shocks located at distances of <20 km. The filling of the reservoir was started in the beginning of 1967, and in June 1969 the lake level corresponded to about 75 meters. In the distance interval of 10–20 km, 43 shocks (all with a magnitude of <2.5) were produced during January through March 1969, somewhat before the period of maximum filling. Most of these shocks were located under the reservoir in the vicinity of the Ortigalita fault.

At Oroville Dam the filling was achieved in March 1968, and seismic activity remained very low until September 1968. An increase in activity occurred in September 1968, but the magnitude of the shocks remained at <0.5. However, Hoffman raises the question of whether these are truly seismic shocks or whether they are explosions, since nearly all were registered during the day. We have encountered the same difficulty of interpretation in France, where the network of seismographs records many more phenomena during the day than at night (quarry explosions, road construction, and so on).

Other examples. Several other cases of seismicity related to the filling of storage reservoirs have been described: Oued Fodda in Algeria [*Gourinard*, 1952], Canelles in Catalonia [*Rothé*, 1970], Piave di Cadore in Italy [*Caloi*, 1964], Contra-Vogorno in Switzerland [*Lombardi*, 1967; *Süsstrunk*, 1968], Marathon in Greece [*Galanopoulos*, 1967], and El Grado in Spain [*Yagüe*, 1969]. *Mickey* [this volume] also mentioned some other cases where a generally weak seismicity has accompanied the filling of some reservoirs in the United States: eastern Washington (1950), Rocky Reach Dam and En-

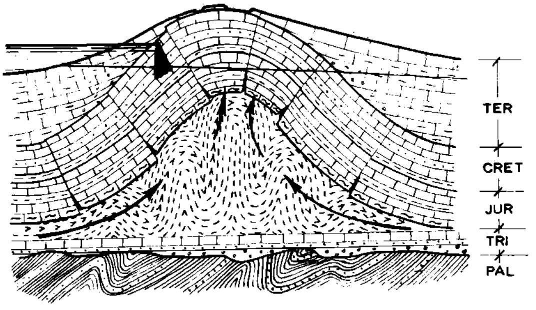


Fig. 8. Geologic section of the location of Camarillas Dam (Spain) with respect to the triassic dome [*Yaguë*, 1969].

tiat Lake (1961), Shasta Dam (1944), Flathead Lake and Kerr Dam in Montana (1969–1970).

SOME CONCLUSIONS

1. Today we know of a score of examples where the observed seismic activity is an artificial activity that must be imputed to the creation of storage reservoirs [*Rothé*, 1970]. Certain of the shocks thus provoked can reach magnitudes of >6 and consequently can cause important damage. It is probable that a longer inquiry would uncover a greater number of cases of provoked seismic activity, since in many cases, in effect, the reports of experts of hydroelectric utilities must remain confidential.

2. The height of the water column appears to play a more important role than the surface area or the total volume of the reservoir; volumes vary from 105 Mm^3 (Vogorno) to 175,000 Mm^3 (Kariba).

3. Seismic activity is particularly pronounced where the depth of the reservoir surpasses 100 meters: Vaiont, 261 meters; Contra (Vogorno), 230 meters; Canelles, 150 meters; Kremasta, 147 meters; Hoover Dam, 142 meters; Monteynard, 130 meters; Kariba, 128 meters; Piave di Cadore, 112 meters; and Koyna, 103 meters.

4. In contrast to what takes place in natural seismic activity, the most violent shocks are most often produced after numerous foreshocks. The frequency of these shocks increases progressively during a more or less long period. The more tectonically quiescent the region (ancient shields), the longer this period will be.

5. The frequency curve of foreshocks and aftershocks in several cases (particularly at Kariba, Kremasta, and Koyna) approaches that represented by Mogi's type 2 [*Comninakis et al.*, 1968; *Gupta et al.*, 1969]. This type corresponds to a heterogeneous prefractured structure subjected to asymmetric exterior forces [*Mogi*, 1963].

6. The seismic activity increases at the time of first filling and after maximum filling has been attained during the course of several years. In one case (Vogorno) the complete emptying of the reservoir after a first filling has resulted in a cessation of shocks.

7. The collected examples [*Rothé*, 1970] contain a share of old terrains where the orogeny is ancient and the natural seismicity is weak (the African shield at Kariba and the Deccan plateau at Koyna) as well as regions of recent orogeny and notable seismicity (Greece, the Alps, the Pyrenees, North Africa, and the Rocky Mountains).

In numerous cases the creation of deep storage reservoirs has not entrained notable seismicity; particular geologic conditions are necessary for the triggering of shocks. Diaclastic formations where great water losses occur (Monteynard and Oued Fodda), networks of faults (Hoover Dam, Kariba, Kremasta, Vogorno, and Monteynard), and heterogeneity of the underlying strata (Koyna and Vaiont), all of which facilitate the circulation of water under pressure, favor the triggering of shocks.

COMPLEMENTARY CONCLUSIONS

Gupta et al. [this volume] have recounted a comparison of the seismic phenomena that have been produced by the filling of certain reservoirs. Their conclusions enlarge and specify some of the points that I have summarized above.

1. By studying the frequency-magnitude relation using the formula $\log N = a - bM$ (where N is the cumulative frequency of shocks of a magnitude equal to or exceeding M), they have determined the value of the coefficient b for the shocks of Kariba, Kremasta, and Koyna for the foreshocks as well as for the aftershocks. Contrary to what is found in natural seisms, the value of b is analogous for both foreshocks and aftershocks. Its value is particularly high for shocks at Koyna: 1.9 for the foreshocks and 1.3 for the aftershocks. In contrast the value for natural seisms on the Indian peninsula is found to be in the neighborhood of only 0.5.

2. The ratio M_1/M_0 of the magnitude of the strongest aftershock M_1 to that of the principal shock M_0 is about 0.9. This value pertains in par-

ticular to the shocks at Boulder, Monteynard, Mangla, Kariba, Kremasta, and Koyna.

3. The curves for the frequency of foreshocks and aftershocks are identical for the three series of Kariba, Koyna, and Kremasta and correspond to Mogi's type 2 model, whereas for natural seisms in the same regions the curves conform to Mogi's type 1 model.
4. The frequency curves of the aftershocks are very analogous.
5. The source mechanisms show that movements along a vertical plane are involved, the reservoirs being situated on the subsiding block.
6. The regions where seismic phenomena have accompanied the filling of reservoirs are characterized by old volcanic activity and by the existence of beds of limestone or reddish clay that are easily affected by water.

The authors believe that the criteria summarized above do permit a distinction of seismic activity associated with reservoir filling from natural seismic activity and that these criteria also lead to a better understanding of the dynamics of the source mechanism.

TRIGGERING MECHANISM

How can the triggering of artificial shocks be explained? For two years the problem has interested more and more researchers [*Gubin*, 1969*a, b*; *Balakrishna and Gowd*, 1970; *Gough and Gough*, 1970*a, b*; *Teisseyre*, 1971; *Healy et al.*, 1970], not only because of the practical interest in a resolution of problems relating to the security of large dams but also because of the theoretical interests relating to the explanation of the mechanism of natural earthquakes [*Evison*, 1970; *Oliver*, 1970].

In a general manner the seismicity appears to be associated with the previous existence of faults in the substratum; these faults have been inactive for a more or less long period, and one may suppose that these faults may play a part in the seismicity by the following different processes: (1) by the direct effect along the preexisting fault plane of shear forces caused by the overload brought on by the water in the reservoir, (2) by the indirect effect of the added forces that liberate orogenic tensions of much greater strength, and (3) by the increase in the interstitial fluid pressure in the blocks of the underlying beds.

The researchers who have studied the shocks at Kariba in detail [*Gough and Gough*, 1970*a, b*] believe that the second working hypothesis cited above is the most likely and that the increase in interstitial fluid pressure, in particular, plays only a minor role in triggering shocks. These authors have calculated the distribution of forces resulting from the overload during the course of the filling and have determined the value of the volume V_τ at whose center the shear stress must exceed 1 bar. The variation of V_τ as a function of time shows a remarkable correlation with the seismic activity. These added forces of 1-2 bars due to the overload have brought about the rupture of fault planes previously exposed to stresses (of tectonic origin?) of several dozen bars.

Evison [1970] has noted that the loading effect of the water was less likely in the case of the seismic activity at Koyna. The study of the focal mechanism showed that there was a sliding movement following a fault plane obviously vertical and oriented north-northwest–south-southeast. Several authors [*Balakrishna and Gowd*, 1970; *Healy et al.*, 1970; *Rothé*, 1970] have been led to attach a greater importance to the variation of fluid pressure at depth.

The involuntary experience at Denver (injection of waste water under pressure in a well 3638 meters deep) has shown that the liberation of stored tectonic energy could be triggered by the penetration of fluid into the crystalline basement rock [*Healy et al.*, 1968; *Healy et al.*, 1970]. This explanation, based on the research of *Hubbert and Rubey* [1959] has brought out the major role played by fluid pressure confined in porous rocks.

In rock containing in its pores a fluid under a pressure p the total force S can be divided into an effective force σ and a force p, the ambient fluid pressure. In fracturing at high pressures in the absence of fluid, according to the well-known formula of Mohr-Coulomb, $\tau = \tau_0 + Sn tg\phi$, where Sn is the normal force along the fault plane, $tg\phi$ is the coefficient of friction, τ is the shear force at the fracture limit, and τ_0 is the force of cohesion.

If a fluid occupies the pores of a rock under pressure p, the preceding equation becomes $\tau = \tau_0 + (Sn - p)tg\phi = \tau_0 + \sigma_n tg\phi$. An increase of the fluid pressure has the effect of reducing the friction resistance and diminishing the normal force σ_n.

In the case of the involuntary experience at Denver the increase in pressure reached 120 bars. It has also been ascertained that the foci of the shocks have become more distant from the well site. Thus the progression of the front of the pressure wave is shown.

It may be noted that this explanation was not immediately accepted, and several authors affirmed that the Denver earthquakes were natural earthquakes [*Hollister and Weimer*, 1968].

It is exceedingly probable that a phenomenon analogous to that observed in Denver has played a part in most of the cases where seismic activity has accompanied the filling of reservoirs, particularly those where great losses of water were observed (Oued Fodda and Monteynard) or those where the substrata are heterogeneous and include interbedded porous layers (Koyna and Kremasta). However, the problem is certainly more complex in the case of reservoirs than in the case of the Denver experience. For a lake of 100-meter depth the fluid pressure is only 10 bars; however, the variation of pressure may spread into porous strata and may play an important role. The artificial lakes may act through the combined effects of the overload and the pore pressure. The triggering forces thus created seem a priori so small that one must conclude that the stored tectonic stresses must already have been near the fracture limit of the rocks [*Evison*, 1970].

It remains surprising that phenomena that are so quantitatively analogous in magnitude (i.e., in energy liberated) have been produced in such widely divergent regions, from a geologic point of view, as the Zambezi graben, Greece, or the Deccan plateau. It is also surprising that the greatest shocks have been observed in every case at the moment of or after the first filling of the reservoir had reached its maximum height.

PROGRAM OF RESEARCH

Because of the theoretical and practical importance of the problem, Unesco convened a working group in Paris in December 1970 composed of representatives of several international associations or commissions having a particular interest in the subject: International Association of Seismology and Physics of the Earth's Interior, International Association of Earthquake Engineering, International Commission on Large Dams, International Union of Geological Sciences, International Association of Engineering Geology, International Society of Soil Mechanics and Foundation, and International Engineering Society of Rock Mechanics.

The conclusions formulated by this group may be summarized as follows. In the present state of knowledge, several factors may be considered to explain the association of earthquakes with the impounding of water in large reservoirs. The relevance of each of these factors will change from case to case, but it would not be prudent to exclude any of them from consideration.

Since the stresses caused by impounded water are small in comparison with the natural stresses present at the depths at which seismic foci have been observed, it must be assumed that the rock masses in question were close to failure before the reservoirs were filled. In some cases the weight of impounded water may be enough to explain the triggering of the stored strain energy. Such triggering action will be favored by the existence of layers having different deformabilities.

On the other hand, the raising of the water level in a reservoir may change the field of effective stresses in the rock mass as a result of the increase in the pore pressures, and failure may occur. This change will occur especially along joints, faults, or other weaknesses and thus will allow flow of the pore fluid. As a result of the increase of pore pressures the normal effective stresses decrease, and this decrease may trigger earthquakes; in such cases the difference between the water level reached in the reservoir and the natural water table level will be an important factor. In both cases (action of water weight or of pore pressures) an increase in the surface area loaded by a reservoir raises the probability of the occurrence of shocks by increasing the rock mass subjected to a given condition of stress.

The working group has emphasized the need to increase the documentation in this field and has invited the associations represented at the Paris meeting to compile reports, as complete as possible, both on reservoirs where filling was accompanied by seismic activity and on those where there was no activity. The comparison of the geologic situations in the different cases should be fruitful.

Finally, from the practical point of view, it was agreed that, in the future, continuous geophysical observations should be made in each region where a new dam is planned. These measures should be started as soon as possible and should comprise the installation of a network of portable seismographs. Detailed geologic and morphologic studies should, of course, also be included. The records should be continued during the filling, and the combination of all information should eventually permit the necessary security measures to be undertaken.

Along these lines the papers by *Hoffman* [this volume] and *Mickey* [this volume] bring out precisely some examples of observations recently undertaken in the United States to study the seismicity at several damsites (Glenn Canyon, Flaming Gorge, San Luis, and Cedar Springs). Natural seismicity is particularly evident at Cedar Springs (682 seisms within 50 km of the site during 28 months of observation). At the other three sites where a dam has been built, the filling of the reservoir did not appear to have provoked an increase over the natural seismicity. It would be interesting if such reports were accompanied by geologic documentation that is as complete as possible.

REFERENCES

Archer, C. B., *A Catalogue of Earthquakes in the Lake Kariba Area, 1959–1968,* Goetz Observatory, Bulawayo, Rhodesia, 1969.

Auden, J. B., Geological report on the seismicity of parts of Western India, including Maharashtra, *Ser. 1519/BMS.RD/SCE,* pp. 1–36, U. N. Educ., Sci. and Cult. Organ., Paris, Sept. 1969.

Balakrishna, S., and T. N. Gowd, Role of fluid pressure in the mechanics of transcurrent faulting at Koyna (India), *Tectonophysics, 9,* 301–321, 1970.

Bhaskara Rao, V., B. V. Satyanarayana Murty, and A. V. S. Satyanarayana Murty, Some geological and geophysical aspects of the Koyna (India) earthquake, December 1967, *Tectonophysics, 7,* 265–271, 1969.

Caloi, P., La geodinamica el servizio delle grandi dighe, *Ann. Geofis., 17*(1), 449–462, 1964.

Caloi, P., L'evento del Vajont nei suoi aspetti geodinamici, *Ann. Geofis., 19*(1), 1–74, 1966.

Carder, D. S., Seismic investigations in the Boulder Dam area, 1940–1944, and the influence of reservoir loading on local earthquake activity, *Bull. Seismol. Soc. Amer., 35,* 175–192, 1945.

Comninakis, P., J. Drakopoulos, G. Moumoulidis, and B. Papazachos, Foreshock and aftershock sequences of the Kremasta earthquake and their relation to the waterloading of the Kremasta artificial lake, *Ann. Geofis., 21*(1), 39–71, 1968.

Drysdall, A. R., and R. K. Weller, Karoo sedimentation in Northern Rhodesia, *Trans. Geol. Soc. S. Afr., 69,* 39–69, 1966.

Dutta, T. K., A note on the source parameter of the Koynanagar earthquake of 10th December 1967, *Bull. Seismol. Soc. Amer., 59,* 935–944, 1969.

Evison, F. F., Seismogenesis, *Tectonophysics, 9,* 113–128, 1970.

Galanopoulos, A. G., The influence of the fluctuation of Marathon Lake elevation on local earthquake activity in the Attica basin area (in Greek), *Ann. Geol. Pays Hellen., 18,* 281–306, 1967.

Geological Survey of India, *A Geological Report on the Koyna Earthquake of December 11, 1967,* Satara, Maharashtra, India, 1968.

Gignoux, M., and R. Barbier, *Geology of Dams and Hydraulic Control Structures* (in French), 343 pp., Masson, Paris, 1955.

Gorshkov, G. P., The seismicity of Africa, in *Investigations of the Resources of the African Continent* (in French), vol. 3, pp. 108–121, United Nations Educational, Scientific and Cultural Organization, Paris, 1963.

Gough, D. I., and W. I. Gough, Stress and deflection in the lithosphere near Lake Kariba, 1, *Geophys. J. Roy. Astron. Soc., 21,* 65–78, 1970*a*.

Gough, D. I., and W. I. Gough, Load-induced earthquakes at Lake Kariba, 2, *Geophys. J. Roy. Astron. Soc., 21,* 79–101, 1970*b*.

Gourinard, Y., La géologie et les problèmes de l'eau en Algérie, 1, Le barrage de l'Oued Fodda, *Congr. Geol. Int. C. R. 19th, 1,* 155–181, 1952.

Gubin, I. E., Seismic zoning of the western margin of the Indian peninsula in Maharashtra state, *Ser. 1519/BMS.RD/SCE,* pp. 39–68, U. N. Educ., Sci. and Cult. Organ., Paris, Sept. 1969*a*.

Gubin, I. E., Koyna earthquake of 1967, *Bull. Int. Inst. Seismol. Earthquake Eng., 6,* 45–62, 1969*b*.

Guha, S. K., P. D. Gosavi, J. G. Padale, and S. C. Marwadi, Crustal disturbance in the Shivajisagar Lake area of the Koyna hydroelectric project (Maharashtra, India), in *Third Symposium on Earthquake Engineering, Roorkee, India, November 4–6, 1966*, pp. 399–416, Sahu Cement Service, New Delhi, 1966.

Guha, S. K., P. D. Gosavi, J. G. Padale, and S. C. Marwadi, Seismic disturbances in the Shivajisagar Lake area of the Koyna hydroelectric project (Maharashtra), report, 16 pp., Cent. Water and Power Res. Sta., Poona, India, 1968*a*.

Guha, S. K., P. D. Gosavi, M. M. Varma, S. P. Agarwal, J. G. Padale, and S. C. Marwadi, Recent seismic disturbances in the Shivajisagar Lake area of the Koyna hydroelectric project, Maharashtra, India, report, 24 pp., Cent. Water and Power Res. Sta., Poona, India, 1968*b*.

Gupta, H., H. Narain, B. K. Rastogi, and I. Mohan, A study of the Koyna earthquake of December 10, 1967, *Bull. Seismol. Soc. Amer., 59,* 1149–1162, 1969.

Gupta, H. K., B. K. Rastogi, and H. Narain, Earthquakes in the Koyna region and common features of reservoir-associated seismicity, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Healy, J. H., W. W. Rubey, D. T. Griggs, and C. B. Raleigh, The Denver earthquakes, *Science, 161*(3848), 1301–1309, 1968.

Healy, J. H., R. M. Hamilton, and C. B. Raleigh, Earthquakes induced by fluid injection and explosion, *Tectonophysics, 9,* 205–214, 1970.

Hoffmann, R. B., Seismic activity and reservoir filling at Oroville and San Luis dams, California, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Hollister, J. C., and R. J. Weimer (Eds.), Geophysical and geological studies of the relationships between the Denver earthquakes and the Rocky Mountain arsenal well, *Quart. Colo. Sch. Mines, 63,* 1–251, 1968.

Hubbert, M. K., and W. W. Rubey, Role of fluid pressure in mechanics of overthrusting faulting, *Geol. Soc. Amer. Bull., 70,* 115–206, 1959.

Indian Standards Institution, *Indian Standard Recommendations for Earthquake Resistant Design of Structures,* 33 pp., New Dehli, 1962.

Lombardi, J., Some problems in rock mechanics studied for the construction of the Contra Dam (Verzasca) (in French), in *Ninth Congress on Large Dams, Istanbul,* pp. 235–252, Commission Internationale des Grands Barrages, Paris, 1967.

Mane, P. M., Earth tremors in Koyna project area, in *Ninth Congress on Large Dams, Istanbul,* pp. 509–518, Commission Internationale des Grands Barrages, Paris, 1967.

Mickey, W. V., Reservoir seismic effects, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Mogi, K., Some discussions on aftershocks, foreshocks and earthquake swarms—The fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena (third paper), *Bull. Earthquake Res. Inst., 41,* 615–658, 1963.

Narain, H., and H. Gupta, Koyna earthquake, *Nature, 217*(5134), 1138–1139, 1968*a*.

Narain, H., and H. Gupta, Observations on Koyna earthquake, *J. Indian Geophys. Union, 5*(1), 30–34, 1968*b*.

Okamoto, S., et al., Koyna earthquake, December 11, 1967, in *Report of the Committee of Experts,* vol. 1, 2, Government of India Press, New Delhi, 1968.

Oliver, J., Recent earthquake prediction research in the U.S.A., *Tectonophysics, 9,* 283–290, 1970.

Petruchevsky, B. A., N. V. Kondorskaya, and N. V. Shebalin, Le tremblement de terre du Dekkan occidental du 10 décembre 1967, *Izv. Akad. Nauk SSSR Fiz. Zemlia,* no. 11, 20–28, 1968.

Rebeyrol, Y., The tremors of the earth may have their origin in the works of man (in French), *Le Monde,* p. 11, Dec. 29, 1967.

Rothé, J. P., Fill a lake, Start an earthquake, *New Sci., 39*(605), 75–78, 1968.

Rothé, J. P., Earthquakes and reservoir loadings, in *Proceedings of the Fourth World Conference on Earthquake Engineering,* vol. 1, pp. 28–38*c*, Associatión Chilena de Sismolgía e Ingenieria Antisimica, Santiago, 1969.

Rothé, J. P., Man-made earthquakes (in French), *Tectonophysics, 9,* 215–238, 1970.

Süsstrunk, A., Seismic shocks in the Verzasca Valley during the filling of the Vogorno Reservoir (in German), *Verh. Schweiz. Naturforsch. Ges., 148,* 89–92, 1968.

Tandon, A. N., and H. M. Chaudhury, Koyna earthquake of December 1967, *Sci. Rep. 59,* pp. 1–12, India Meteorol. Dep., New Delhi, 1968.

Teisseyre, R., Hydrodynamical effects in the problem of tectonic energy release and tensile cracking, 12th General Assembly of the European Seismology Commission, Luxembourg, September 21–29, 1970, *Observ. Roy. Belg. Commun., Ser. A, 13,* 134–140, 1971.

Yaguë, A. G., Earth tremors in reservoirs (in Spanish), report, 5 pp., Asoc. de Ing. Sismica, Madrid, 1969.

Earthquakes in the Koyna Region and Common Features of the Reservoir-Associated Seismicity

HARSH K. GUPTA, B. K. RASTOGI, AND HARI NARAIN
National Geophysical Research Institute, Hyderabad, India

Seismicity in the Koyna region of India increased considerably following the impounding of the reservoir in 1962. A detailed examination of the foreshock-aftershock pattern, frequency and magnitude relations, and source dynamics of the earthquakes in this region [*Narain and Gupta*, 1968*a, b; Gupta et al.*, 1969, 1971] showed different characteristics from those of the recently well-studied earthquake sequence in the Godavari Valley, which also belongs to peninsular India [*Gupta et al.*, 1970].

The association of seismic activity with artificial lakes was noted for the first time by *Carder* [1945] for Lake Mead, where thousands of earthquakes occurred following the filling of the lake. Later, a number of examples were cited by various investigators. *Rothé* [1968, 1969, 1970] has made a comprehensive study of the phenomenon. His main conclusions are that seismicity is particularly noticeable when the reservoirs are deeper than 100 meters, that the main shock is preceded by a number of foreshocks, and that some particular geologic conditions are necessary for such an earthquake occurrence. *Rothé* [1969] has cited about a dozen examples showing the relation between water levels or injection and seismic activity. No precise mechanism is suggested. Considering the importance of the phenomenon and its economic implications, *Gupta et al.* [1972*a, b*] have examined these cases in detail and found certain common characteristics. Some of these characteristics are useful in distinguishing reservoir-associated earthquakes from normal earthquakes of the regions and also have prediction potentialities. In the text to follow, these findings are briefly discussed.

INITIATION AND LOCALIZATION OF THE SEISMIC ACTIVITY

In all the cases examined, it is noticed that, following the impounding of artificial lakes, seismic activity is initiated or abnormally increased and that the epicenters are confined to the vicinity of the reservoir.

Lake Mead (United States). Following the filling of the lake in 1935 the earthquakes started to be felt in 1936. No such reports are available for at least 15 years prior to the filling of the lake. During 1937, about 100 tremors were felt, and, after the installation of seismographs in 1938, some thousands of tremors were located. In 1942 the nearby observatories were equipped with sensitive Benioff seismometers, which were able to locate the epicenters of earthquakes up to a magnitude of 2. All the epicenters were found in the vicinity of the reservoir [*Carder*, 1945].

Monteynard (France). The area is tectonically disturbed, but the first earthquake in the region occurred in April 1962 when filling of the reservoir started. The epicenter of this earthquake was 12 km from Monteynard. A damaging earthquake occurred on April 25, 1963, and its epicenter was close to the reservoir and focal depth 0. A swarm of shocks was recorded from the region in 1966, and an earthquake of a magnitude of 4.3 occurred on August 24, 1966 [*Rothé*, 1969].

Grandval (France). A few shocks, some of them accompanied by underground noises, were observed near the lake in December 1961 and January 1962 after the first filling was completed. In 1963 and 1964 a few shocks were felt with an intensity of 5, and the focus was exactly under the reservoir [*Rothé*, 1969].

Vaiont (Italy). Over 200 local earthquakes were recorded near the Vaiont Reservoir in the period 1960–1963, and these are believed to have disturbed the unstable equilibrium of the strata and thus to have caused the disastrous landslide in 1963 [*Caloi*, 1966].

Mangla (Pakistan). Adams [1969] reported a 2½ times increase in seismic activity in the region after impounding of the reservoir.

Catalogne (Spain). Fontsèrè [1963] reported some shocks near the reservoirs in Catalogne, and his isoseismic maps indicate that the epicenters were close to the hydroelectric works.

Oued Fodda (Algeria). Filling started at the end of 1932. From January to May 1933, many shocks were produced; these shocks were felt only in the neighboring areas of the dam [*Gourinard*, 1952].

Contra (Switzerland). Commencement of filling of the Contra Reservoir took place in August 1964, and the seismic activity started in May 1965. Underground noises and several hundred local shocks were produced at the end of first filling. Epicenters were localized in Berzona in a region limited by two faults, one in the south and another in the north. Because of some strong shocks, the village of Berzona was evacuated for some time [*Süsstrunk*, 1968].

Arsenal Well (United States). The record of only one earthquake (that of 1882) is available for the Denver area. A swarm of seismic activity (epicenters near the well) started in 1962 within 7 weeks of the start of water injection [*Evans*, 1966; *Healy et al.*, 1968].

Mississippi River Valley (United States). Some 70 earthquakes with an intensity of ≥5 have occurred in the Mississippi region since 1811. The epicenters are concentrated near the rivers. *McGinnis* [1963] mentioned that 65% of the epicenters lie within the area filled with alluvials.

Kariba (Zambia). The Kariba region was considered to be nonseismic, and, in the report of *Gorshkov* [1963], no epicenters were given for this region before the lake filling. The filling started in 1959, and the seismic activity soon followed. A total of about 1400 shocks were recorded in a period of 10 years from 1959 to 1968. During August–September 1963, strong earthquakes with magnitudes of up to 6 occurred in this region. These epicenters were confined to the lake vicinity [*Gough and Gough*, 1970*a*, *b*].

Kremasta (Greece). Although this region is seismically active, in the 15 years preceding the construction of the Kremasta Dam, activity was restricted to the lower part of the Acheloos Valley, about 40 km away from the damsite. The filling started on July 21, 1965, and the earthquakes were felt in the vicinity of the lake in August. In December, activity started increasing exponentially, and the main shock with a magnitude of 6.3 occurred on February 5, 1966. Epicenters of these earthquakes are close to the lake [*Comninakis et al.*, 1968]. Valsamata station recorded 740 foreshocks and 2580 aftershocks.

Marathon (Greece). Galanopoulos [1967] reported a swarm of tremors around Marathon Lake at peak reservoir level in 1953.

Koyna (India). No reports of earthquakes being felt were available for the period prior to the start of impounding in 1962. A scrutiny of seismograms written since 1950 by Benioff seismometers at Poona at a distance of 115 km showed very little activity. Soon after the impounding in 1962 the reports of felt earthquakes became prevalent. Making use of the data of nearby observatories, *Guha et al.* [1968] located these epicenters. They depict a certain migrational pattern of the activity along the reservoir. All these epicenters, including that of the December 10, 1967, earthquake (magnitude of 6), are within 10 km of the reservoir.

FREQUENCY OF EARTHQUAKES IN RELATION TO WATER LEVEL OR INJECTION

The frequency of the shocks seems to depend on the following factors: rate of increase of water level, duration of loading, maximum level achieved, and duration for which the high level is maintained. The increase in the water level is followed by an increase in seismic activity, whereas a decrease in water level is followed by a decrease in seismic activity. Every significant rise in water level is followed by a conspicuous burst of seismic activity, and the water level minimums invariably correspond to relatively quiescent periods.

Lake Mead. Every rise in the water level from 1936 to 1944 was followed by a burst of seismic activity. Between these rises a period of constant or decreased level was followed by decreased seismic activity. Maximum seismic activity and the strongest earthquake (magnitude of 5) occurred in May 1939, about 9 months after the lake had reached its normal level of 144.7 meters.

Monteynard. Rothé [1969] has pointed out that the energy released in the earthquakes

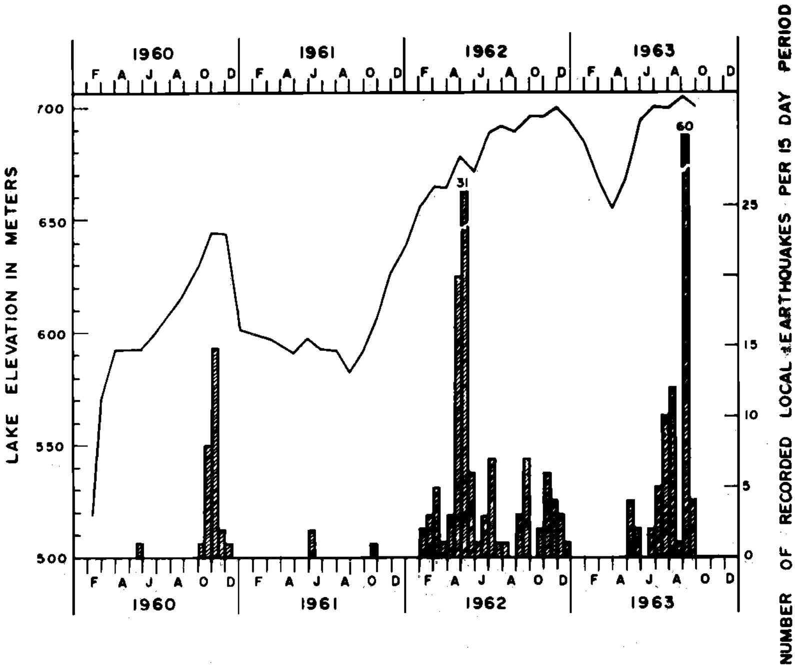


Fig. 1. Seasonal fluctuations of Vaiont reservoir and the local earthquakes [*Galanopoulos*, 1967].

associated with Monteynard Lake in 1963 could be well compared with the lake levels. The two largest earthquakes were the one of April 25, 1963, which caused some damage, and that of August 24, 1966, with a magnitude of 4.3; both these earthquakes occurred at the highest water level of 490 meters.

Grandval. *Rothé* [1969] has reported that the two strongest shocks occurred when the lake reached its maximum level. During August–September 1963 the maximum level of 741 meters was reached. An earthquake with an intensity of 5 followed on August 5. Another strong earthquake occurred in 2 months.

Vaiont. Seismic activity followed the trend of water level very faithfully, as is shown in Figure 1. The three rises in the water level are all followed by an enhanced seismic activity, and after every rise the decrease in water level is followed by decreased seismic activity. Maximum activity was recorded in September 1963 at the time of peak level and was followed by a high rate of loading.

Mangla. Seismic activity increased in the region after impounding of the reservoir. The rise and fall in seismic activity correspond well with the rise and fall of water level. *Adams* [1969] made a striking observation that a quiescent period of seismic activity between April 1 and July 12, 1968, corresponded to the time when the reservoir was at its seasonal low and that a large number of earthquakes occurred in July and August, when the rate of increase of water level was quite high and reached the seasonal peak.

Contra. *Rothé* [1970] mentioned that an increase in lake level was followed by an increase in frequency of shocks with a time lag of 3–6 weeks. After a few weeks of maximum lake level the strongest shocks were produced in October and November 1965.

Denver. Monthly seismic activity (Figure 2)

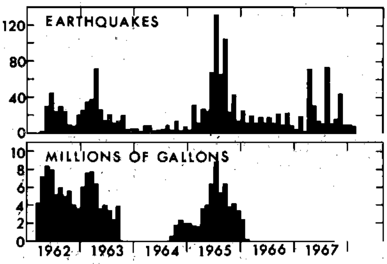


Fig. 2. Number of earthquakes per month recorded in the Denver area and monthly volume of injected water in the deep Arsenal Well [*Major and Simon*, 1968].

shows a strong positive correlation with the monthly amount of injected fluid for 1962–1965, as was pointed out by *Evans* [1966] and *Healy et al.* [1968]. Strikingly, the period of no fluid injection from October 1963 to September 1964 corresponds to a period of low seismicity. However, following the large injections during 1965, the seismic activity continued during 1966 and 1967.

Mississippi River Valley. *McGinnis* [1963] has shown a striking positive correlation between the earthquake frequency in the region and the rate of change of the river stage for the Mississippi River at Hickman, Kentucky.

Kariba. It is evident from Figure 3 that every rise in the water level has a corresponding increase in the seismic activity. When the water level is constant or decreases, the seismic activity also decreases. The strongest shocks in 1963 occurred beneath the deepest portion of the lake and corresponded to the lake level maximum.

Kremasta. The high rate of increase in water level from November 1965 to January 1966 gave rise to an increase in seismic activity since November 1965 and a burst of tremors during January–February 1966 (Figure 4). The peak activity occurred in February, just after a long period with an extremely high rate of loading. The activity decreased during March 1966 and thereafter when the reservoir level was more or less constant.

Marathon. Somewhat similar to Kremasta is the case of the relatively smaller Marathon Lake situated close by. Figure 5 shows that the seismic activity increased following the loading in January 1951 and that the seismic activity maximums occurred just after a long period with a high rate of loading. Activity died down as the water level decreased. *Galanopoulos* [1967] showed that seasonal fluctuations in the lake level from 1958 to 1966 were followed by quite marked seismic activity.

Koyna. Figure 6 shows the reservoir level versus tremor frequency relation for the Koyna region for the period 1963–1967. Seismic activity is found to increase every year following the rainy season. *Gupta et al.* [1969] have pointed out that the highest water levels for the longest duration were retained during August–December 1967. This period of high water level corresponded to a period of maximum seismic activity, when >300 earthquakes were identified within a week by nearby observatories and an earthquake with a magnitude of 6 occurred on December 10, 1967. Second highest levels were reached during August–October 1965; this water level corresponds well with the occurrence of the second most conspicuous activity in November 1965. The small rate of loading and comparatively lower levels following the rainy seasons in 1964 and 1966 are characterized by relatively much less conspicuous seismic activity. In general, the seismic activity follows reservoir loading with a certain lag of time. The absence of seismic activity before the filling of the reservoir and these examples indicate a correlation between the reservoir levels and the seismicity of the region.

VALUES IN THE FREQUENCY AND MAGNITUDE RELATIONS

For the Gutenberg-Richter linear relation $\log N = a - bM$, where N is the cumulative frequency of earthquakes of magnitude $\geq M$ and b is the slope, it has been observed by many workers that the b values for the foreshocks of a particular sequence are lower than those of the aftershocks. The b values are basically dependent on the mechanical structure of the media and the mechanism of the strain accumulation and release. Among the various cases of reservoir-associated seismicities, those of Kariba, Kremasta, and Koyna are of specific interest in view of the occurrence of earthquakes of magnitudes of ≥6. For these regions, foreshock and aftershock b values for the reservoir-associated earthquakes, b values of any normal earthquake aftershock sequence, and the regional b values from earthquakes of different magnitudes (not including the aftershocks) have been examined (Table 1).

It is clear from Table 1 that for these three cases of reservoir-associated seismicities the foreshock b values are comparable or higher than the aftershock b values and that both values are higher than the regional b values and those observed for aftershock sequences of other earthquakes. Similarly high b values for seismic activities at Lake Mead, Monteynard, and Mangla have been found by *Gupta et al.* [1972*a*, *b*]. Lack of data did not permit similar examination for other cases.

Berg [1968] reviewed the foreshock b values for four earthquakes of magnitudes of 4–8 in Japan, Alaska, Greece, and Chile and found that the b values ranged from 0.3 to 0.6 for the foreshocks, almost half the values for the aftershocks. He

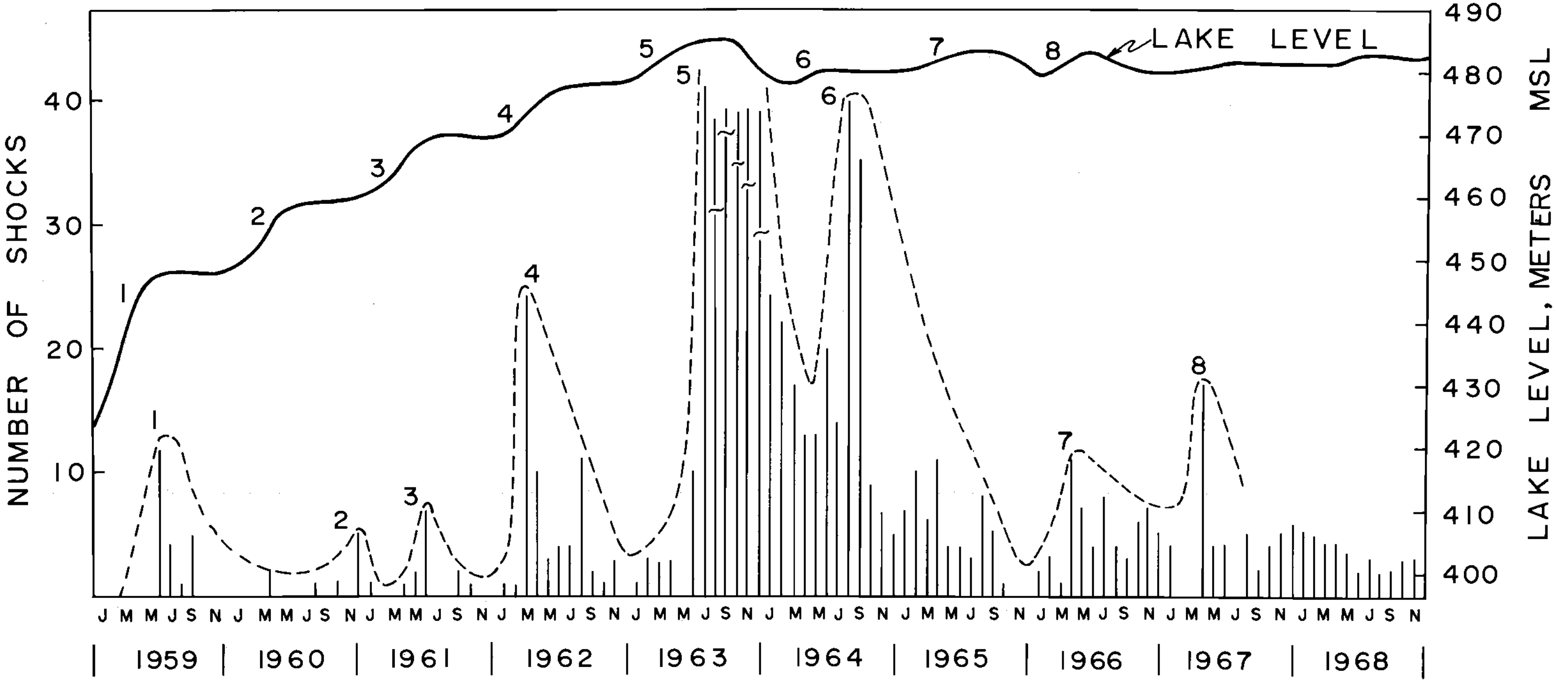


Fig. 3. Monthly tremor frequency and water levels in Lake Kariba during 1959–1968 from the data of *Archer* [1969]. Rises in the water level and corresponding bursts of seismic activities are marked by numbers 1–8.

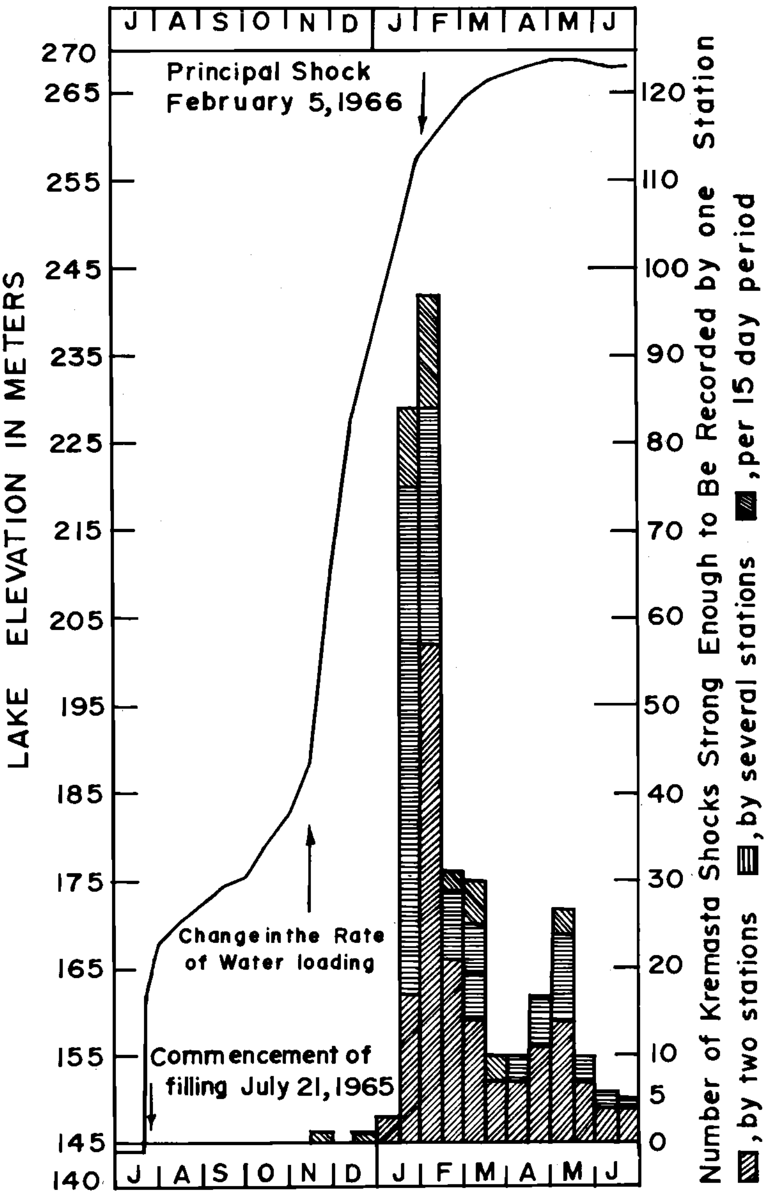


Fig. 4. Kremasta Lake elevations and the earthquake activity in the region [*Galanopoulos*, 1967].

mentioned that if a high *b* value of 0.5–0.6 is exhibited in a foreshock sequence, a large earthquake of a magnitude of 8 should be expected. But, in the case of Kariba, Kremasta, and Koyna, foreshock *b* values are found to be 1.1, 1.4, and 1.9, respectively, whereas the magnitudes of these earthquakes were only of the order of 6.

MAGNITUDE RATIO OF THE LARGEST AFTERSHOCK TO THE MAIN SHOCK

In the study of Californian earthquake sequences, *McEvilly and Casaday* [1967] and *McEvilly et al.* [1967] have pointed out that for the sequences with low *b* values the largest aftershock magnitude is at least 0.9 times that of

TABLE 1. Foreshock and Aftershock *b* Values for the Kariba, Kremasta, and Koyna Sequences

	b Value	Comments
Kariba		
Foreshocks of large earthquakes	1.1	*Gough and Gough* [1970*a*, *b*]
Shocks before, during, and after the main activity	1.0	*Gough and Gough* [1970*a*, *b*]
Aftershock of any other earthquake sequence of the region	...	...
Regional	0.8	for Africa [*Gupta et al.*, 1972*b*]
Kremasta		
Foreshock	1.4	*Comninakis et al.* [1968]
Aftershock	1.1	*Comninakis et al.* [1968]
Aftershock of any other earthquake sequence of the region	0.7	average value of 30 aftershock sequences in Greece [*Papazachos et al.*, 1967]
Regional	0.8	for Greece [*Galanopoulos*, 1967]
Koyna		
Foreshock	1.9	*Gupta et al.* [1972*b*]
Aftershock	1.3	*Gupta et al.* [1972*b*]
Aftershock of any other earthquake sequence of the region	0.5	Godavari Valley earthquake sequence of April 1969 [*Gupta et al.*, 1970]
Regional	0.5	for peninsular India [*Gupta et al.*, 1972*b*]

the main shock and that for higher values of *b* the magnitude ratio is about 0.6–0.7. On the other hand, *Gupta et al.* [1969] found that for Koyna the *b* values were high and so was the ratio. They postulated that this feature may be typical of reservoir-associated seismicities. An examination of the available data [*Gupta et al.*, 1972*a*] shows this feature to be present in other cases (Table 2).

The ratio M_1/M_0 for other sequences studied in Greece is high (i.e., on the order of 0.8 or 0.9) [*Papazachos et al.*, 1967], whereas the *b* values are generally low (around 0.6). For the Kremasta earthquake a high value of 0.9 for the ratio M_1/M_0 is associated with a high *b* value of 1.1. The case of Koyna is similar: a value of 0.87 for M_1/M_0 is associated with a *b* value of 1.3. For the earthquake sequence in Godavari Valley, also belonging to peninsular India, a value of 0.88 for M_1/M_0 is associated with a low *b* value of 0.5 [*Gupta et al.*, 1970].

FORESHOCK-AFTERSHOCK PATTERNS

Mogi [1963], after studying the foreshock-aftershock patterns experimentally on models and comparing them with natural earthquake occurrences, has classified these patterns into three types (Figure 11*b*). The main earthquakes at Kariba, Kremasta, and Koyna are preceded by a number of foreshocks, and the foreshock-aftershock pattern is identical to type 2 of Mogi's classification. The normal earthquakes of these regions belong to type 1 of Mogi's classification.

Figure 7 shows the foreshock-aftershock pattern for the main Kariba earthquake at 09:01:57 on September 23, 1963. This shock had been preceded by about 20 foreshocks in 1 day. The number of shocks increased abruptly to a maximum at the time of the main shock, and the aftershocks decreased rapidly. In 1 week, some 360 aftershocks were recorded.

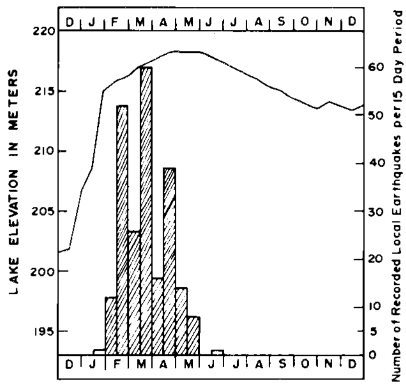


Fig. 5. Seasonal fluctuation of Marathon Lake elevation and local microearthquakes ($3 > M \geq 1$) recorded at Athens in 1951 [*Galanopoulos*, 1967].

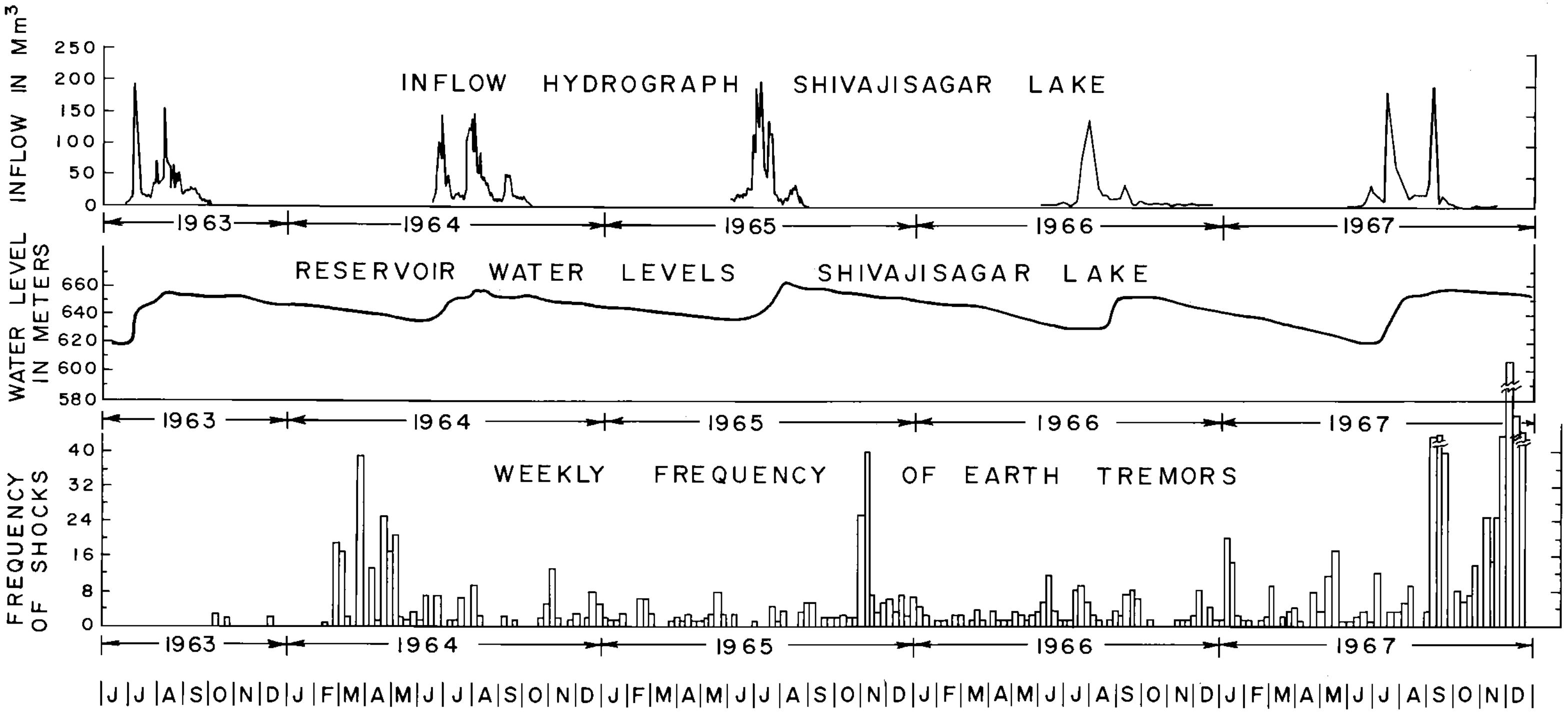


Fig. 6. Inflow hydrograph and water level of the reservoir at Koyna Dam and the seismic activity near the dam. Figure is adapted from a report by *Guha et al.* [1968].

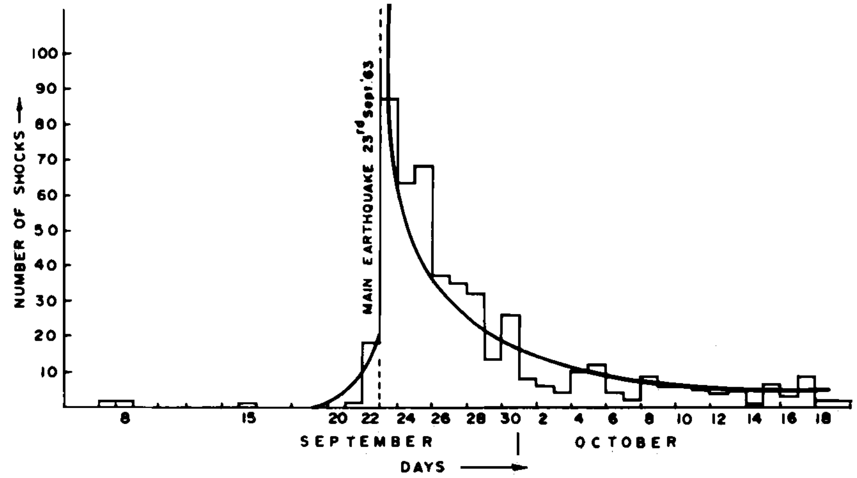


Fig. 7. Foreshock-aftershock pattern for the Kariba earthquake [*Gupta et al.*, 1972*b*].

The foreshock-aftershock pattern for the main Kremasta earthquake at 02:01:43 on February 5, 1966, is shown in Figure 8. In a period of 1 month before the main earthquake, 17 foreshocks were recorded. Earthquake frequency rose to a maximum at the time of the main earthquake, and then the aftershocks decreased rapidly. *Papazachos et al.* [1967] have studied foreshocks and aftershocks of 60 large earthquakes ($M \geq 6$) of Greece and have reported a rare occurrence of foreshocks; hence nearly all these earthquakes could be said to be type 1 earthquakes.

Figures 9 and 10 [*Guha et al.*, 1968] show the foreshock-aftershock patterns for the Koyna earthquakes of September 13 and December 10, 1967, respectively. The patterns are identical to type 2 of Mogi's model. For the main earthquake of December 1967, about 90 foreshocks in a period of 10 days and >400 aftershocks in a period of 20 days were recorded. Figure 11*a* exhibits the foreshock-aftershock pattern for the Godavari Valley earthquake [*Gupta et al.*, 1970]. Like Koyna, Godavari Valley belongs to peninsular India, and the Godavari Valley earthquake had a magnitude comparable to that of the Koyna earthquake. The Godavari earthquake belongs to type 1 of Mogi's classification (Figure 11*b*).

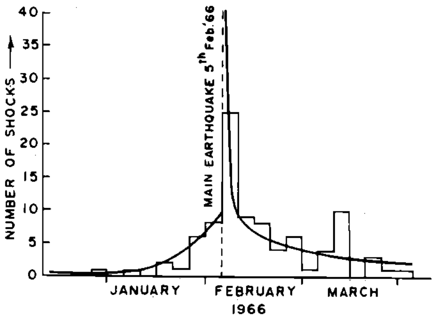


Fig. 8. Foreshock-aftershock pattern for the Kremasta earthquake [*Gupta et al.*, 1972*b*].

TIME DISTRIBUTION OF AFTERSHOCKS

Figures 12, 13, and 14 show the time distribution of the aftershocks of the main earthquakes of Kariba, Kremasta, and Koyna, respectively. The distributions are identical, and the number of aftershocks on the tth day after the main shock could be given by three similar relations: $n(t) = 130t^{-1}$ for Kariba, $n(t) = 134t^{-0.78}$ for Kremasta, and $n(t) = 180t^{-1}$ for Koyna. The relation for

TABLE 2. Largest Aftershock to the Main Shock Magnitude Ratios and the b Values

Region	Main Shock Magnitude M_0	Largest Aftershock Magnitude M_1	M_1/M_0	b Value
Boulder	5.0	4.4	0.88	1.4
Monteynard	4.9	4.5	0.92	0.7
Mangla	3.5	3.3	0.94	1.0
Kariba	6.1	6.0	0.98	1.0
Kremasta	6.2	5.5	0.89	1.1
Koyna	6.0	5.2	0.87	1.3

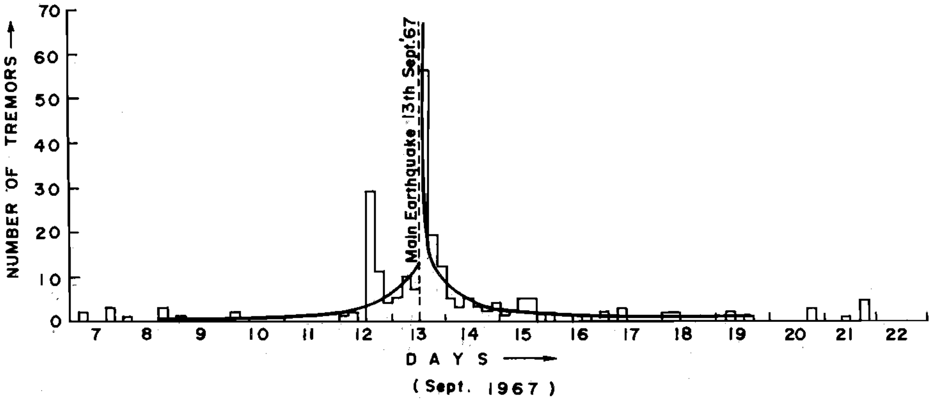


Fig. 9. Foreshock-aftershock pattern for the Koyna earthquake of September 13, 1967 [*Guha et al.*, 1968].

Kremasta given above has been found by *Comninakis et al.* [1968].

GEOLOGY, FAULTING, AND SUBSIDENCE

It has been observed that the reservoirs that gave rise to seismicity are generally situated in regions having some heterogeneity. Specifically, the Kariba, Kremasta, and Koyna regions had evidences of volcanism in the past and are characterized by the presence of rocks easily affected by water. The Zambezi Valley, in which Kariba Lake is situated, consists of karoo sediments of the Mesozoic and Paleozoic ages. During the final stages of karoo history a vast amount of lava was poured out and formed a basaltic plateau. The maximum thickness of this flow is about 700 meters, and these beds are interstratified with red eolian sandstones. Kremasta Lake is mainly based on sedimentary rocks of the Eocene-Oligocene period that came into contact with Jurassic limestones by faults situated some 10 km north of the dam. The earthquakes following the impounding of the lake originated at this zone. The region of Greece had a volcanic past. Koyna Dam and Shivajisagar Lake, formed by the dam, are situated on the volcanic basalt rocks of peninsular India, generally known as the Deccan traps. The lava

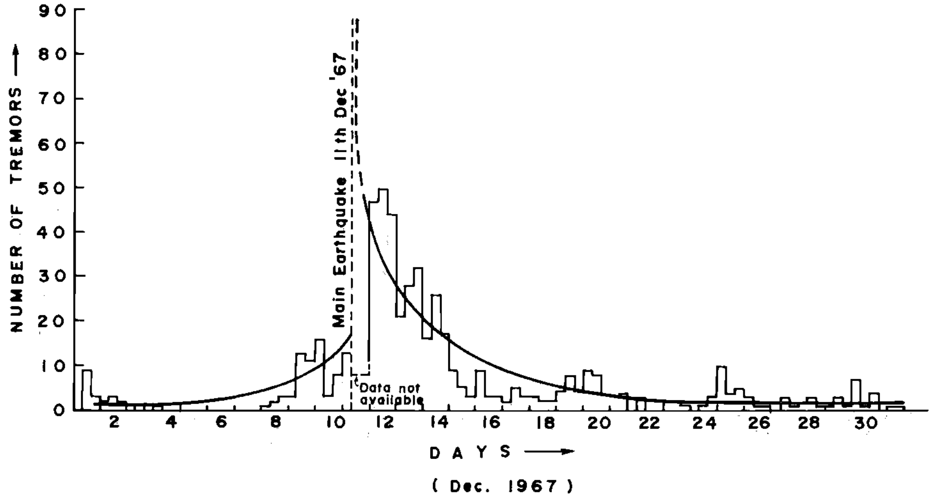


Fig. 10. Foreshock-aftershock pattern for the Koyna earthquake of December 10, 1967 [*Guha et al.*, 1968].

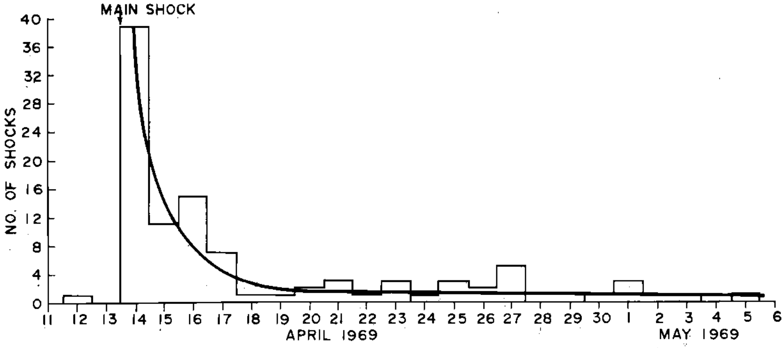


Fig. 11*a*. Foreshock-aftershock pattern for the Godavari Valley earthquake [*Gupta et al.*, 1970].

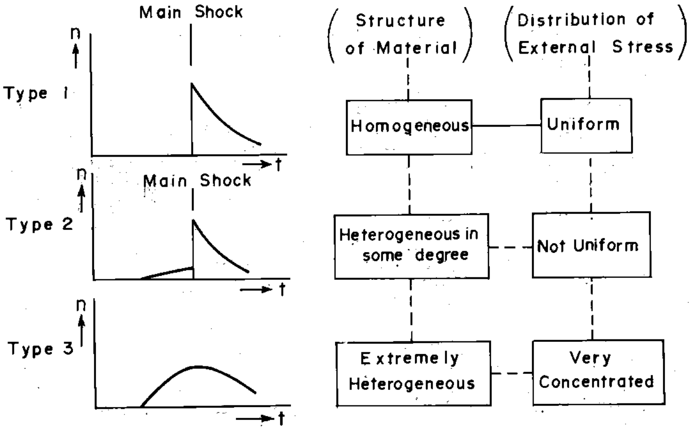


Fig. 11*b*. *Mogi*'s [1963] classification of foreshock-aftershock patterns.

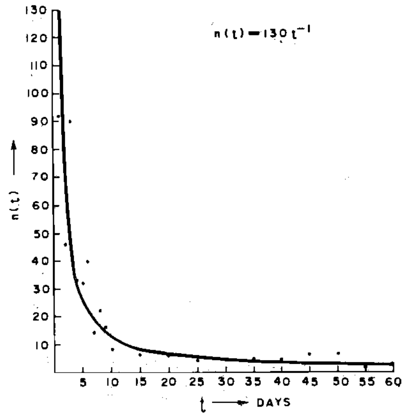


Fig. 12. Time distribution of Kariba aftershocks [*Gupta et al.*, 1972*b*].

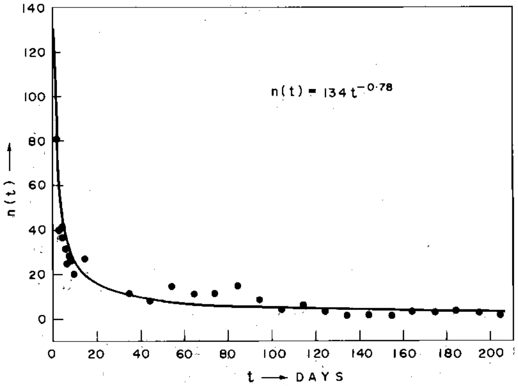


Fig. 13. Time distribution of Kremasta aftershocks [*Comninakis et al.*, 1968].

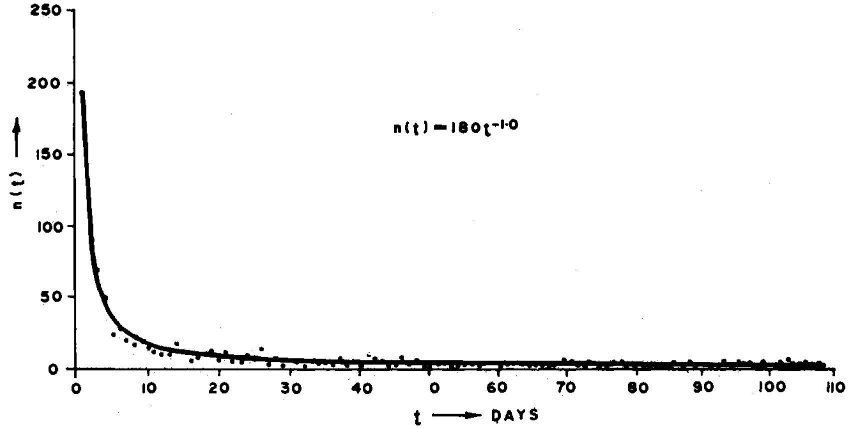


Fig. 14. Time distribution of Koyna aftershocks [*Gupta et al.*, 1972*b*].

flows are alternated by thin layers of trap ash or red boles.

The focal mechanism is found to be similar and characterized by movements on a vertical plane, the lake being situated on the sinking block for Kariba, Kremasta, and Koyna earthquakes. *Gough and Gough* [1970*a*, *b*] reported vertical movements of blocks on fault planes associated with the earthquakes of Kariba. The fault plane responsible for the Kremasta earthquake has been found by *Comninakis et al.* [1968]. They reported it to be an almost vertical thrust fault, Kremasta Lake being situated on the sinking block. The strike of the fault plane determined by *Gupta et al.* [1969] is N32°W for the main Koyna earthquake, and it has been pointed out that the northeastern side has gone down with respect to the southwestern side. The epicenter of the earthquake was determined to be near the dam, and the lake is on the northeastern side of the fault, which is the downthrow side.

CONCLUDING REMARKS

In the present investigation, certain criteria are formulated that are common to the reservoir-associated seismicities and that distinguish these earthquakes from the other normal earthquakes of the concerned regions. Specifically, the high *b* values, the high ratio of the magnitude of the largest aftershock to the main shock, and the typical foreshock-aftershock pattern are extremely useful in understanding this complex phenomenon. *Gupta et al.* [1972*b*] suggest that reservoir impoundings increase the heterogeneity of the media and that this increase consequently decreases the competence of the rocks and results in the release of the accumulated strain. This explanation is supported by the high *b* values and seems feasible when we consider the geology of the regions studied. *Gupta et al.* [1971] have studied the source dynamics of the Koyna earthquake of December 10, 1967, by interpreting the correlograms of seismic arrays and other observatory data and have found this earthquake to be a multiple seismic event. It is hoped that the detailed source studies for other reservoir-associated earthquakes along with more detailed geologic and laboratory investigations will make it possible to understand the puzzling phenomenon.

REFERENCES

Adams, R. D., Seismic effects at Mangla Dam, *Ser. 975/BMS*, pp. 1–15, U.N. Educ., Sci. and Cult. Organ., Paris, 1969.

Archer, C. B., *A Catalogue of Earthquakes in the Lake Kariba Area, 1959–1968*, Goetz Observatory, Bulawayo, Rhodesia, 1969.

Berg, E., Relation between earthquake foreshocks stress and main shocks, *Nature, 219*(5159), 1141–1143, 1968.

Caloi, P., L'evento del Vajont nei suoi aspetti geodinamici, *Ann. Geofis.*, *19*(1), 1–74, 1966.

Carder, D. S., Seismic investigations in the Boulder Dam area, 1940–1944, and the influence of reservoir loading on local earthquake activity, *Bull. Seismol. Soc. Amer.*, *35*, 175–192, 1945.

Comninakis, P., J. Drakopoulos, G. Moumoulidis, B. Papazachos, Foreshock and aftershock sequences of the Kremasta earthquake and their relation to the waterloading of the Kremasta artificial lake, *Ann. Geofis.*, *21*(1), 39–71, 1968.

Evans, M. D., Man-made earthquakes in Denver, *Geotimes*, *10*, 11–17, 1966.

Fontséré, E., Los temblores de tierra catalanes de los anos 1959 a 1962, report, 9 pp., Real Acad. Ciencias Artes Barcelona, Fabra Observ., Barcelona, 1963.

Galanopoulos, A. G., The influence of the fluctuation of Marathon Lake elevation on local earthquake activity in the Attica basin area (in Greek), *Ann. Geol. Pays Hellen.*, *18*, 281-306, 1967.

Gourinard, Y., La géologie et les problèmes de l'eau en Algéria, 1, Le barrage de l'Oued Fodda, *Congr. Geol. Int. C. R. 19th*, 155-181, 1952.

Gorshkov, G. P., The seismicity of Africa, in *Investigations of the Resources of the African Continent* (in French), vol. 3, pp. 108-121, United Nations Educational, Scientific and Cultural Organization, Paris, 1963.

Gough, D. I., and W. I. Gough, Stress and deflection in the lithosphere near Lake Kariba, 1, *Geophys. J. Roy. Astron. Soc.*, *21*, 65-78, 1970*a*.

Gough, D. I., and W. I. Gough, Load-induced earthquakes at Lake Kariba, 2, *Geophys. J. Roy. Astron. Soc.*, *21*, 79-101, 1970*b*.

Guha, S. K., P. D. Gosavi, M. M. Varma, S. P. Agarwal, J. G. Padale, and S. C. Marwadi, Recent seismic disturbances in the Shivajisagar Lake area of the Koyna hydroelectric project, Maharashtra, India, report, 24 pp., Cent. Water and Power Res. Sta., Poona, India, 1968.

Gupta, H. K., H. Narain, B. K. Rastogi, and I. Mohan, A study of the Koyna earthquake of December 10, 1967, *Bull. Seismol. Soc. Amer.*, *59*, 1149-1162, 1969.

Gupta, H. K., H. Narain, and I. Mohan, The Godavari earthquake sequence of April 13, 1969, *Bull. Seismol. Soc. Amer.*, *60*, 601-615, 1970.

Gupta, H. K., B. K. Rastogi, and H. Narain, The Koyna earthquake of December 10, 1967: A multiple seismic event, *Bull. Seismol. Soc. Amer.*, *61*, 167-176, 1971.

Gupta, H. K., B. K. Rastogi, and H. Narain, Common features of reservoir-associated seismic activities, *Bull. Seismol. Soc. Amer.*, *62*, 481-492, 1972*a*.

Gupta, H. K., B. K. Rastogi, and H. Narain, Some discriminatory characteristics of earthquakes near the Kariba, Kremasta, and Koyna artificial lakes, *Bull. Seismol. Soc. Amer.*, *62*, 493-507, 1972*b*.

Healey, J. H., W. W. Rubey, D. T. Griggs, and C. B. Raleigh, The Denver earthquakes, *Science*, *161*(3848), 1301-1309, 1968.

Major, M. W., and R. B. Simon, A seismic study of the Denver (Derby) earthquakes, *Quart. Colo. Sch. Mines*, *63*(1), 9-55, 1968.

McEvilly, T. V., and K. B. Casaday, The earthquake sequence of September 1965 near Antioch, California, *Bull. Seismol. Soc. Amer.*, *57*, 113-124, 1967.

McEvilly, T. V., W. H. Bakun, and K. B. Casaday, The Parkfield, California, earthquakes of 1966, *Bull. Seismol. Soc. Amer.*, *57*, 1221-1224, 1967.

McGinnis, L. D., Earthquakes and crustal movements as related to water load in the Mississippi Valley region, *Ill. State Water Surv. Circ.*, *344*, 1963.

Mogi, K., Some discussions on aftershocks, foreshocks and earthquake swarms—The fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena (third paper), *Bull. Earthquake Res. Inst.*, *41*, 615-658, 1963.

Narain, H., and H. K. Gupta, Observations on the Koyna earthquake, *J. Indian Geophys. Union*, *5*(1), 30-34, 1968*a*.

Narain, H., and H. K. Gupta, Koyna earthquake, *Nature*, *217*(5134), 1138-1139, 1968*b*.

Papazachos, B., N. Delibasis, N. Liapis, G. Moumoulidis, G. Purcasu, Aftershock sequence of some large earthquakes in the region of Greece, *Ann. Geofis.*, *20*(1), 1-93, 1967.

Rothé, J. P., Fill a lake, Start an earthquake, *New Sci.*, *39*(605), 75-78, 1968.

Rothé, J. P., Earthquakes and reservoir loadings, in *Proceedings of the Fourth World Conference on Earthquake Engineering*, vol. 1, pp. 28-38*c*, Associatiǒn Chilena de Sismologia e Ingenieria Antisimica, Santiago, 1969.

Rothé, J. P., Man-made earthquakes (in French), *Tectonophysics*, *9*(2/3), 215-238, 1970.

Süsstrunk, A., Seismic shocks in the Verzasca Valley during the filling of the Vogorno Reservoir (in German), *Verh. Schweiz. Naturforsch. Ges.*, *148*, 89-92, 1968.

Seismic Activity and Reservoir Filling at Oroville and San Luis Dams, California

RENNER B. HOFMANN

Department of Water Resources, Sacramento, California 95814

TECTONIC SETTING

The California water project is so large (it is deployed over 1000 km) that nearly the entire state must be considered. Its aqueducts cross active faults 17 times and are closely parallel to the San Andreas fault system over most of their length. Major dams are in areas of both high- and low-current seismicity. Examples are Cedar Springs and Oroville dams, respectively. Locations of project dams also range from areas near where the San Andreas fault slips freely to areas that apparently have been locked and have been accumulating strain for >100 years [*Whitten,* 1960; *Meade,* 1963]. Examples are the San Luis Dam and southern California dams (Castaic, Pyramid, Cedar Springs, and Perris), respectively. Abutments or foundations range from igneous or metamorphic rocks to only slightly consolidated sedimentary rocks. Examples are the Oroville and Castaic dams, respectively.

Average fault movement on the San Andreas system from 1959 to 1968, as measured by the geodimeter program of the Department of Water Resources (DWR) of the state of California, varies from 4-5 cm/yr of slip south of the San Francisco Bay area and Hollister to no slip and evidence of crustal compression in the Tehachapi Mountains [*Hofmann,* 1970].

Federal surveys by the U.S. Coast and Geodetic Survey (USCGS), which is now the National Oceanic and Atmospheric Administration (NOAA), indicate that the San Jacinto branch of the fault system moves as much as 7 cm/yr in extreme southern California. These surveys also indicate that the San Andreas fault has been locked in the Tehachapi Mountains since 1857 and north of San Francisco since 1906. A crude relationship between the azimuth of geodimeter lines in locked areas of the fault and the amount that these lines shorten each year has been found [*Hofmann,* 1968, 1970]. This relationship is evidence of compression of the earth's crust where several major dams are being constructed. The high levels of strain stored in the locked portions of the fault are similar to the amounts of strain released in major earthquakes such as the San Francisco earthquake in 1906.

SEISMIC MONITORING SYSTEM

Project dams are currently monitored in Sacramento via telephone telemetry. There are three-component stations at Oroville, San Luis, and Perris dams. A single three-component station is shared by Pyramid and Castaic dams. One vertical seismometer monitors Cedar Springs Dam. In addition, there are several intermittently operating portable magnetic tape-recording units. Instrumentation is similar to that of the Australian Snowy Mountain project. The basic recording medium is 16-mm film. In addition, seismic data are exchanged with the USCGS, the Earthquake Mechanisms Laboratory in San Francisco, the University of California at Berkeley, the California Institute of Technology, and the University of Nevada at Reno. Thus a 14-station network is provided for rapid alerting of large shocks.

Close monitoring of individual reservoirs is, however, dependent on the single stations at each dam. An exception is Oroville, which has two ancillary vertical seismometers in addition to the three-component long- and short-period systems at the main station. Most project dams are also instrumented with remote strong-motion accelerometers that record at the dam. These employ Systron and Donner force balance acceleration sensors with an extremely wide frequency and dynamic range. These units could simultaneously provide additional sensitive monitoring as well as strong-motion monitoring with suitable amplification. This capability is, of course, contingent on a reasonable noise level in the dam. Experiments at Oroville have verified this capability, although it is not ordinarily used at present.

SEISMIC ACTIVITY AT SAN LUIS RESERVOIR

Earthquakes prior to reservoir filling. A three-component short-period seismograph has been operated at San Luis Reservoir by the USCGS under contract to the U.S. Bureau of Reclamation since 1965. Most shocks occurred on the nearby San Andreas system, and a few shocks occurred on the Ortigalita fault alignment that crosses the reservoir. Only four shocks were recorded from 1965 to 1967 within 20 km of the station.

Since October 1965, under a DWR contract, the seismographic station of the University of California at Berkeley has reported epicenters within 40 km of the California aqueduct in this area. Recordings of the Berkeley network west of the reservoir and those of the DWR-sponsored Jamestown station in the Sierras, 80 miles east of the reservoir, provided accuracies that were better than those previously available. Jamestown data are presently telemetered to both Berkeley and Sacramento. Because large segments of the active Calaveras and San Andreas fault zones lie between 20 and 40 km from the station, small changes in seismic activity associated with the reservoir must be limited to events within 20 km.

Earthquakes during and after reservoir filling. Reservoir level and seismic activity in the distance range of 10–20 km from the San Luis station are well correlated. This distance range includes the part of San Luis Reservoir underlain by the Ortigalita fault, a vertical fault with at least 608 meters of displacement. Several of the shocks in the January–March 1969 sequence were well recorded on all three components of the San Luis station. The azimuths and *P-S* intervals placed these events on or near the Ortigalita fault under the reservoir. All 43 events in this series were of magnitudes of <2.5. No further buildup in activity has been noted since the sequence that accompanied the initial filling and the first cycling of the reservoir.

Activity along this trend was pointed out by Dr. Bruce Bolt at the International Union of Geodesy and Geophysics meeting in 1967. Earthquakes have often occurred on or near this alignment along the eastern margin of the California Coast Ranges, essentially under the aqueduct. A particularly striking example occurred in April 1967 when six epicenters were located along a 230-km reach of the aqueduct. An extension of this alignment northward toward Vallejo would include the large 1894 shock that caused some damage in Sacramento.

SEISMIC ACTIVITY AT SOUTHERN CALIFORNIA DAMSITES

Several major project dams are being built in southern California: Castaic, Cedar Springs, Pyramid, and Perris. All are within 30 miles of the San Andreas or San Jacinto faults. *Mickey* [1970] of the USCGS reported on activity at the Cedar Springs damsite, where a seismograph had been operated for DWR for several years. He indicated that >300 earthquakes occurred within 40 km of the site between March 1965 and June 1967. This trend has since continued. Several small shocks occurred at zero distance from a portable seismograph operated at the site of the dam's axis before construction began.

Unfortunately, the determination of accurate locations of small shocks in the vicinity of these dams is not possible because there is less than one permanent station per damsite. Portable magnetic tape-recording seismographs were also deployed, but difficulties in maintaining good timing over a period of months prevented attainment of the desired accuracy. Two small radio telemetry units are now being fabricated to allow recording in Sacramento.

SEISMIC ACTIVITY AT OROVILLE RESERVOIR

Earthquakes prior to reservoir filling. Oroville seismographic data were analyzed for DWR by contract with the University of California from March 1964 to August 1968. Table 1 lists earthquakes recorded within 50 km of the Oroville station. The earthquakes, with one exception, are all farther than 10 km from Oroville Dam. About 400 explosions at known quarries or construction sites were omitted. The blasts are usually identifiable not only because of their location but also because of the higher frequencies on the seismogram than those usually characteristic of small earthquakes in this area.

Most of the shocks were recorded by no more than two stations, Oroville and the Mineral station of the University of California at Berkeley. Many shocks were recorded at the Oroville

TABLE 1. Earthquake Activity near Oroville Dam

Year	Month	Day	Distance, km	Magnitude	Remarks
1968	February	10	31	...	small, local
1966	May	28	40	1.4	north of Chico
	January	7	32	2.75	7 km southwest of Chico
1965	May	5	37	3	10 km south of Bucks Lane
	April	22	26	1.5	west-southwest of Oroville
		22	26	1.3	west-southwest of Oroville
		24	26	1.4	west-southwest of Oroville
	March	17	26	1.5	5 km northwest of Gridley
	January	29	47	1.3	southwest of Oroville
		30	37	1.1	north of Oroville
1964	November	12	35	2.6	near Forest Ranch
	September	18	48	2.5	southeast of Willows
	July	17	51	1.0	northwesterly
		25	38	2.2	25 km southeast of Mineral
	June	3	35	2.1	southwesterly
		6	38	1.3	westerly
	April	13	3.5	1.5	northwesterly
		23	33	0.6	northeasterly
	March	7	24	0.3	northeasterly
		20	35	0.1	southerly

Analysis of the earthquake activity was made by the University of California at Berkeley.

main station only. Consequently, locations are primarily based on azimuths derived from horizontal amplitudes and *P-S* distances.

The nearest event was about 3.5 km northwest of the dam; most other events were within 24 km. Seventy percent of the events originated in the northwest and southwest quadrants from the main station on the northwest dam abutment. The Chico sheet of the geologic map of California shows no faulting southwest of the station. However, the alignment of shocks in this quadrant, parallel to faults mapped farther east, suggests a possible shear zone beneath the valley sediments.

Earthquakes during and after reservoir filling. Little seismic activity was observed near Oroville prior to September 1968. The reservoir was nearly filled in March 1968. In July 1968, DWR began telemetering seismic data from Oroville. An apparent increase in seismic activity at distances of up to 40 km occurred in August 1968. This increase may have been because of the tenfold increase in magnification made possible by the telemetry system and 16-mm film instead of the drum recording. However, an increase in the number of shocks within 10 km of the dam did not begin until September. Most magnitudes for events from July through December 1968 were <0.5. The number of events reached a peak in October, about 6 months after the reservoir level stabilized near 240 meters. Few of these small shocks would have been evident on paper seismograms if this type of recording had been continued. From January to May 1969, spillway noise obscured any shocks of this size that may have occurred. After spilling ceased, seismic activity at Oroville remained at a low level. Magnitudes of the few events recorded were small.

Most of the small events were visible only on the records of the Oroville main station even though the ancillary stations were moved in attempts to improve gain and accessibility. Those events for which epicenters were determined occurred southeast of the dam apparently along branching faults of the relatively inactive Foothill fault zone.

Earthquakes or blasts? As during the period prior to reservoir filling, several hundred blasts were obviously recorded and eliminated from reporting. No blasts were clearly from the area near the dam, and inquiries directed to personnel at the dam did not reveal knowledge of blasting in the area. However, a close examination of the times of the 83 events recorded from September through December within 20 km of the dam indicated that nearly all the events occurred during daylight hours. Further investigation with state, federal, and private contractors revealed that a sewer project was under way in this area during the 6-month period from July to December. Records of blasting were imperfectly kept. Field notes sometimes indicated only that blasting had occurred on a certain day. Eight of these days corresponded to days when events were recorded. For three of these days the times of blasting in the field notes corresponded with the recorded times of seismic events, which, incidentally, had been identified on the seismograms as earthquakes because their appearance differed from typical blasts. Consequently, it is likely that this apparent increase in seismicity has been fortuitously caused by sewer line excavation.

CONCLUSIONS

There are lessons to be learned from this experience. Even with a seismic trinet in operation at a reservoir, accurate location of very small shocks may not be possible unless seismometers can be moved easily to surround the area where activity is taking place. This capability seems doubly important because records of blasting are not usually kept in detail. In areas of growing cultural activity like most of California, not only must high epicentral accuracies be attainable, but they must be available on a day-to-day basis if cultural activity is to be positively identified. Also, in areas where active faulting regularly produces many earthquakes, like much of California, the traditional method of counting the number of shocks occurring within an 80-km radius of a dam is obviously inadequate. All shocks must be located to separate those regularly occurring on known active faults from those attributable to a reservoir.

There is the question of whether monitoring very small events should be considered important. The tragic loss of life at Koyna and Vaiont suggests that, indeed, all activity should be carefully monitored and assessed; however, larger, more obvious seismic events than those seen at San Luis and Oroville dams were observed to precede the catastrophies at Koyna and Vaiont but to no avail. Perhaps the more basic problem is to establish guidelines concerning what action should be taken when various seismic events or ground movements are observed and to establish what minimum instrumentation and observations should be mandatory for a given sized dam.

Acknowledgments. Paul Morrison of the California Department of Water Resources was responsible for developing much of the data used in this paper. Dan Cooke and Larry Reifschneider of Cooke Engineering, Oroville, provided access to field notes of the sewer interceptor construction project. A debt is also due the department's Consulting Board for Earthquake Analysis, now composed of Drs. Clarence Allen (Chairman), Bruce Bolt, H. B. Seed, James Sherrard, John Blume, and George Housner. Particular thanks is due Dr. Hugo Benioff (deceased), who was responsible for recommending these efforts first as a consultant and later as the first chairman of the consulting board.

REFERENCES

Hofmann, R. B., Geodimeter fault movement investigations in California, *Bull. 116-6*, Calif. Dep. of Water Resour., Sacramento, May 1968.

Hofmann, R. B., Earthquake predictions from fault movement and strain precoursers in California, in *Earthquake Displacement Fields of the Earth*, edited by L. Mansinha, D. E. Smylie, and A. E. Beck, D. Reidel, Dordrecht, Netherlands, 1970.

Meade, B. K., Horizontal crustal movements in the United States, paper presented at 2nd Symposium on Recent Crustal Movements, Int. Union of Geod. and Geophys., Berkeley, Calif., 1963.

Mickey, W. V., Earthquakes and dams, paper presented at Man-Made Earthquake Symposium, Annual Meeting, Geol. Soc. of Amer., Milwaukee, Wis., Nov. 1970.

Whitten, C. A., Horizontal movement in the earth's crust, *J. Geophys. Res.*, *65*(9), 2839–2844, 1960.

Reservoir Seismic Effects

WENDELL V. MICKEY[1]

National Ocean Survey, U.S. Department of Commerce
Rockville, Maryland 20852

The occurrence of earthquakes in the vicinity of large dams and reservoirs has been studied by many investigators in several regions of the world [*Barnett,* 1968; *Gough and Gough,* 1970*a, b; Rothé,* 1968, 1969, 1970; *McGinnis,* 1963]. Historically, probably the first reported concern for the effects of reservoir loading on the earth's crust was at Lake Mead [*Mead and Carder,* 1941].

The National Ocean Survey (formerly the U.S. Coast and Geodetic Survey) has been active in monitoring the seismicity around large dams and reservoirs in the United States since establishing a station near Lake Mead in 1938. Many instances have been reported in the literature relating seismic activity to man-made hydrologic structures. Five sites in four states were selected for a detailed study of the seismic characteristics near reservoirs: Glen Canyon, Arizona; Flaming Gorge, Utah; Hoover Dam and Lake Mead, Nevada; San Luis, California; and Cedar Springs, California.

FLAMING GORGE AND GLEN CANYON

These two dams and reservoirs are grouped because the observing area overlaps and both are in the Colorado River storage project. Flaming Gorge Dam, Utah (Green River), is 151 meters high with a reservoir capacity of 4674×10^6 m^3. It was first loaded in November 1962. Seismic measurements started in June 1960.

Glen Canyon Dam, Arizona (Colorado River), is 216 meters high with a reservoir capacity of $33{,}304.2 \times 10^6$ m^3. It was first loaded in May 1963. On-site seismic measurements started in June 1960.

The station locations and the observation area are shown in Figure 1 with the earthquake epicenters for 1968. The major seismic activity is to the west of the two reservoirs along the more prominent tectonic features.

Figure 2 shows the cumulative number of earthquakes per month for Flaming Gorge and Glen Canyon from 1960 through 1968 at different distances from the station. If the reservoir was effecting the local seismicity, it should be apparent in the range of 0–40 km. There was a decrease in seismic activity in this distance zone following reservoir loading. Although Glen Canyon is 65 meters higher and the reservoir is 7 times larger, it has much less seismic activity than Flaming Gorge. The seismicity characteristics for Glen Canyon were affected by the earthquakes series during 1966 in southeast Nevada.

Extreme probability statistics are shown in Figure 3 for Flaming Gorge for 36 months. The equivalent slope is 0.89, very near that for southern California. Although the area is very much less active than southern California, the rate of occurrence of small to large earthquakes is similar.

Figure 4 is a contoured map using the square root of the source seismic energy, which is proportional to strain release. The shaded areas are progressively more seismically active for the period of the present observations. The most active areas correspond to the tectonic zones trending north-northeast with a transverse trend from near Grand Junction, Colorado, to Price, Utah. The areas with the least seismic activity are in the vicinity of Glen Canyon (GCA) and Flaming Gorge (FGU). From September 1960 through December 1968, there were 3182 earthquakes recorded at Flaming Gorge, and there were 1506 recorded at Glen Canyon within the 350-km radius of each station. There were many explosions, rock bursts, and coal bumps recorded at each station, and every effort was made to exclude these data. The data were substantiated by nearby seismograph stations at Logan, Salt Lake

---

[1] Now at National Oceanic and Atmospheric Administration, Boulder, Colorado 80302.

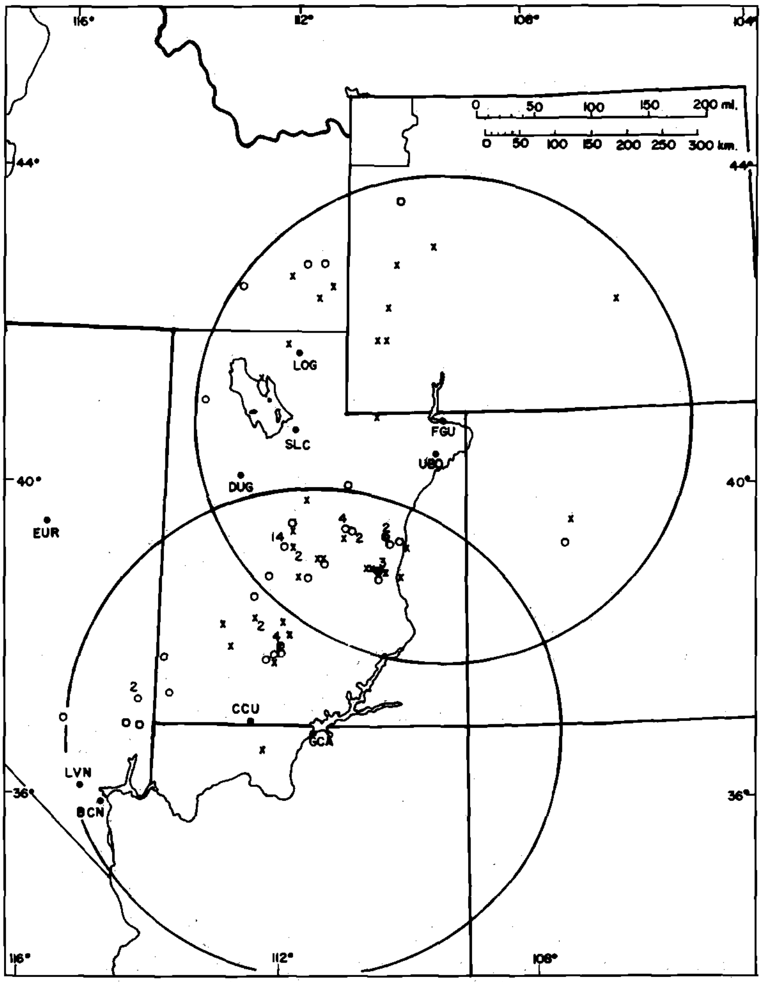


Fig. 1. Seismograph station map showing Flaming Gorge, Utah (FGU), and Glen Canyon, Arizona (GCA), with the area of observations within the 350-km-radius circles. Also shown are stations at Logan (LOG), Salt Lake City (SLC), Dugway (DUG), Cedar City (CCU), and Uinta basin (UBD) in Utah and stations at Eureka (EUR), Las Vegas (LVN), and Boulder City (BCN) in Nevada. Epicenters for 1968 earthquakes within the 350-km radius of Flaming Gorge and Glen Canyon are shown. The open circles indicate the epicenters according to computer solution. The crosses indicate the epicenters according to graphic solution. The closed circles indicate the seismograph stations.

City, Dugway, and Cedar City in Utah and at Eureka, Boulder City, and Las Vegas in Nevada.

SAN LUIS DAM

A histogram of the seismicity within 80 km of San Luis Dam, California, from November 1965 through July 1970 is shown in Figure 5. This dam is 93 meters high and was first filled in June 1965.

The number of earthquakes per month within 80 km of the station varied from 16 to 89, and the average was 52. The size of earthquakes M_L ranged from 0.2 to 5.0. The average monthly minimum-distance earthquake was 7.2 km from the station. During the 57-month monitoring period, there were 2968 earthquakes occurring within 80 km, and 560 of these occurred at distances of ≤ 25 km. The high seismic activity of this area is influenced by a major fault system 22.5 km to the southwest.

Extreme probability techniques were used to compare nearby seismicity to the overall zone of 0–80 km. Figure 6 shows that the rate of oc-

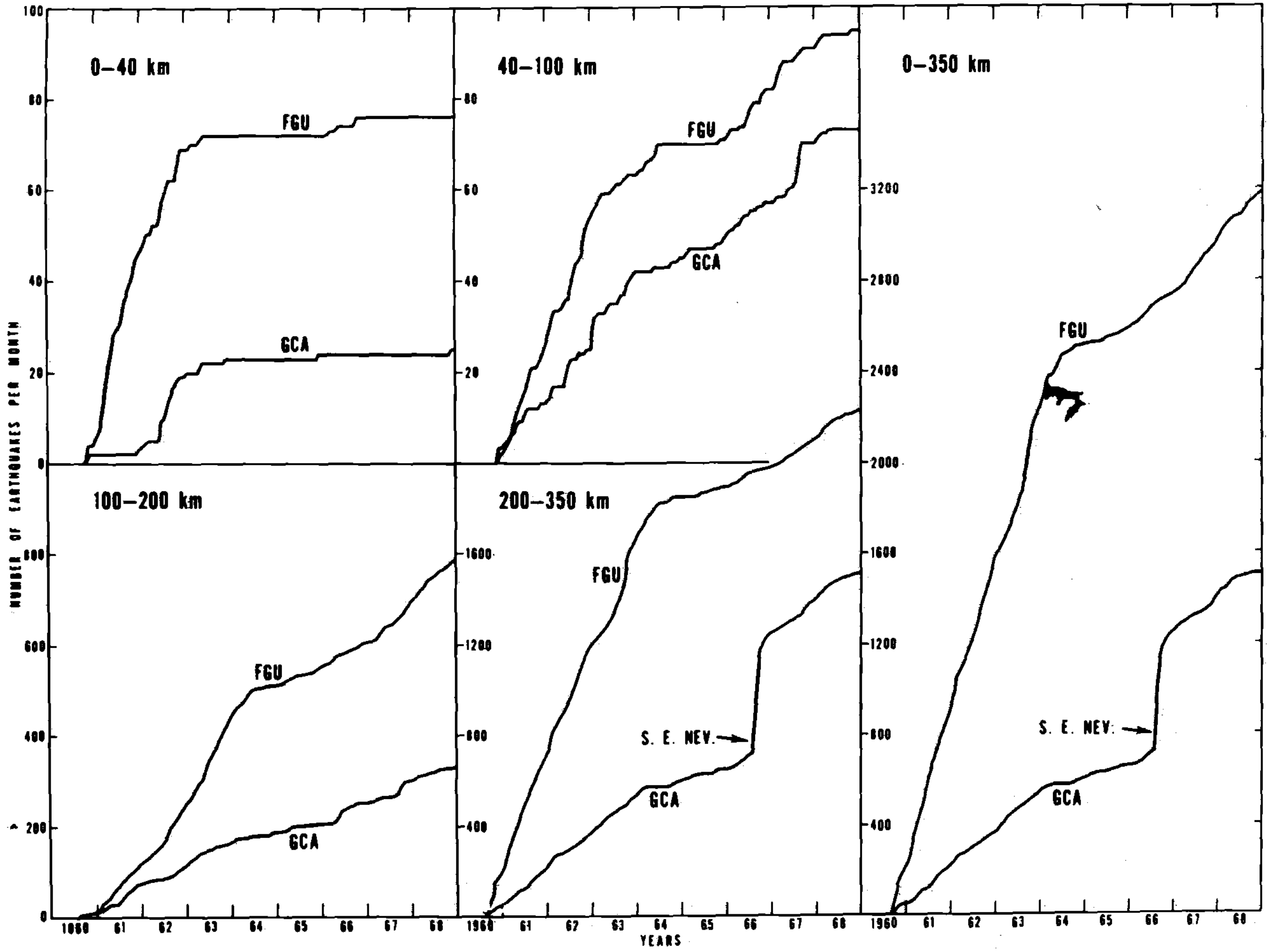


Fig. 2. Cumulative earthquakes per month from 1960 through 1968 at Glen Canyon (GCA) and Flaming Gorge (FGU) at different distance ranges from the station.

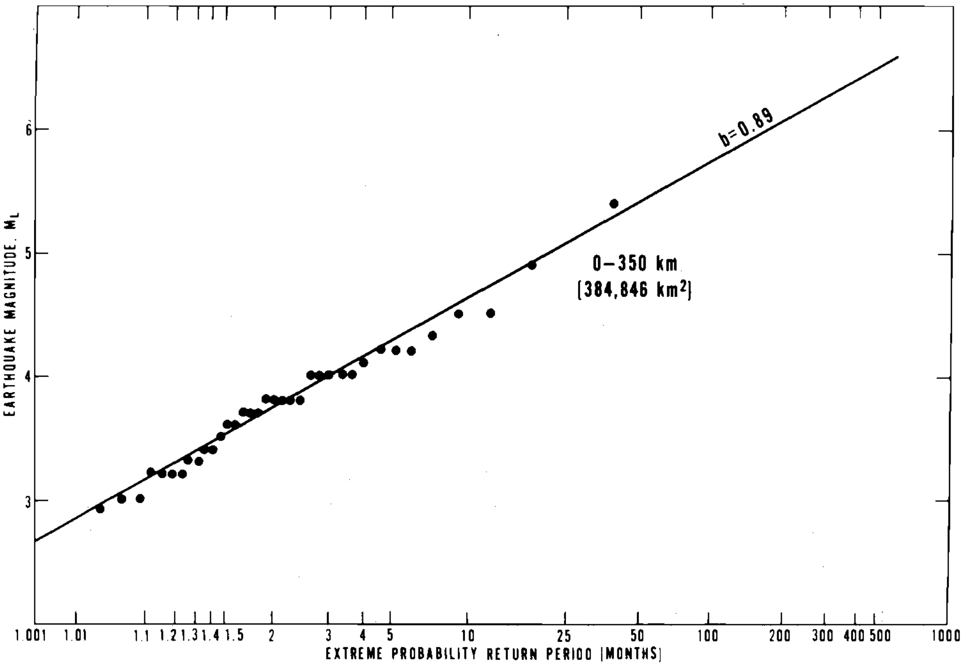


Fig. 3. Extreme probability graph for monthly return period of earthquakes recorded at Flaming Gorge, Utah, for a period of 36 months occurring within 350 km from the station.

currence is similar and that there are identical *b* values of 0.7. When the observing area was reduced by a factor of 10, the probabilities were also reduced a similar amount.

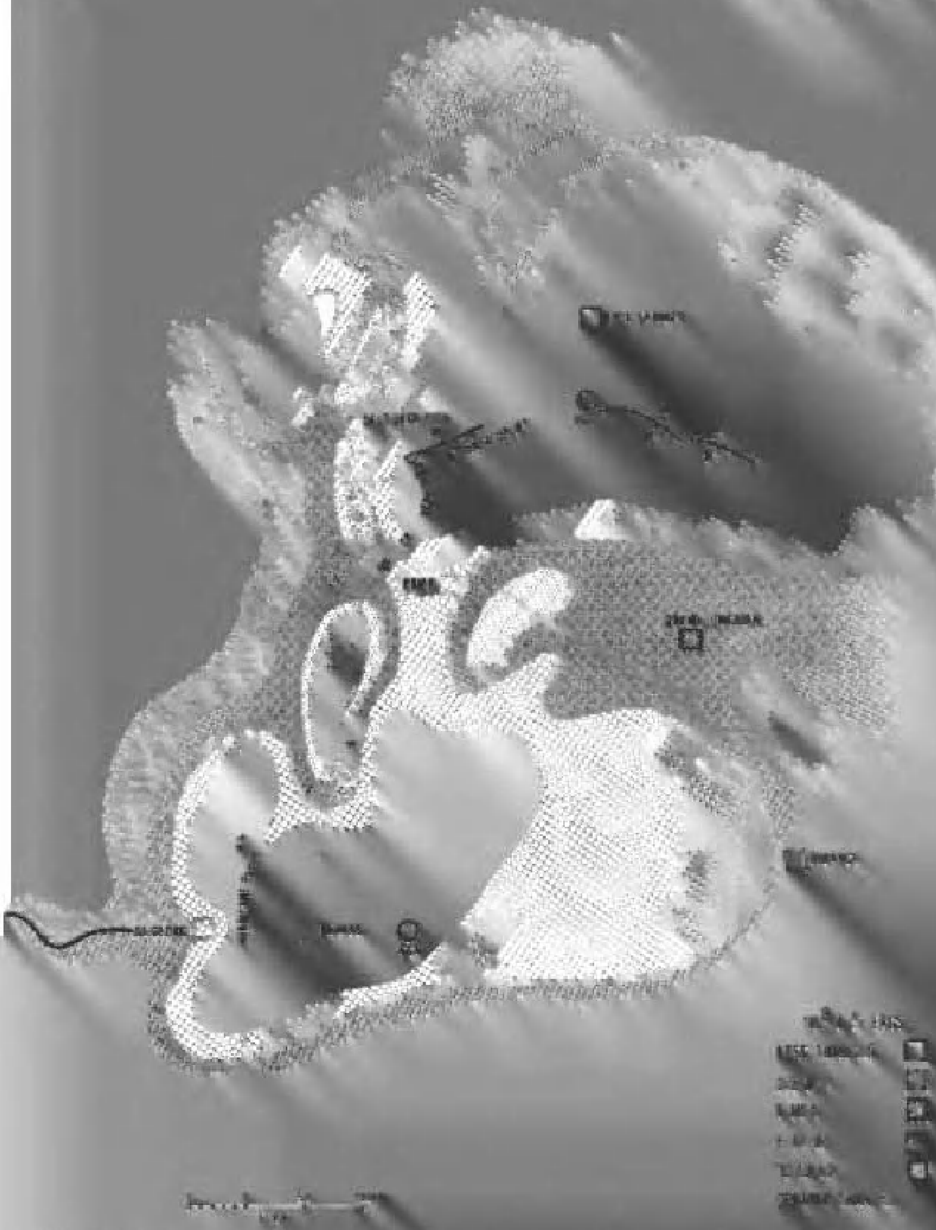
CEDAR SPRINGS DAMSITE, CALIFORNIA

The Cedar Springs project is about 80 km east of Los Angeles on the north edge of the San Bernardino Mountains. The seismograph station at this site started operations in February 1965. Figure 7 shows the occurrence characteristics of this site. There were 682 earthquakes within a 50-km radius of the site during the 28-month monitoring period ranging in size M_L from <1 to 3.7. This site differs from the others discussed because it shows more seismic activity near the site (radius of 25 km and area of 1964 km^2) than in an area 3 times as large (annulus of 25–50 km and area of 5890 km^2). The other major difference is that the reservoir has not been built in this area as yet. This site is near an active area of the San Andreas fault.

HOOVER DAM AND LAKE MEAD, NEVADA

Hoover Dam, 40 km southeast of Las Vagas, Nevada, was completed in 1936. Its height is 221 meters and the reservoir capacity is $38{,}296.2 \times 10^6$ m^3. A seismograph monitoring system of one or more units has been in operation near the dam from 1938 to the present time. There have been several reports written about the seismic characteristics of this area [*Carder and Small,* 1948; *Mead and Carder,* 1941; *Jones,* 1944; *Carder,* 1945; *Carder,* 1968].

Figure 8 shows the seismic activity at Lake Mead from 1939 through 1951. The data were especially prepared to check for periodicity and correlation of seismic activity with reservoir water level. The top curve is the average monthly water level for the period plotted from January through December; the period from January through September is repeated so that more than one cycle is shown. Because of the reservoir recharge characteristics, the water level in Lake Mead is periodic, and the high levels usually occur in July and minimum levels occur in April. The second curve is the number of earthquakes for a 3-month period, plotted at the center month; i.e., the first point is plotted above *M* for March and is 1242, which is the number of earthquakes that occurred during the period of February, March, and April. The third graph is prepared as the second but represents the



[illegible]

[illegible]

[illegible]

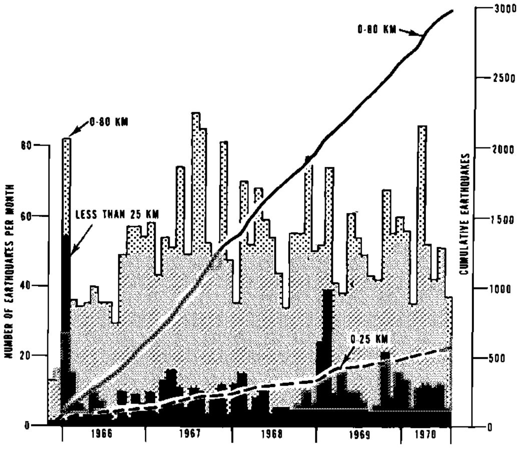


Fig. 5. Number of earthquakes per month at San Luis Dam, California, from November 1965 through July 1970 in two distance ranges.

Dam and Lake Mead, Nevada; (4) Flaming Gorge, Utah; and (5) Glen Canyon, Arizona.

Cedar Springs was the most seismically active, but the dam and reservoir have not been built. The seismic activity near San Luis Dam is along a fault zone that was active historically before the dam was built. Of the five areas considered, the seismicity around Lake Mead seems to be related to the reservoir. *Jones* [1944] reported,

> According to T. C. Mead, of the Bureau of Reclamation, no earthquakes were reported by the few local inhabitants in the fifteen-year period prior to the construction of Boulder Dam.

Since 1936, there have been >10,000 earthquakes recorded, and approximately 10% were felt in the Hoover Dam and Lake Mead area.

RECOMMENDATIONS

Although four of the five examples of reservoir seismicity did not indicate effects of reservoir loading, the scientific literature is replete with references affirming a causal relationship. The best place to build a dam is in a deep narrow gorge with an upstream reservoir of sufficient

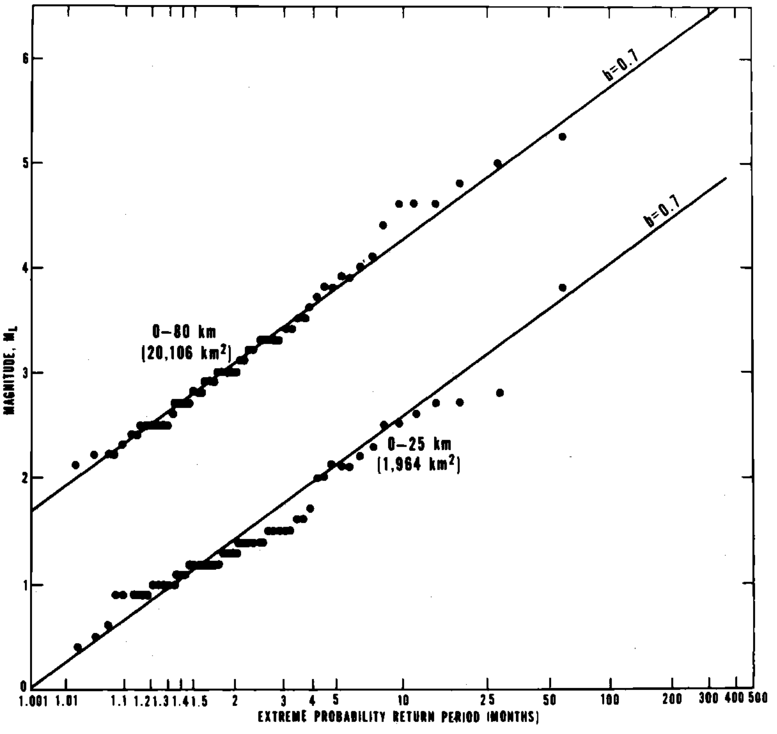


Fig. 6. Extreme probability statistics for the seismicity within 0–80 km and 0–25 km at San Luis Dam from November 1965 through July 1970.

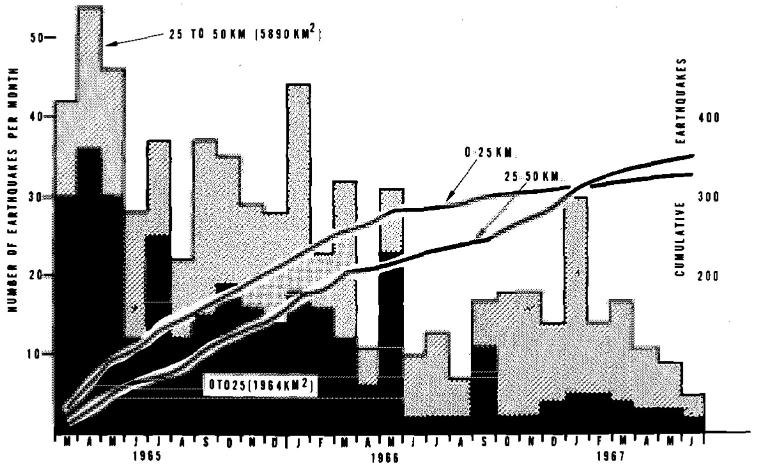


Fig. 7. Earthquake occurrence characteristics in two distance ranges from Cedar Springs, California, and cumulative number of earthquakes from March 1965 through June 1967 (total of 682 earthquakes).

dimensions and inflow potentials to make such a project feasible and economical. These optimum areas are also where past tectonic activity has been present to create the desired deep narrow gorge, which is associated with faulted structures and concomitant earthquakes. Current seismic activity, however small, along the faults within the reservoir indicates a potential for fault movement.

It is recommended that a seismograph station be installed in proposed areas of large man-made lakes, dams, and reservoirs at the time the site is proposed to provide a history of seismicity prior to construction.

If the area is seismically active, additional stations should be deployed to locate the earthquake hypocenters and, if possible, to determine the earthquake mechanisms in addition to frequency of occurrence characteristics and magnitudes. Close coordination should be maintained with the project geologists. If the earthquakes can be considered associated with surface

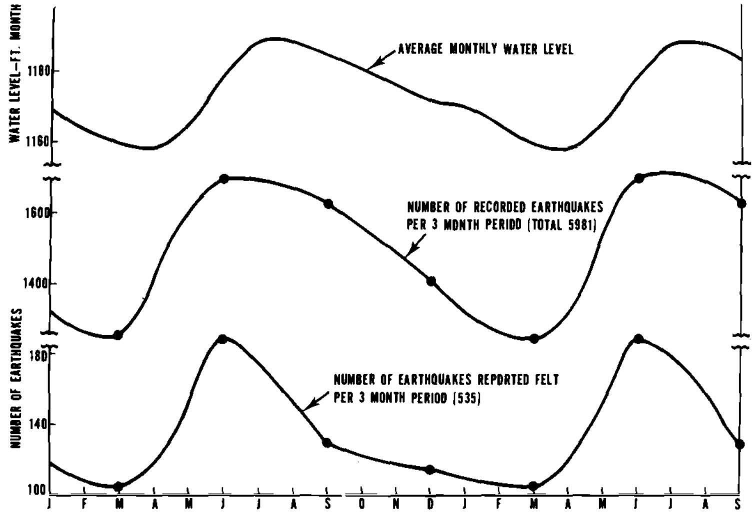


Fig. 8. Periodicity and correlation plots of average monthly water level, number of earthquakes recorded per 3-month period, and number of felt earthquakes per 3-month period for Lake Mead from 1939 through 1951.

faulting, there should be monitoring networks of stations across the fault to determine if there is movement.

The demand for water reservoirs will increase, and the construction rate of man-made lakes will increase. *Mermel* [1970] reported that there are 125 dams a year being built in the United States with heights of >15 meters. Worldwide, >300 dams a year are being constructed.

REFERENCES

Barnett, M. (Ed.), Dams that shake the earth, *Ann. N. Y. Acad. Sci., 8*(11), 1968.

Carder, D. S., Seismic investigations in the Boulder Dam area, 1940–1944, and the influence of reservoir loading on earthquake activity, *Bull. Seismol. Soc. Amer., 35,* 175–192, 1945.

Carder, D. S., Reservoir and local earthquakes, in *Proceedings of the 6th Annual Engineering Geology and Soils Engineering Symposium, Boise, Idaho, 1968,* Department of Highways, Boise, Idaho, 1968.

Carder, D. S., and J. B. Small, Level divergences, seismic activity, and reservoir loading in the Lake Mead area, Nevada and Arizona, *Eos Trans. AGU, 29*(6), 767–771, 1948.

Gough, D. I., and W. I. Gough, Stress and deflection in the lithosphere near Lake Kariba, 1, *Geophys. J. Roy. Astron. Soc., 21,* 65–78, 1970*a*.

Gough, D. I., and W. I. Gough, Load-induced earthquakes at Lake Kariba, 2, *Geophys. J. Roy. Astron. Soc., 21,* 79–101, 1970*b*.

Jones, A. E., Earthquake magnitudes, efficiency of stations, and perceptibility of local earthquakes in the Lake Mead area, *Bull. Seismol. Soc. Amer., 34,* 161–173, 1944.

McGinnis, L. D., Earthquakes and crustal movements as related to water load in the Mississippi Valley region, *Ill. State Water Surv. Circ., 344,* 1963.

Mead, T. C., and D. S. Carder, Seismic investigations in the Boulder Dam area in 1940, *Bull. Seismol. Soc. Amer., 31,* 321–324, 1941.

Mermel, T. W., World's highest and largest dams, *Proc. Amer. Soc. Civ. Eng., 96*(7), 73–76, 1970.

Rothé, J. P., Fill a lake, Start an earthquake, *New Sci., 39*(605), 75–78, 1968.

Rothé, J. P. Earthquakes and reservoir loadings, in *Proceedings of the Fourth World Conference on Earthquake Engineering,* vol. 1, pp. 28–38*c*, Asociatión Chilena de Sismología e Ingeniería Antisimica, Santiago, 1969.

Rothé, J. P., Man-made earthquakes (in French), *Tectonophysics, 9,* 215–238, 1970.

Summary: Physical Limnology of Man-Made Lakes

B. R. ALLANSON

Department of Zoology and Entomology, Institute for Freshwater Studies
Rhodes University, Grahamstown, South Africa

It has been my privilege to review and summarize the papers that are presented in whole or in part in this section on the physical limnology of reservoirs. The contributed papers have been arranged in three groups: (1) limnological surveys, (2) hydrology and ecosystem models, and (3) physical and chemical problems of eutrophication. The following discussion is an attempt to synthesize the ideas that emerge from these papers and other pertinent data. In my concluding remarks, attention is drawn to four central problems that merit serious consideration.

DISCUSSION

The man-made lakes or reservoirs included in this section embrace wide differences in size and climatic conditions. In addition, we recognize two quite distinct types of investigation: those investigations placed against the background of considerable limnological experience available in Europe and North America and those in regions where a limnological background is only now developing, e.g., Africa, Australia, and India. In these limnologically developing countries it is perfectly natural that the first steps should be surveys of different durations and intensities, whereas in Europe and North America we may expect to find a greater involvement in more sophisticated ecosystem analysis leading to an increased understanding of the interaction between components of a limnological system.

Africa south of the Sahara has been served limnologically for a great many years. I refer of course in particular to studies of the Great Rift Valley lakes, but these have had improvement in their respective fisheries as their raison d'être, so that by and large biologists have been responsible for the physical limnology that was done. We know a good deal from their work, but the smaller water masses that occur in the more arid south hold little if any attraction for limnological workers. We can trace with reasonable certainty the beginnings of serious limnological study in this region to Hutchinson's work [*Hutchinson et al.*, 1932], which included both natural and artificial lentic systems. A gap of some 25 years exists between his work and that of *Allanson and Gieskes* [1961], which focused attention on the need to build on Hutchinson's work in southern Africa. In the same year, *Harding* [1961] published the first results on Lake Kariba, at that time the major man-made lake in the world. Lake McIlwaine, a reservoir to the northeast of Salisbury, was studied by *Munro* [1966] and by A. C. Falconer et al. (unpublished report, 1970). The only other published study was that of *Imevbore* [1967] on Eleiyele Reservoir in Nigeria. Conventional physical and chemical limnological procedures and techniques were used in all surveys of existing conditions.

Nevertheless many of these studies provide only anecdotal records sufficient to satisfy the immediate needs of water supply engineers. Although such studies form part of the limnological spectrum of a country, they should not be construed as providing the final and complete answer, since it is painfully obvious that they do not. Reservoirs have various functions and produce various effects, both good and bad, and, since they are man-made, they become integral units in the social development or modifications of the areas in which they are built. They represent one of the grossest forms of hydrologic interference, so that their effects on the ecosystem must be effectively analyzed and interpreted. Survey attitudes alone are not enough data on which to base this analysis and interpretation. Laying aside the socioeconomic problems that are not included in the mandate of this view of physical limnology, where should we begin to intensify our limnological studies? I submit that we should begin at the level of those abiotic factors that provide the basis of all ecosystem analysis.

Straškraba [this volume] has stressed the need to understand the multifactorial nature of reservoir ecosystems and stated that until multifactorial models are designed we cannot hope for 'adequate quantitative testing.' The basis of Straškraba's viewpoint is that the physical limnology of all reservoirs is influenced to a lesser or a greater extent by both retention time and density currents and that these two factors can in general be said to differentiate the limnology of lakes and reservoirs. Some useful data on average replacement times of reservoirs and lakes in Africa have been provided: Lake McIlwaine (a reservoir), 0.82 year (A. C. Falconer et al., unpublished report, 1970); Lake Kariba (a reservoir), 3.8 years [*Coche,* 1968]; Lake Victoria, central Africa, 120 years (A. C. Falconer et al., unpublished report, 1970); and Lake Tanganyika, 1500 years (A. C. Falconer et al., unpublished report, 1970).

The stress that has been laid on the temperature subsystem and internal mixing by Straškraba and by *Arai* [this volume] emphasizes that temperature models are of major importance in the development of limnological analogs of reservoirs. Arai's figure for a proposed model effectively covers the variables. A careful examination of this model shows how little is really known of the magnitude of the variables and their interactions in the reservoirs studied so far. Such physical models and their computer analogs are often poorly understood by nonmathematicians. In addition, much of the temperature study in reservoirs is based on methods that give immediately observable results but that do not necessarily give accurate causal pictures, namely, the measurement of temperature profiles and the construction of seasonal or daily isothermal diagrams. Nevertheless many important conclusions have been drawn from these studies particularly in lakes and reservoirs, but their role in the model described by Straškraba is poorly defined.

In general, we feel that to know the variations in temperature, dissolved oxygen, and *p*H is to understand a good deal of the limnology of the reservoir. Although *Straškraba* [this volume] has indicated that the application of lake techniques may produce results of zero value, I believe it is significant that in reservoirs where retention times are very much greater than 38 days the application of such techniques does produce meaningful data from which the limnological behavior may be adduced. Nevertheless Straškraba has given us a timely warning. We must consider retention times and the influence of density flows more carefully than we have. Indeed, in many of the African reservoir studies these potent factors have been overlooked.

Henderson's [this volume] report on Kainji Lake and the work of *Coche* [1968] on the Zambezi River, *Bowmaker* [1969] on the Mwenda River, and *Caulton* [1970] on the Sanyati River in Lake Kariba indicate that these factors are being taken into consideration but that it will take time to understand the overall influence on the larger man-made lakes.

I would like at this point to comment a little further on *Arai* 's [this volume] important paper. He has stressed the great importance of advective heat transfer and provided quantitative data to show the direct relation between the diffusivity coefficient and the maximum velocity in reservoirs. (However, as a classical limnologist, I fail to see how one can assume complete freedom from direct surface heating effects!) Thus we arrive at a point of some importance. We must be careful to distinguish (limnologically) between reservoirs in high or constant rainfall areas, where inflows are continuous and dependable, and those in semiarid or seasonal rainfall areas, where river flow is strikingly variable, so that for long periods minimum inflows occur. This situation is typical in Africa, excluding the equatorial belt, and in Australia and the Indian peninsula. In these areas advective heat resources may well be minimal, and surface heating and consequently eddy diffusion may come to play an important role in the thermal regime of the reservoir.

To the physical limnologist, or more correctly hydrologist, much of the behavior of lakes and reservoirs depends on the setting up of temperature-induced pycnoclines in the water column. These density differences play a vital role in reservoirs in that they contribute to the factors that determine the dimensions of the withdrawal zone. Few if any reservoirs are constructed for surface spillway functions only, and, although many reservoirs may have only a single deep withdrawal inlet, it is becoming increasingly desirable to incorporate a number of withdrawal inlets in the construction of the wall. Although we can appreciate the sensibility of this approach on a priori grounds, little if any concrete information on the effects on reservoir limnology is available. *Grace* [this volume] in his contribution to this symposium has taken us a long way toward an understanding of this particular phenomenon and at the same time clearly indicated where future research effort should be directed. Grace's demonstration that the zone of withdrawal behind a submerged orifice is limited by densimetric factors and that the locations of the upper and lower limits of the zone are independent of each other must have considerable impact on the arguments and models of Straškraba and Arai.

I think that it is pertinent to return to *Naumann*'s [1932, p. 30] original use of the term eutrophy and to try to discover in what way we have moved away from or retained the original definition:

> The term 'Eutrophy' must only be used for the description of a certain lake type when the water is rich in phytoplankton, showing the typical coloration of the vegetation from spring to autumn, and when there is a high production of phytoplankton for a rather long period during summer. The opposite are the terms 'oligotrophy' and 'dystrophy,' both concerned with waters poor in phytoplankton. The former term is used in regard to clear waters, the latter in regard to brown waters.

Contrast this definition with *Nursall*'s [1969] statement about many small kettle lakes in the region of Edmonton: '. . . yet all the lakes are rapidly eutrophicating, i.e. accumulating inorganic and organic solids, and are superficially similar in appearance.'

Significantly, Naumann in the same paper did not or could not specify N and P. He gave no numerical definition of the N and P 'spectrum.' Consequently, he used a biological indicator, the production of algae.

Hutchinson [1967] stresses the importance of retaining the priority of meaning and keeps within the limit of definition as stated by Naumann.

Throughout the period since Naumann published his lake classification, many if not all workers have accepted the terms eutrophy and oligotrophy (particularly eutrophy modified to eutrophication) and have argued about 'rates of eutrophication,' 'eutrophication control,' and 'eutrophication processes.'

In this regard we must remember that Naumann was describing the effects of variation in natural water quality depending on the geology of the areas over which the influent rivers or seepages flowed. He did, however, recognize that eutrophy of an otherwise oligotrophic condition could occur through the entrance of effluent of human origin into the lake catchment; this he considered a heterotrophic change [*Hutchinson*, 1967]. I do not propose a change in nomenclature, but I believe it is important to keep in mind the changes that the term eutrophy first described and consequently to assess in what way our increase in knowledge about the factors responsible for algal production has developed our understanding and so expanded the meaning given to the term eutrophy or 'eutrophication.'

Of particular significance at this point is that a great deal of time has been spent on techniques for estimating the extent of this production rather than the causes of it. In recent years, since *Nauwerck*'s [1963] and *Straškraba*'s [1965] significant studies of phytoplankton and zooplankton interrelationships, we have begun to realize that microbial heterotrophic processes may have a significant effect on the production processes in aquatic ecosystems. *Wright and Hobbie* [1966, p. 447] said that,

> One of the most important unsolved problems in aquatic ecology is the relationship between the dissolved organic matter in natural waters and the organisms that produce, transfer, and use it. The heterotrophic bacteria of the plankton are undoubtedly the most important organisms existing on this organic material.

During the last 5 years a great deal of interest has been shown in heterotrophic biosynthesis in freshwater, and effective quantitative work has been reported by *Overbeck* [1970], *Sorokin* [1970], *Kusnetsov and Romanenko* [1966], and *Hobbie and Wright* [1968].

Eutrophication processes in nearly all cases have been considered to be associated with increases in the N, P, and Si fractions of freshwater. Little if any attention has been given to the C fractions and the limiting role that they may play. In recent months the validity of this approach has been questioned by *Keuntzel* [1970] and his colleagues. The present discussions arise from the decision of the governments of North America to restrict the use of phosphate-loaded synthetic detergents, and, although many of us may argue that much of what has been said both for and against the decision rests more on vested interests than on good science, it nevertheless behooves us not only to examine the work and ideas of Keuntzel and his colleagues but also to initiate studies aimed at resolving the present crisis. I believe that the current argument throws into sharp relief our lack of knowledge of the way in which the various abiotic and biotic factors bring about increasing reservoir or lake eutrophy. *McLachlan* [1970] has reported a number of interesting results relating to effects of reservoir level fluctuation on the water chemistry over two gradually shelving areas in Lake Kariba. Increases of K^+, Na^+, and PO_4^{+++} were positively correlated with rising water levels in the surface 20-cm; pH and O_2 were inversely correlated. *McLachlan* [1970] draws our attention to the possible significance of the effect of level fluctuation in Lake Kariba following on the loss of PO_4 and NO_3 from the hypolimnion via the turbine intakes that occur below the thermocline. As the floodwater of the Zambezi brings in water of a lower ionic content than that of the lake water, this annual injection of nutrients resulting from the inundation of reservoir margins may be of considerable importance. He draws our attention to the role of 'fallowing' in European fish farming to maintain high productivity. A. C. Falconer et al. (unpublished report, 1970) have stressed the important role of the bottom sediments in lake eutrophy, and, although they believe that the bottom muds of Lake McIlwaine are comparable to those of Lake Klamath, Oregon and California, in which it was estimated that the equivalent of 60 years of nutrient input could be found in the top 2–3 cm, they stress the lack of information on instant release from muds in the reservoir that they were studying.

All the papers in this book that deal specifically with eutrophication studies show a refreshing tendency to reexamine the premises on which eutrophication may be adduced. Obviously, the basis of understanding must arise from the extensive and diverse studies on algal productivity that have been conducted by limnologists in the northern hemisphere. However, even at this level we have to realize that many problems particularly of interpretation still exist, as the United Nations Educational, Scientific and Cultural Organization and International Biological Program symposium on productivity problems in freshwater held in Poland in May 1970 has shown.

CONCLUDING REMARKS

There is a good deal of casting about to find effective answers in often the shortest possible time. Governmental policy and the urgency to provide potable water result in forcing this attitude on the engineer and the physical and biological limnologist. We have come to realize that, unless intensive short-term studies become rapidly incorporated into our limnological research programs, very serious difficulties surrounding water supply will result.

Although this approach is essential in highly developed countries, I believe that in those regions of the world where industrial development has not reached such peaks of sophistication there is time for the serious long-term work that is essential to our understanding of the interactions of each aspect of impoundment construction and on which subsequent development will depend.

In this regard I must draw your attention to two earlier international symposiums on the same subject, namely, a symposium under the auspices of the Institute of Biology [*Lowe-McConnell*, 1966] and the man-made lakes symposium held in Accra in 1966 [*Obeng*, 1969]. Both of these were devoted primarily to biological aspects of man-made lakes, although careful attention was always given to those physical features that were considered important in providing a background against which the biologists could relate their own findings.

There arise from these symposiums and the work of the section on physical limnology that I have been privileged to review a number of central problems that, I believe, merit our serious attention.

First, there is the conclusion that reservoirs differ markedly in their physical limnology from lakes and that this difference is largely the responsibility of the current flow regime developed in them consequent on subsurface inflows and subsurface or surface discharges. Although the evidence for this conclusion may be considered overwhelming by some of us, the dimensions of this difference are not really adequately known for large man-made reservoirs, particularly for those in Africa. If this conclusion is accepted, it could be argued that a number of our interpretations relating to the limnological behavior of such reservoirs could be misleading. The work of Efford and his colleagues on Lake Marion in Canada and that of Rawson on the

Churchill lakes in Canada suggest that the validity of this conclusion is open to question. Flushing rates of lakes may well be higher than we initially thought, so that jet streams and density currents may play important roles, particularly in small lakes.

Second, arising from the first conclusion is the advisability, which has been stressed by Straškraba, of developing model systems for reservoir limnology. Keeping in mind the widely different hydrologic and climatological regimes of the reservoirs of the world, although we may feel that to erect such models may be somewhat premature at this stage because so few of us have had the opportunity to extend our studies over long periods of time as our Czechoslovakian colleagues have, it is reasonable to expect that the development of a generalized model will provide us with a sensitive inductive basis on which to develop our research. The dimensions of the variables in a model such as that envisaged by Straškraba will vary within wide limits, but once they are known their integration of a particular reservoir function in physical terms into a working hypothesis becomes a reality.

Third, virtually without exception we still tend to be limited to the determination of N and P with only a passing glance at C when we are working with eutrophy problems. However, the views of *Toetz* [this volume] and others in this book and the reviews of Keuntzel and his colleagues have been clearly expressed and must cause us to reconsider the direction of our research in the study of eutrophication. In short, could we be looking at the wrong things? Is it possible that N and P have become so entrenched in our analytical limnology that we will admit no further additions to a difficult analytical procedure.

Fourth, the large man-made lakes, Volta, Kariba, Kainji, Nasser, and Bratsk, are really too recent to speak of with complete authority in the field of physical limnology. I believe that, although these water masses, particularly those in Africa, have been the center of much stimulating biological work, the physical limnologist has not played an equal role. The work of the Czechoslovakian group over many years has shown the enormous advantages accruing from a sustained research effort by all disciplines, and, if we are to be equally successful, we will have to convince both ourselves and our funding authorities of the long-term benefits of sustained effort in reservoir limnology.

REFERENCES

Allanson, B. R., and J. M. T. M. Gieskes, Investigations into the ecology of polluted inland waters in the Transvaal, 2, An introduction to the limnology of Hartebeespoort Dam with special reference to the effect of industrial and domestic pollution, *Hydrobiologia, 18*(1/2), 77–94, 1961.

Arai, T., Thermal structure of the artificial reservoir, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Bowmaker, A. P., Aspects of the physical hydrology of the Mwenda River mouth, Lake Kariba, *Limnol. Soc. S. Afr. Newslett., 13*, suppl., 9–14, 1969.

Caulton, M. S., A quantitative analysis of the mode of replacement of inorganic phosphates and nitrates in the waters of Lake Kariba during the period December 1969–January 1970, *Limnol. Soc. S. Afr. Newslett., 15*, 52–61, 1970.

Coche, A. G., Description of physico-chemical aspects of Lake Kariba, an impoundment, in Zambia-Rhodesia, *Fish. Res. Bull. Zambia, 5*, 200–267, 1968.

Grace, J. L., Selective withdrawal from man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Harding, D., Limnological trends in Lake Kariba, *Nature, 191*(4784), 119–121, 1961.

Henderson, F., Stratification and circulation in Kainji Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Hobbie, J. E., and R. T. Wright, A new method for the study of bacteria in lakes: Description and results, *Mitt. Int. Ver. Limnol., 14*(1), 64–71, 1968.

Hutchinson, G. E., *A Treatise on Limnology*, vol. 2, *Introduction to Lake Biology and Limnoplankton*, John Wiley, New York, 1967.

Hutchinson, G. E., G. E. Pickford, and J. F. M. Schuurman, A contribution to the hydrobiology of pans and other inland waters of southern Africa, *Arch. Hydrobiol., 24*(1), 1–154, 1932.

Imevbore, A. M. A., Hydrology and plankton of Eleiyele Reservoir Ibadan, Niger, *Hydrobiologia, 30*(1), 154–176, 1967.

Keuntzel, L. E., Bioresources of shallow water environments, in *Bacteria-Algae Symbiosis—A Cause of Algal Blooms, Proceedings of the National Symposium on Hydrobiology*, pp. 321–334, American Water Resources Association, Urbana, Ill., 1970.

Kusnetsov, S. I., and W. I. Romanenko, Produktion der Biomasse heterotropher Bakterien und die Geschwindigkeit ihrer Vermehrung in Rybinsk-Stausee, *Verh. Int. Ver. Limnol., 16*(3), 1493–1500, 1966.

Lowe-McConnell, R. H. (Ed.), *Man-Made Lakes*, Academic, London, 1966.

McLachlan, S. M., The influence of lake level fluctuations and the thermocline on water chemistry in two gradually shelving areas in Lake Kariba, central Africa, *Arch. Hydrobiol.*, *66*(4), 499-510, 1970.

Munro, J. L., A limnological survey of Lake McIlwaine, Rhodesia, *Hydrobiologia*, *28*(2), 281-308, 1966.

Naumann, E., Grundzüge der regionalen Limnologie, *Binnegewässer*, *11*(9), 1-176, 1932.

Nauwerck, A., Die Beziehungen zwischen Zooplankton und Phytoplankton in See Erken, *Symb. Bot. Upsal.*, *27*(5), 1-163, 1963.

Nursall, J. R., The general analysis of a eutrophic system, *Verh. Int. Ver. Limnol.*, *17*(1), 109-115, 1969.

Obeng, L. E. (Ed.), *Man-Made Lakes, The Accra Symposium*, Ghana Universities Press, Accra, 1969.

Overbeck, J., A computer analysis of the distribution pattern of phytoplankton and bacteria in lakes, measurement of rate of microbial decomposition of organic water by means of kinetic parameters and remarks on the bacterial production in lakes, in *Productivity Problems of Freshwater*, pp. 515-522, United Nations Educational, Scientific and Cultural Organization and the International Biological Program, Warsaw, Poland, 1970.

Sorokin, J. I., Biological productivity of the Rybinsk Reservoir, in *Productivity Problems of Freshwater*, pp. 403-415, United Nations Educational, Scientific and Cultural Organization and the International Biological Program, Warsaw, Poland, 1970.

Straškraba, M., Interrelations between zooplankton and phytoplankton in reservoirs Slápy and Klíčava, *Verh. Int. Ver. Limnol.*, *16*, 719-726, 1965.

Straškraba, M., Limnological basis for modeling reservoir ecosystems, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Toetz, D. W., Nitrogen budgets of Great Plains impoundments, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Wright, R. T., and J. E. Hobbie, The use of glucose and acetate by bacteria and algae in aquatic ecosystems, *Ecology*, *47*(3), 447-464, 1966.

Stratification and Circulation in Kainji Lake

F. HENDERSON

UNDP/FAO Kainji Lake Research Project, New Bussa, Nigeria

Kainji Lake is a new reservoir in Nigeria formed by damming the River Niger at a distance of about 1000 km from its mouth on the Gulf of Guinea. It lies in the savanna belt of northern Nigeria at a point where the river passed over a series of rock ledges in several rapids and has an area of 1200 km², about 70% of which is in an extensive central floodplain where the old river had branched into two widely separated channels (Figure 1). The mean depth of the lake is 12 meters (11 meters relative to mean annual lake level), and the maximum depth is about 65 meters near the dam.

The climate of the area is fully divided into a wet season from April to November and a dry season from November to April. Line squalls with winds to 90 km/hr are frequent during the rainy period, especially near the beginning and end. Rainfall is about 100 cm/yr, whereas evapotranspiration is estimated at about 150–200 cm/yr [*Joint Consultants*, 1961]. The temperature of the air ranges from a minimum of about 15°C in January–February to a maximum of around 40°C in March–April, when the humidity is very high.

The winds are generally northerly in December, January, and February and southerly the rest of the year. The northerly winds (harmattan) are cool and dry and frequently bear large amounts of dust that may reduce visibility to < 1 km for several days. The mean daily wind velocity at Yelwa near the northern end of the lake is about 4 km/hr in August through February but rises in the intervening months to a high of about 10 km/hr in May. Although the surrounding topography is of low relief, air flow is considerably modified by low-lying hills, especially in the southern arm of the basin. The strongest winds, to 100 km/hr, are associated with squalls that blow from the east and southeast and are of short duration.

The lake is strongly influenced by seasonal variation in the flow of the River Niger, which has two periods of flood, the 'white flood' peaking in September and the 'black flood' peaking in February.

Additional information on the general limnological and hydrologic characteristics of the lake may be found in the case history paper by *El-Zarka* [this volume].

METHODS

Beginning in August 1969, 1 year after the formation of the lake, a number of survey cruises were made from the damsite to Foge Island (Figure 1) along the track of the old river. These cruises were accomplished at approximately 6-week intervals. At preselected stations (Figure 1), temperature profiles were obtained with a bathythermograph, and three to four samples of water were taken with Van Dorn bottles at depths from 0.5 meter to near the bottom. The samples were analyzed for oxygen, *p*H, total alkalinity, and conductivity. Beginning in July 1970, turbidity was determined with a Hack portable colorimeter and a blue filter (no. 5330). Oxygen and alkalinity were determined by titration, *p*H was usually determined colorimetrically (occasionally with a meter), and conductivity was determined with a Hack portable conductivity bridge. Secchi disk transparency was also measured at each station. Since the rise of the August flood in 1970, additional samples have been collected for the determination of deuterium concentration under a joint program of the International Atomic Energy Commission, the University of Ife (Nigeria), and the Kainji Lake Research Project; these samples are sent to the University of Heidelberg for analysis.

ANNUAL CYCLE OF STRATIFICATION

Stable stratification appears to be the rule from February to May (Figure 2). Although

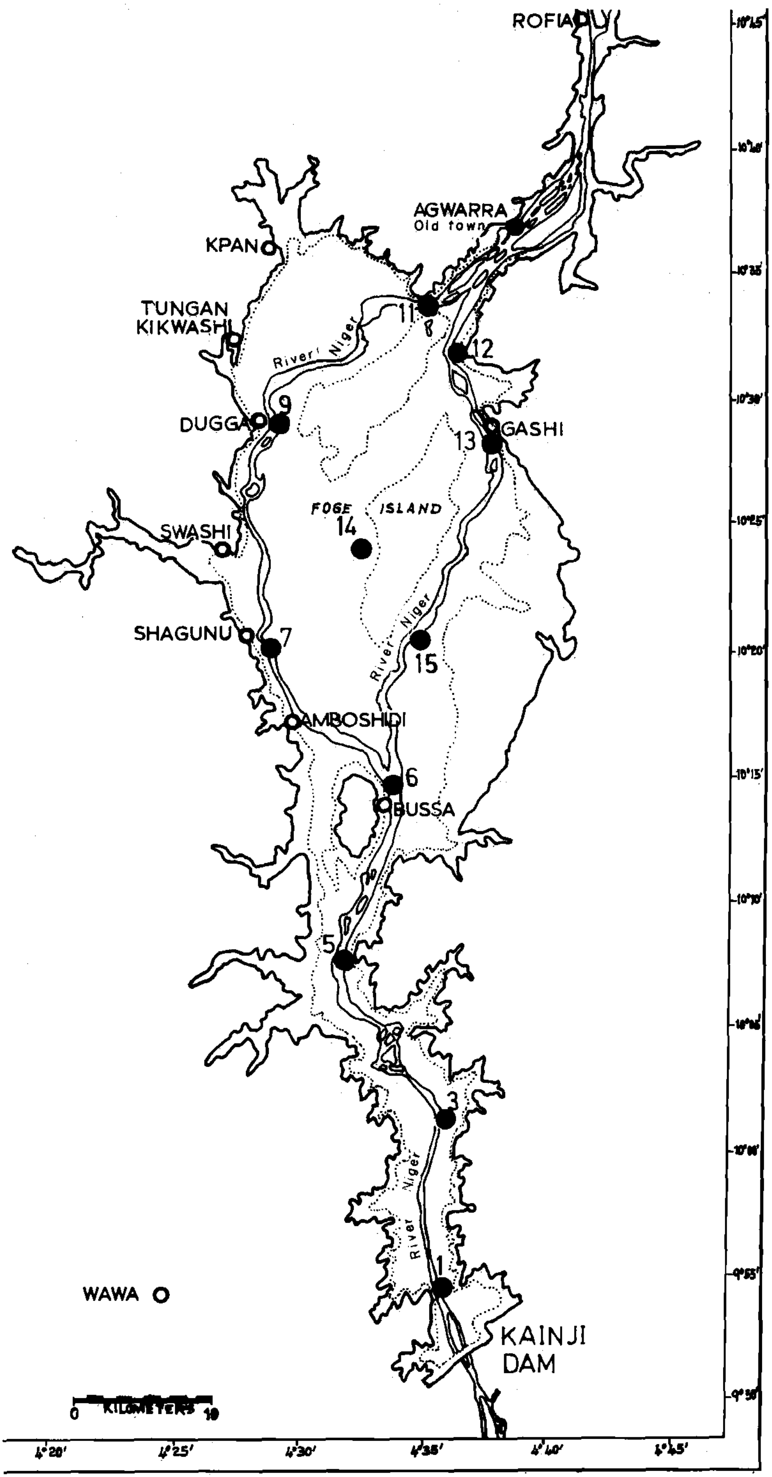


Fig. 1. Limnological sampling stations and extent of low and high water at Kainji Lake. The solid lines represent the high-water mark, the dotted lines represent the low-water mark, the solid dots are the sampling stations, and the open dots are fishing villages and towns.

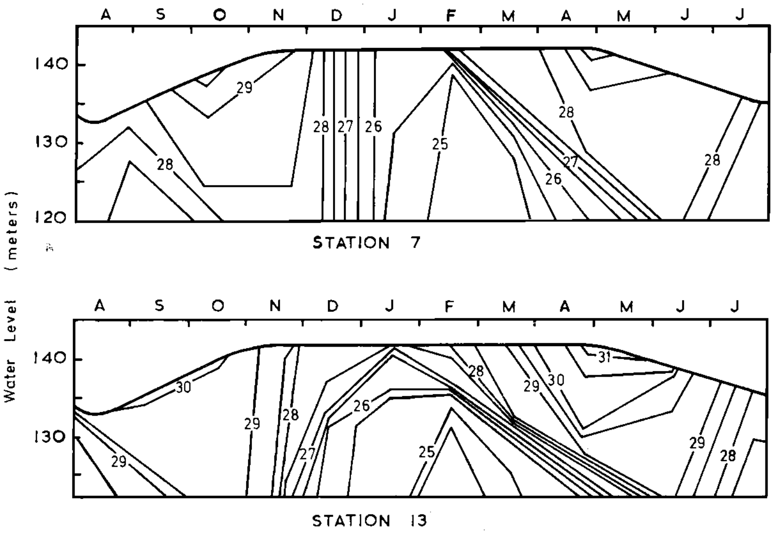


Fig. 2. Water level relative to mean sea level and isotherms at two stations in Kainji Lake for August 1969 to August 1970. Station 7 is on the western side, whereas station 13 is on the eastern side of the central basin of the lake (Figure 1).

temperature profiles for this season were obtained only during 1970, the Niger Dams Authority reported a strong sulfide odor at the spillway in March and April of 1969, which is strong evidence of similar stratification in that year. The spillway outlet lies 15 meters below the surface at high water, but the intake to the turbines is 30 meters below the surface. Hence, from February to April, discharge is taken entirely from below the thermocline. The rapid deepening of the epilimnion during stratification is readily explained by this withdrawal of deep water. The oxygen concentration of the hypolimnion drops rapidly to near 0 in the first month of stratification. At present (1970), most of the discharge is passed through the spillway, where it is strongly aerated. Turbine discharge, however, is not aerated; it passes through a separate channel below the dam before it joins the main flow about 1 km downriver. Fishermen abandon this water from February to May, although at other times of the year the stretch is heavily fished.

Thermal gradients throughout the water column and partial deoxygenation of deep water also occur from July through November at the same time as the white flood and the refilling of the lake. These gradients were much more pronounced in 1970 than in 1969. Full stratification may occur, though wind velocities are low except for occasional squalls and our sampling was not sufficiently frequent to follow temporary changes in thermal conditions.

In December the temperature of the upper river drops appreciably from 28° to 30°C down to 22° to 25°C. Decreased humidity and lowered air temperatures at night increase the rate of heat loss from the lake, and the harmattan dust substantially reduces incoming radiation [*McComb and Iyamabo,* 1968]. These factors lead to a rapid cooling of the lake and an extended period, through January, of isothermy and mixing. This period, coinciding with the rise of the black flood, is of sufficient duration to permit complete replacement of the volume of the lake with black floodwater.

The preceding description is typical of the deeper southern arm and the western half of the large central basin. Conditions in the northern arm are presumably more or less riverine; however, only surface characteristics have been measured. Although the eastern half of the central basin (Figure 1, stations 12, 13, and 15) follows the main elements of the description above, it shows a greater tendency to stratification (Figure 2). The difference was less pronounced in 1970 (November–December) than in 1969, but it was evident in both years. The period of rapid cooling occurred nearly 1 month earlier in 1970 than in 1969 with an earlier and more intense harmattan season. The reasons for the different behavior of the two sides of the central basin are not yet clear, though it is suspected that the rather large throughflow of water tends to stabilize the pattern of currents in the lake. Indeed, the period of minimum discharge, inflow, and water level (June and July) coincides with the period of greatest similarity between stations located on opposite sides of the central basin. Initially, it was thought that much of the inflow was diverted to the west of Foge Island, but recent evidence suggests that the flow pattern through the central basin is complex.

CIRCULATION IN THE CENTRAL BASIN

It has not been possible to carry out current observations in sufficient detail to describe water movement in the central region of the lake. A few indirect observations and scattered current measurements with drogues suggest some general features of water movement through the lake.

Both white and black floodwater can be readily recognized by changes in turbidity. Preliminary results of the study of deuterium concentration, based on samples obtained during the flood, show a high correlation between turbidity (measured with a colorimeter) and deuterium concentration. As the deuterium concentration is determined by differential evaporation of heavy and light water, the black floodwater exhibits much higher concentrations of deuterium than the white floodwater. Mixing seems to be fairly rapid during the periods of transition between old floodwater and new white and new black floodwater. It has been assumed, however, that the observed horizontal gradients in turbidity are indicative of the general pattern of circulation.

At the onset of the white flood in late July and through August the lake level was at its lowest, 10 meters below the normal maximum level. At that time the western channel around Foge Island presented the largest cross section to flow (the mean depth being 6 meters) and was protected from the generally southerly winds by the island itself. The eastern channel, however, was open to the wind through a large angle but had a mean depth of about 4 meters. Furthermore, the deepest part of the western channel was to the right of the current (toward the western bank), whereas the deepest part of the eastern channel was near the center. Turbidity measurements of the surface water showed the eastern channel to be filled with old water except near the bottom of the old riverbed, but the western channel was filled with white floodwater from surface to bottom. A gradual gradient of turbidity was traceable through the full length of the western half of the central basin, whereas the eastern half had very low turbidity all the way to the bottom.

By early September, after a threefold rise in inflow and a rise of 2 meters in the lake level, the highest turbidities were to be found in the eastern channel, though differences between east and west were small. Low turbidity was found toward the southeast (Figure 1, stations 6, 14, and 15). Apparently, the flow extended from both sides of submerged Foge Island toward the southwest across the central shallows over the island. One month later the inflow had diminished in turbidity owing to mixing upriver with the rising black flood and was less turbid than the lake water. The lake level had risen another 6 meters to within 2 meters of the maximum. The distribution of turbidity suggests preferential flow to the east of inundated Foge Island. At high water the eastern channel was much broader than the western channel, so that the eastern channel presented the largest cross section at that time. The incoming water appeared to have moved almost directly southward from the eastern channel, and higher turbidities were found on both sides of the basin. Although the lake had been nearly isothermal during the preceding months, a pronounced thermal gradient was present at that time, the warmer inflow spreading over the existing water. Measurements of currents with drogues at stations 11, 12, 14, and 15 were consistent with the results above, which were based on measurements taken only at stations 11, 12, 14, and 15 (Figure 1). By the end of November the turbidity had dropped throughout the lake to values too low to be measured with precision by the available instrumentation.

In mid-November a detailed set of measurements was made of the currents in each of the two channels around Foge Island. Drogues were released at five locations across each channel at depths of 0.5, 2.5, 5, 10, and, where depth permitted, 15 meters at each location. The results showed a clear displacement of the inflow toward the western side of each channel as a result of Coriolis force. A well-developed thermocline was present on both sides of the island, a shallow secondary thermocline also being present on the east.

The net flow in the western channel was nearly

0 with strong inflowing currents below the thermocline. The inflow calculated for the eastern channel was 4.5 times that of the western channel; however, the inflow through the eastern channel extended above the thermocline to the shallow secondary thermocline. The northerly surface flow lay across the eastern half of this channel and was probably driven by the southerly wind (about 9 km/hr). The much greater surface currents of the western channel flowed against a light wind, since Foge Island provides a substantial barrier to southerly winds in this channel. As it seems likely that the northerly flow in the western channel joined the southerly flow in the eastern channel but was separated by the primary thermocline, the actual ratio of 'new' inflowing water between the two sides was evidently about 3 rather than 4.5.

DISCUSSION

Kainji Lake exhibits several features of interest in relation to the other man-made lakes of tropical Africa. Its low storage ratio and extended period of flood effect complete renewal of its water each year. Indeed, evidence from the distribution of the colloidal clay of the white flood indicates a double renewal annually, first with water derived from runoff of the Nigerian savanna and second with water of more remote origin. It is rather surprising that these two types of water differ so little in gross physical and chemical characteristics. *Imevbore* [1970] has presented evidence of differences in the proportions of various ions between the two floods, but we have found only a weak relationship between turbidity and conductivity, though a strong relationship between turbidity and deuterium concentration appears to exist.

Full stratification with accompanying deoxygenation of the hypolimnion seems to be an annual event beginning with the rise in humidity and windiness at the start of the rains. Rapid withdrawal of hypolimnetic water lowers the level of the thermocline about 10 meters per month, almost double the rate in Lake Kariba [*Harding,* 1966]. This destratification by deep discharge establishes a condition that is potentially polymictic until the end of the rainy season. Both the origin of this condition and the demands of tidy classification suggest that the period following the disappearance of the thermocline through the bottom so to speak might better be regarded as a period of 'virtual stratification!' Subsequent temporary or weak stratification that is limited in development by the difficulty of heating surface waters already at elevated temperatures [*Hutchinson,* 1957] could then be regarded as being similar to epilimnetic or secondary stratification. This period is also coincident with reduced average winds and high humidity and cloudiness and includes the period of the fall and rise of the water level. Partial deoxygenation of deep water occurred throughout this period, and concentrations at the surface also tended to be rather low (5–6 mg/l).

The large central basin with a mean depth of 10 meters is divided longitudinally by the extensive shallows of submerged Foge Island, which becomes partially exposed at low water. These shallows were cleared of trees and brush prior to flooding. At the upper end a small permanent island divides the flow from the riverine arm into the central basin. During the floods extending from August to April the average currents through the channels to either side of this island must be of the order of 5 cm/sec as deduced from hydrologic data. Our observations suggest that the inflow to the central basin generally occupies the deeper parts of these channels and is generally cooler than the surface water of the lake. At low water levels when southerly winds are dominant and the eastern channel is shallow, inflow follows the western channel around the island and continues down the western side of the basin. With a rising water level and continued southerly winds, flow shifts to the eastern channel. A substantial counterflow may appear in the western channel, perhaps as a result of the setup in the northwest bay. Regardless of which channel the inflow takes the highest turbidities are maintained across the central shallows toward the southwest. Later, inflowing black floodwater appears to follow a similar course as is shown by decreased turbidity down through the center of the basin. With the fall of the inflow temperature in December the coolest temperatures are found to the north and west of the basin, although the water is vertically isothermal.

These deduced patterns of flow are consistent with the apparent difference in the regime of stratification between the eastern and the western parts of the lake. Nevertheless, these deductions must remain tentative, and the significance of this difference must remain in question. As the peculiarities of the basin admit consideration of alterations in the channels around Foge Island for the control of circulation, more attention to the problem seems warranted.

Only slight changes in the circulation of the reservoir are expected with the diversion of discharge from the spillway to the intakes as additional turbines are installed. At full capacity with 3 times the present number of turbines, most of the discharge will be used for power, and more marked effects are to be expected downstream of the lake, deoxygenated water extending as far downstream as the Awuru rapids during the period of stratification of the lake above. Although the river below the dam is scheduled to be flooded by a second dam at Jebba, 90 km downstream, its construction is not to be started until nearly the full hydroelectric capacity at Kainji has been achieved.

SUMMARY

Kainji Lake is essentially monomictic; i.e., it passes through an extended period of partial mixing beginning with the complete withdrawal of the hypolimnion in May and ending with thorough mixing and cooling at the onset of the dry season. Full renewal of the water of the lake occurs annually prior to stratification in February. Before this time, additional nutrients are added as ash from the savanna fires of the dry season.

Although a monomictic regime is typical of tropical lakes of moderate size in the savanna regions, Kainji Lake is somewhat unusual owing to its large throughflow and longitudinally divided major basin. These factors contribute to more thorough vertical mixing, although they tend to increase differences across the lake arising from differences in the characteristics of the water of the two floods due, perhaps, to the dividing island at the upper end of the major basin.

REFERENCES

El-Zarka, S. E.-D., Kainji Lake, Nigeria, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Harding, D., Lake Kariba, The hydrology and development of fisheries, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 7–20, Academic, London, 1966.

Hutchinson, G. E., *A Treatise on Limnology,* vol. 1, *Geography, Physics, and Chemistry,* pp. 503, 509, John Wiley, New York, 1957.

Joint Consultants (Nedeco and Balfour, Beatty and Company, Ltd.), *Niger Dams Project,* vols. 2, 5, Federal Government of Nigeria, Lagos, 1961.

Imevbore, A. M. A., The chemistry of the River Niger in the Kainji Reservoir area, *Arch. Hydrobiol 67*(3), 412–431, 1970.

McComb, A. L., and D. E. Iyamabo, Some solar radiation measurements at Samaru, Nigeria, with an actinograph and radiation integrators, *Res. Leafl. 1,* 6 pp., Savannah Forest. Res. Sta., Zaria, Nigeria, 1968.

Man-Made Lakes and the Changing Limnological Environment in Australia

W. D. WILLIAMS

Department of Zoology, Monash University, Clayton, Victoria 3168, Australia

Australia has one of the lowest human population densities of any habitable area of the world (<2 persons/km^2). Most of this density is the result of immigration and population growth during only the last 200 years, i.e., since Caucasian man arrived. Therefore it would seem likely that the natural environment in general and the limnological environment in particular are subject to less man-made alteration in Australia than in other countries. However, Australia is also, apart from Antarctica, the most arid continent in the world. Of the relatively small proportion that has adequate rainfall for human needs and crops (the mean annual rainfall of the mainland is 42 cm, and slightly less than 30% of Australia has >50 cm rain per annum), only part occurs in temperate latitudes, where most of the population growth has resulted. The total mean annual runoff from all Australian rivers, 350 km^3, is just marginally greater than that, for example, of a single European river, the Danube. Moreover, in populated areas and elsewhere on the continent the climate undergoes considerable fluctuations of a secular and seasonal nature.

As a result of these fluctuations and the overall aridity, extensive direct changes to the inland aquatic environment have been necessary for water supply and storage. In part, these changes have been exacerbated because Australia is more urbanized than other countries (83% of the total population is urban), a phenomenon that reflects both historical and economic factors and a discussion of which is beyond the scope of this paper. Additionally, and particularly in Tasmania, demands for hydroelectricity have also caused extensive direct changes.

Apart from direct changes to the inland aquatic environment, several other sorts of change are involved. All mirror worldwide changes, but the effects of at least some have been intensified by the unique composition of the biota and by other distinctive features of Australian inland waters.

In summary, despite low human population densities and a relatively short history of man-made change, very little of the Australian inland aquatic environment remains in a natural unaltered state. Only in remote and generally very arid areas is the inland aquatic environment natural.

DIRECT CHANGES

The most obvious direct man-made change has been the conversion of many freshwater lakes into storage impoundments and the damming of rivers to create completely new standing bodies of water. They are referred to throughout this paper as reservoirs, although it is usual official practice in Australia to refer to them as 'lakes' (Table 1). The conversion process has gone so far that throughout temperate Australia there remain few freshwater lakes of any significant size that are not now subject to control for storage purposes or scheduled for control. Frequently, such lakes have become part of huge man-made reticulation systems to increase storage efficacy, as they have, for example, in Tasmania, where most of the larger lakes of the central highlands (as well as some reservoirs) are now linked by an intricate series of connections. Similar reticulation may also operate between reservoirs. The most distinctive example is the Snowy Mountains scheme in the highlands of New South Wales, where a large number of reticulated reservoirs have been created to stop the waters of the Snowy River from flowing southward. Now most of the water flows inland to augment the flow of the Murray and Murrumbidgee rivers.

Although some lake drainage has occurred, the overall direct effect of man on standing water has been to increase its total volume. With the exception of Tasmania, there are, however, profound limnological differences between the contemporary lentic environment and the former natural one. First, many standing bodies of freshwater now occur in regions where formerly such waters were either nonexistent or ephemeral. This result is most apparent perhaps in the central arid region overlying the Great Australian artesian basin, where the use of subsurface water has frequently entailed construction of numerous surface storage impoundments.

Second, strong differences are obvious in certain morphometric and chemical characteristics.

TABLE 1. Major Reservoirs and Storage Lakes in Australia

Reservoir (a) or Storage Lake (b)	Capacity, km^3	Height of Dam, meters	Main Purpose*
	Victoria		
Existing			
Eildon (a)	3.40	79	i, h
Waranga (a)	0.41	14	i
Rocklands (a)	0.34	28	w
Eppalock (a)	0.32	46	w, i
Upper Yarra (a)	0.20	82	w
Glenmaggie (a)	0.19	37	i
Cairn Curran (a)	0.15	44	i
Under construction			
Mokoan (b)	0.37	11	i
Projected			
Dartmouth (a)	3.7	180	c
Buffalo (a)	0.99	79	i
Cardinia Creek (a)	0.27	79	w
	New South Wales		
Existing			
Eucumbene (a)	4.80	116	i, h
Hume (a)	3.06	43	w, i, h
Menindee lakes (b)	2.5	...	c
Warragamba (a)	2.06	115	w, h, f
Burrendong (a)	1.7	76	w
Blowering (a)	1.6	112	i, h
Burrinjuck (a)	1.03	81	i, h
Wyangala (a)	0.69	67	w, i, h
Jindabyne (a)	0.69	72	i, h
Lake Victoria (b)	0.68	...	i
Keepit (a)	0.43	54	w, h
Glenbawn (a)	0.36	77	c, i, f
Tantangara (a)	0.25	45	i, h
Avon (a)	0.20	71	w
Grahamstown (a)	0.18	11	w
Lake Brewster (b)	0.15	...	w, c
Under construction			
Copeton (a)	1.36	114	i
Wyangala (extension) (a)	1.23	85	w, i, h
Talbingo (a)	0.92	162	i, h
Projected			
Warkworth (a)	0.50	40	f, i
	Queensland		
Existing			
Somerset (a)	0.91	53	w, f, h
Tinaroo Falls (a)	0.41	42	i
Koombooloomba (a)	0.18	38	h, i
Under construction			
Fairbairn (a)	1.45	45	i
Wuruma (a)	0.19	37	i
Eungella (a)	0.13	40	e, w, i
Projected			
Pike Creek (a)	0.25	46	i
North Pine (a)	0.20	38	w
	South Australia		
Projected			
Chowilla (a)	6.17	12.5	c

TABLE 1. (continued)

Reservoir (a) or Storage Lake (b)	Capacity, km^3	Height of Dam, meters	Main Purpose*
	Western Australia		
Existing			
Wellington (a)	0.18	34	i, w
Serpentine (a)	0.18	52	w
Under construction			
Ord River (a)	5.70	67	i, h, f
	Tasmania		
Existing			
Miena (Great Lake) (b)	2.11	19	h
Lake Echo (b)	0.54	19	h
Clark	0.53	67	h
Arthur Lakes (b)	0.51	15	h
Lake St. Clair (b)	0.19	...	h
Rowallan (a)	0.14	43	h
Under construction			
Gordon (a)	11.90	137	h
Serpentine (a) }	0.38	41	h
Scotts Peak (a) }		49	h

Only reservoirs and storage lakes with a capacity greater than about 0.125 km^3 are listed. Many smaller reservoirs and storage lakes occur. The basic data (recalculated) are from the *Commonwealth Bureau of Census and Statistics* [1969].

* The symbol i stands for irrigation; h, generation of hydroelectricity; w, supplies for domestic and/or stock purposes; c, water conservation and/or regulation; f, flood mitigation; and e, cooling water for thermal power generation.

Thus, with few exceptions, freshwater lakes on the Australian continent are naturally shallow and have significantly higher salinities and different ionic compositions than 'world average freshwater' (sensu *Conway* [1942], although in reality Conway's data apply strictly to world average river water). In Victoria, the most temperate continental state, over two thirds of all lakes still have salinities >1‰, and throughout Australia in freshwater as well as saline water the principal ions in the lakes are sodium and chloride [*Williams,* 1967*a*].

When the present total lentic environment is considered, this situation changes. The depths of those lakes now used for water storage have generally been increased, and almost all reservoirs have lower area-volume relationships than lakes of comparable areas. Further, since storage lakes and reservoirs must contain freshwater to be useful, there has been a decrease in the mean salinity of large bodies of freshwater and a proportionate upward shift in the importance of calcium and bicarbonate ions. (In spite of the decrease in mean salinity the salinity of many domestic water supplies to inland centers of population exceeds 500 ppm, the value given as the 'maximum acceptable concentration' for potable waters by the *World Health Organization* [1963].)

These changes have been accompanied by marked disturbance to the natural pattern of fluctuation in the water levels of rivers across which dams have been constructed and in the water levels of storage lakes. Diurnal fluctuations in hydroelectric power, seasonal demands for irrigation water, and flood control measures are factors of importance in this respect. Although it is now too late to gage precisely the importance of this disturbance to the inland aquatic biota, it seems highly likely that it has been of considerably greater importance in Australia than in other countries. Thus some Australian freshwater fish and invertebrates are known to have breeding cycles correlated with seasonal or even longer term fluctuations in river and lake water levels (e.g., *Paratya,* an atyid prawn, and *Plectroplites ambiguus,* a fish). Disturbing the pattern of these fluctuations clearly has important repercussions for the survival of such species. No major river in any area of temperate Australia exhibits a natural pattern of water level fluctuation, and much of the lowland lotic environment in such areas has also been subjected to different degrees of alteration in other directions (straightening, dredging, 'improvement' schemes, and so on).

Alterations to river temperatures caused by the creation of upstream reservoirs is another phenomenon, the importance of which is probably greater in Australia than in other countries, although it cannot now be determined. It has been suggested that *Maccullochella macquariensis*, the Murray cod, has been largely replaced by introduced trout, *Salmo trutta*, in certain southeastern Australian rivers because of reservoir-induced lowered water temperatures.

INDIRECT CHANGES

As most of the population of Australia lives in coastal cities, changes to the inland aquatic environment and the biota caused by domestic and industrial waste discharge have to some extent been minimized. Nevertheless, waters in metropolitan areas are frequently grossly polluted, and many noncoastal centers of population cause significant local pollution [see *Senate Select Committee on Water Pollution*, 1970]. Additionally, agriculture has caused other sorts of pollution, so that this phenomenon is by no means restricted to areas near towns. For example, *Butcher* [1965], referring to freshwater fish in Victoria where large tracts of unsprayed land still occur, noted that no specimens could be found without pesticide residues in them, and *Brown* [1963], discussing the density of certain sorts of bacteria in 10 widely distributed inland rivers in New South Wales, noted that 'none [could] be regarded as safe, from the bacteriological viewpoint, for human consumption.'

Eutrophication of some smaller standing waters near centers of populations (coastal or otherwise) is also beginning to assume an unwelcome significance. Note that the high salinities and concomitant nutrient concentrations (phosphates and nitrates) of many Australian lakes, presently noneutrophicated, preclude direct comparisons of nutrient concentration and loading values with data derived from the study of northern hemisphere lakes that are undergoing eutrophication.

Other indirect changes to Australian inland waters have resulted principally from deforestation, overgrazing, disturbance to the natural pattern of vegetational burning, and the introduction of exotic biota. It is unnecessary to provide details of these processes and their effects [*Williams*, 1967*b*], but it is important to note that they seem likely to have had a more profound effect in Australia than in most other countries. Thus, if modern concepts concerning ecosystem evolution and function are upheld [e.g., *Margalef*, 1968; *Odum*, 1969], it seems probable, as a reflection of the high degree of climatic stress, that ecosystem homeostatic mechanisms in Australia are less effective than those of many other ecosystems in which natural environmental perturbations are smaller. Consequently, the effect of human disturbance on Australian aquatic ecosystems has probably been further intensified, the more so since the effects have been compressed into a shorter time interval than has been usual outside Australia.

The high degree of endemicity that developed in the aquatic fauna following the long biogeographic separation of Australia has probably been of particular importance to the intensity of the impact of introduced species. However, little that is definite can be written on this matter because we do not yet know enough about it. At all events, the unique character of the fauna needs no elaboration [cf. *Williams*, 1968], and from a biological viewpoint alone any decrease in its diversity would be unfortunate. *Brundin* [1967] has recently stressed the critical importance to modern biogeography of the fauna of the southern hemisphere as a whole and the probable shortage of time that is left for its study.

Apart from threats to the endemic biota in particular, several introduced species perhaps pose more severe threats to the environment in general. Both *Eichhornia crassipes*, the water hyacinth, and *Salvinia auriculata*, the water fern, have been introduced, and several tropical or semitropical reservoirs already exist as potential sites for the development of noxious conditions. At present, *E. crassipes* infests many smaller bodies of water in northern New South Wales and southern Queensland, whereas so far *S. auriculata* is less pestiferous. Some other well-known nuisance macrophytes have been introduced but are not troublesome, at least not yet. The two introduced animals that cause the most environmental damage are *Cyprinus carpio*, a carp, and *Bufo marinus*, the cane toad. The carp, it is claimed [*Butcher*, 1962], causes great physical disturbance to the environment because of its habit of 'roiling' bottom deposits. The cane toad at certain seasons becomes very abundant;

when populations subsequently crash, dead individuals cause fetid conditions in water holes where they die.

PROBLEMS

From a biological viewpoint the major fundamental problems involved in the management of reservoirs and storage lakes in Australia are (1) the inapplicability of much research done overseas and (2) the lack of appreciable basic indigenous research.

The first point is of course a corollary of the various distinctive features of Australian inland waters already mentioned. Another feature of this sort that can be mentioned and may be of considerable importance to management relates to the thermal characteristics of Australian lentic waters. The significance of thermal behavior in terms of chemical and biological repercussions needs little emphasis. Recently, *Bayly and Williams* [1973] have carefully examined the depth-temperature relationships of various Australian lakes, and from their examination they note several interesting facts. First, the thermal structure of the sort of lake on which most limnological research has been conducted, that is, a dimictic lake with spring and autumn holomixis, does not occur in any Australian lake or by implication reservoir. The most important type of thermal behavior is the warm monomictic one, as is shown, for example, by Eildon Reservoir, Victoria. Second, some of the smaller lakes in Australian highland temperate regions freeze in winter and are holomictic in summer at temperatures >4°C. They do not therefore fit into existing thermal classifications of monomictic lakes. (Bayly has proposed a suitably modified classification and terminology.) Third, polymictic lakes are much commoner in Australia in more temperate conditions and at lower altitudes than the existing limnological literature would predict.

Finally, with regard to the lack of basic indigenous research, note briefly that Australia, despite the importance of water as a basic resource, remains the only major scientifically developed nation with a marked lack of financial support for fundamental ecological studies on inland waters. Considerable support is given to related applied research [cf. *Bastow*, 1963] and to fisheries investigations, but there is usually a narrow interpretation of 'applied,' and fisheries investigations in the main have of necessity been motivated primarily by angling requirements. An associated feature is the dearth of ecologically trained personnel in the employ of water supply and control authorities. Only one government instrumentality, the Metropolitan Water Sewerage and Drainage Board, Sydney, employs biologists specifically for purposes of water storage management.

Acknowledgments. I would like to thank Dr. I. A. E. Bayly, Monash University, for commenting on a draft of this paper and for permission to quote from unpublished information on the thermal characteristics of Australian lakes. Thanks are also extended to the State Rivers and Water Supply Commission of Victoria for their cooperation.

REFERENCES

Bastow, S. H., Organization in C.S.I.R.O., in *Investigation and Research: National Symposium on Water Resources, Use and Management*, part E, pp. 500–502, Australian Academy of Science, Canberra, 1963.

Bayly, I. A. E., and W. D. Williams, *Inland Waters and Their Ecology*, pp. 78–82, Longmans, Melbourne, 1973.

Brown, J. K., The extent of bacterial pollution in stream water in New South Wales, Australia, M.Sc. thesis, Univ. of N. S. W., Sydney, Aust., 1963.

Brundin, L., Insects and the problem of austral disjunctive distribution, *Annu. Rev. Entomol., 12,* 149–168, 1967.

Butcher, A. D., Why destroy the European carp?, *Fish. Circ. 6,* 6 pp., Fish. and Wildlife Dep. of Victoria, Melbourne, 1962.

Butcher, A. D., Wildlife hazards from the use of pesticides, *Aust. J. Pharm.*, suppl., 105–109, 1965.

Commonwealth Bureau of Census and Statistics, *Official Yearbook of the Commonwealth of Australia*, vol. 55, Government Printer, Canberra, 1969.

Conway, E. J., Mean geochemical data in relation to oceanic evolution, *Proc. Roy. Irish Acad., Sect. B, 48,* 119–160, 1942.

Margalef, R., *Perspectives in Ecological Theory,* University of Chicago Press, Chicago, Ill., 1968.

Odum, E. P., The strategy of ecosystem development, *Science, 164,* 262–270, 1969.

Senate Select Committee on Water Pollution, *Water Pollution in Australia,* Government Printer, Canberra, 1970.

Williams, W. D., The chemical characteristics of lentic surface waters in Australia: A review, in *Australian Inland Waters and Their Fauna, Eleven Studies,* edited by A. H. Weatherley, chap. 2, pp. 18–27, Australian National University Press, Canberra, 1967*a*.

Williams, W. D., The changing limnological scene in Victoria, in *Australian Inland Waters and Their Fauna, Eleven Studies*, edited by A. H. Weatherley, chap. 10, pp. 240–251, Australian National University Press, Canberra, 1967*b*.

Williams, W. D., *Australian Freshwater Life: The Invertebrates of Australian Inland Waters*, Sun Books, Melbourne, 1968.

World Health Organization, *International Standards for Drinking Water,* p. 29, Geneva, 1963.

A Limnological Reconnaissance of Lake Gorewada, Nagpur, India

S. U. HUSSAINY AND M. K. ABDULAPPA

Central Public Health Engineering Research Institute, Nagpur, India

Man-made lakes are becoming important in many parts of the world. They are primarily intended as sources of either public water supply or hydroelectric power. In addition, they provide many new opportunities for irrigated farming, fisheries development, transport, and recreation.

In recent years many lakes and reservoirs have been impounded in India to provide a continuous water supply for hydroelectric power plants farther downstream, for irrigation, or for the public to use. The impoundment of these reservoirs provided an opportunity to investigate the seasonal variation in physicochemical and biological factors. The importance of such studies has been stressed by several workers. The studies on Indian lakes and reservoirs include those of *Ganapati* [1960], *Sreenivasan* [1964], and *Hussainy* [1966, 1967]. *Ganapati* [1960] studied in detail the physicochemical factors of Errakuppum Reservoir and the three upland lakes in Madras to evaluate the water quality. *Sreenivasan* [1964] carried out his studies in reservoirs used for irrigation and fish production. *Hussainy* [1966, 1967] investigated in detail limnological features and primary production in Vehar Lake, a source of public water supply to the city of Bombay.

The present paper incorporates the results of an investigation carried out in Lake Gorewada during March 2–3, 1966. The investigation included observations on primary production, physicochemical, and biological factors.

TOPOGRAPHY AND MORPHOMETRY

Lake Gorewada is one of the sources of public water supply to the city of Nagpur. It contributes about 18 ml of treated water and is situated about 4 km on the northwest of Nagpur at 21.09°N and 70.07°E at an elevation of about 300 meters above mean sea level. It has a catchment area of 2800 ha and a water-spread area of 259 ha. The maximum depth of the lake is about 5 meters. The average annual rainfall in the area is about 100 cm. The shore is irregular, and the littoral vegetation is composed of *Vallisneria* sp., *Chara* sp., *Potamogeton alpinus*, and *P. falciformis*. The catchment area is well protected, and there is no source of pollution at the lake.

METHODS OF INVESTIGATION

Water samples were collected for 24 hours at 2-hour intervals from surface to bottom at a depth increment of 1 meter by using a Kemmerer water sampler. Field temperatures were measured by using a 37.5-cm mercury thermometer with 0.1°C divisions. The samples were analyzed for dissolved oxygen (DO), alkalinity, *p*H, and carbon dioxide in the field. The samples were analyzed for total dissolved solids, sulfates, chlorides, phosphates, nitrates, calcium, and magnesium in the laboratory. The methods of analyses were those described by *Standard Methods for the Examination of Water, Sewage, and Industrial Wastes* [*American Public Health Association*, 1955]. After 24 hours a primary productivity experiment using light and dark bottle technique [*Hull*, 1964] was also conducted.

Plankton collections were made when the water samples were collected. A known volume of water was passed through a cone net made of bottling cloth of 80 mesh per linear centimeter. The quantitative analyses of plankton were made by using a Sedgwick-Rafter cell.

OBSERVATIONS AND DISCUSSION

Temperature. The temperature of the surface water during the period of investigation ranged between 27.7° and 22°C (Figure 1). The maximum temperature was recorded at 12:30 P.M. on March 2, and the minimum was recorded from 2:30 to 4:30 A.M. on March 3. The amplitude of diurnal variation in the surface water was 5.5°C. The temperature of the bottom water ranged between 23.0° and 19.5°C. The maximum

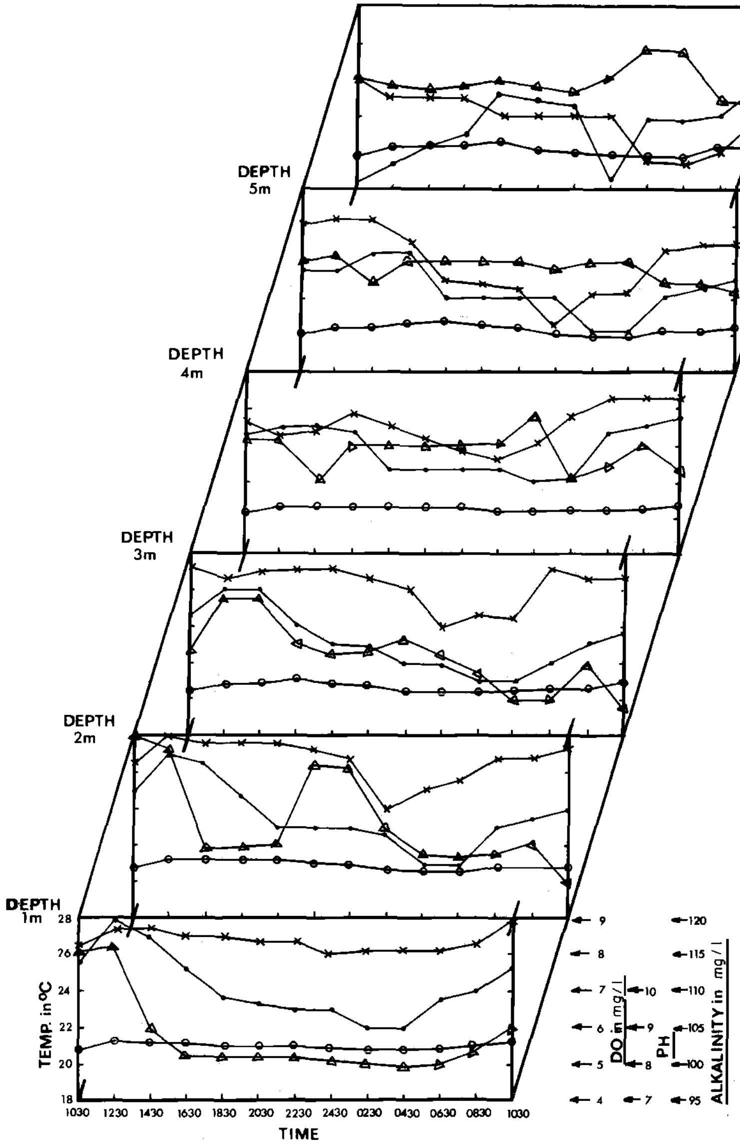


Fig. 1. Diurnal variation of temperature (solid dots), DO (crosses), *p*H (open dots), and total alkalinity (open triangles) on March 2-3, 1966.

temperature was recorded from 10:30 A.M. to 2:30 P.M. on March 2, and the minimum was recorded from 2:30 to 4:30 A.M. on March 3. The amplitude of variation was 3.5°C.

The temperature of the surface water was always greater than that of the bottom water. The range of variation changed during different hours of the day. The maximum amplitude of variation was observed to be 4.7°C at 12:30 P.M., and the minimum was 1.0°C at 12:30 A.M. The data further indicate that there is no thermal stratification. Lake Gorewada is polymictic in nature. Similar observations have been recorded by *Sreenivasan* [1964] in lakes and reservoirs in Madras state and by *Hussainy* [1967] in Vehar Lake, Bombay. The superficial stratification during the day was probably caused by solar heating and was destroyed at night by nocturnal cooling and complete mixing. *Worthington* [1930], *Talling* [1957], and *Baxter et al.* [1965] recorded similar observations for South African lakes.

Dissolved oxygen. The DO content of the surface water ranged between 8.0 and 9.0 mg/l. The highest content was recorded at 10:30 A.M. on March 3, and the lowest was recorded at 12:30 A.M. on the same day. The amplitude of variation was 1.0 mg/l.

The DO in the bottom water ranged between 6.6 and 4.1 mg/l. The maximum concentration was recorded at 6:30 P.M. on March 2, and the minimum was recorded at 12:30 A.M. on March 3. A variation of 4.7 mg/l between the surface and the bottom water was recorded at 12:30 P.M. The DO concentration at various depths increased from 10:30 A.M. to 12:30 P.M. From 12:30 to 2:30 P.M., there was no change in the DO concentration. The fluctuation in the DO concentration was due mostly to the variation in the photosynthetic activity of the algae.

Carbon dioxide. Carbon dioxide was not recorded in the surface water during the study period. In the hypolimnion, carbon dioxide was recorded at 10:30 A.M. and from 10:30 P.M. to 9:30 A.M. on March 2. The maximum concentration, 6.0 mg/l, was recorded from 2:30 to 4:30 A.M. During the day, when the temperature and light intensity are optimum, other things being the same, the CO_2 released at the hypolimnion is used by the algae during photosynthesis. However, during the night, when the light intensity is not at its optimum, the photosynthetic activity is reduced, so that CO_2 accumulates at the hypolimnion. We can assume that the light intensity may be acting as a limiting factor for carbon assimilation.

Alkalinity. The total alkalinity of the surface water was found to be 100–117 mg/l. The highest value was recorded at 12:30 P.M., and the lowest was recorded between 2:30 and 6:30 A.M. The total alkalinity was greater during the day than during the night. The surface water was always found to be alkaline to phenolphthalein during the investigation period. It is evident from the phenolphthalein alkalinity that the surface water alkalinity is due to carbonates and bicarbonates.

The bottom water was alkaline to phenolphthalein from 12:30 to 8:30 P.M. on March 2 and from 6:30 to 8:30 A.M. on March 3. During the rest of the study period the bottom water was alkaline to methyl orange only. The data further indicated that, owing to active photosynthesis during the light hours, increased amounts of bicarbonates were used for the release of carbon dioxide to meet the photosynthetic demand. During the dark hours, when respiration exceeded photosynthesis, the excess carbon dioxide accumulated combined with the monocarbonates to form bicarbonates. The fluctuation in the alkalinity during different parts of the day indicates that light may be acting as a limiting factor for the photosynthetic activity of the algae.

pH. The *p*H of the surface water ranged between 8.4 and 8.6. The lowest value was recorded from 12:30 A.M. to 6:30 P.M., and the highest value was recorded from 10:30 A.M. to 2:30 P.M. The amplitude of variation was 0.2. The *p*H of the bottom water ranged between 7.9 and 8.3. The lowest value was recorded at 10:30 A.M. on March 2 and between 12:30 and 4:30 A.M. on March 3. The amplitude of variation was 0.4. The *p*H of the bottom water was always less than that of the surface water. The amplitude of variation from the surface and bottom water was 0.2 to 0.5.

The data indicated that there was an unstable *p*H stratification from surface to bottom but that the degree of variation in the bottom water was less than that in the surface water. The *p*H of the surface water was always >8.1; i.e., photosynthesis exceeded respiration [*Atkins and Harris,* 1924]. The *p*H at the bottom during the dark hours was <8.1; i.e., respiration exceeded photosynthesis.

The diurnal variations of *p*H, DO, alkalinity, carbon dioxide, and temperature at different depths indicate that these factors follow a regular pattern. Temperature and light intensity seem to be responsible for regulating the factors. The data indicate that there are no stable stratifications with respect to any of these factors.

Primary production. The specific bioactivity of a biosystem is its capacity for the formation of potential energy and for the subsequent conversion of this potential energy into kinetic energy per unit time and per unit volume or surface area [*Ohle,* 1956]. To assess the productive potentiality of the lake, a 24-hour light and dark bottle experiment was conducted on March 2–3, 1966. Water samples were collected from surface to bottom at a depth increment of 1 meter by using a Kemmerer water sampler. These were analyzed for their initial DO content. One dark bottle and one light bottle of 300 ml capacity (glass stoppered) were filled with the samples of each depth. These bottles were lowered by means of a graduated cord to the depth from which they were collected and

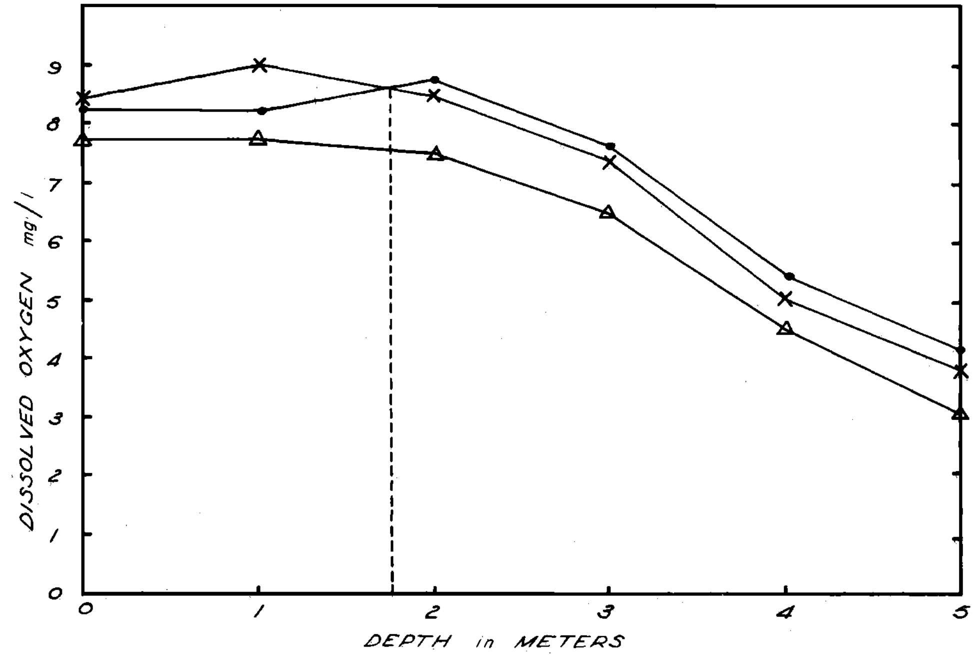


Fig. 2. Fluctuation of DO based on the productivity experiment conducted on March 2–3, 1966. The solid dots represent the initial DO, the crosses represent the final DO in the white bottle, the open triangles represent the final DO in the dark bottle, and the compensation depth is 1.62 meters.

were suspended for 24 hours. At the end of the experiment they were analyzed for their DO content.

The initial oxygen depth profile and the final oxygen depth profiles in both light and dark bottles are shown in Figure 2. The changes in the oxygen content in the light bottle during the exposure period give the net oxygen production, photosynthesis minus respiration. The changes in the oxygen content in the dark bottle during the exposure period give the measure of the respiratory activity at each depth [*Hull,* 1964]. The differences between the final oxygen contents of light and dark bottles indicate the gross production during the exposure period. The intersection point of the curves representing the initial DO and the final DO in the light bottle gives the compensation depth or the depth at which the oxygen production by the planktonic algae is just sufficient to meet the respiratory need of the algae themselves, bacteria, and other organisms. The total oxygen demand of the water for the last period is completely balanced by the photosynthetic oxygen production at and above the compensation depth. The compensation depth was found to be 1.52 meters. A measure of oxygen production provides a means of calculating carbon assimilation [*Hull,* 1964]. For each milliliter of oxygen set free, 0.375 mg of carbon will be assimilated. The surface water produced 0.8 ml/l of oxygen during the 24-hour period. This figure corresponds to 0.3 g C/m²/day and is comparable to the figures of *Hussainy* [1967] and *Sreenivasan* [1964] in similar reservoirs.

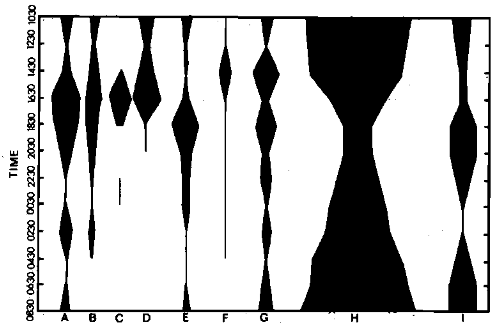


Fig. 3. Diurnal variation of zooplankton in surface water: (*a*) *Orthocyclops* sp., (*b*) *Mesocyclops* sp., (*c*) *Diaptomus* sp., (*d*) nauplii, (*e*) *Moina micrura,* (*f*) *Bosmina* sp., (*g*) *Alonella* sp., (*h*) *Ceratium* sp., and (*i*) Rotifera.

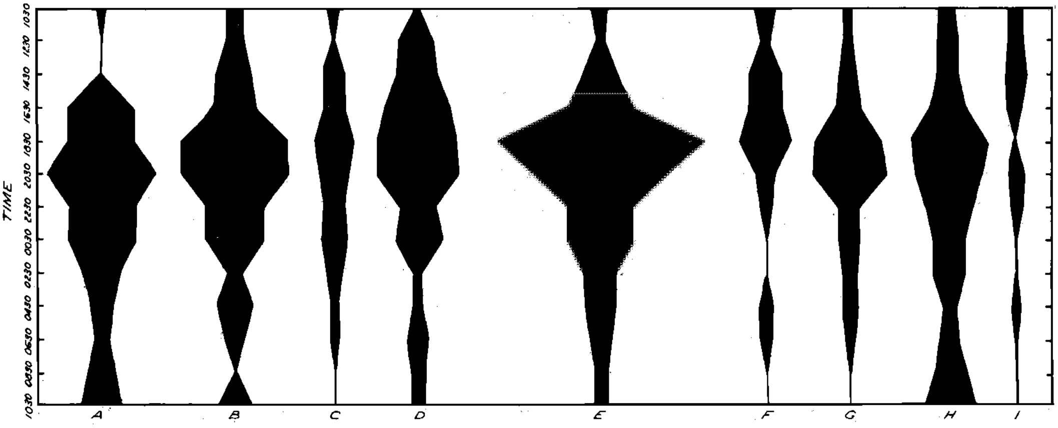


Fig. 4. Diurnal variation of zooplankton species at 1.3 meters (see legend for Figure 3).

Phosphate and nitrate. Phosphates were not detected during the present study. Their concentration was found to be exceedingly low, and hence they could not be detected. These observations agree with those of *Sreenivasan* [1964], *Ganapati* [1960], and *Hussainy* [1967].

Studies of *Barlow and Bishop* [1965] have shown that the regeneration of phosphorus by zooplankton in the epilimnion is adequate to meet the normal daily requirements of the algae. During the investigation period, *Ceratium* sp. was found to be in bloom concentrations. The rate of phosphate use by the bloom is much faster than the rate of phosphate release into the environment.

Nitrates and nitrites were not detected in the surface water. They are usually recorded in very low concentrations in tropical freshwater [*Hutchinson*, 1957]. The appearance of *Ceratium* sp. in bloom concentrations might be one of the factors responsible for the undetectable concentrations of nitrates and nitrites. The absence of nitrates and nitrites in Indian waters has been recorded by *Ganapati* [1960] and by *Sreenivasan* [1964].

Other chemical factors. Total dissolved solids ranged from 100–120 mg/l. Chlorides ranged from 7–10 mg/l. Sulfates were not detected. The anionic dominance is $CO_2 > Cl > SO_4$.

Among the cations, only calcium and magnesium were estimated. Calcium was 52 mg/l, and magnesium was 40 mg/l. The cationic dominance is Ca > Mg > Na. Sodium was estimated by subtracting the sum of calcium and magnesium from the sum of cations.

Biological factors. The study was restricted to

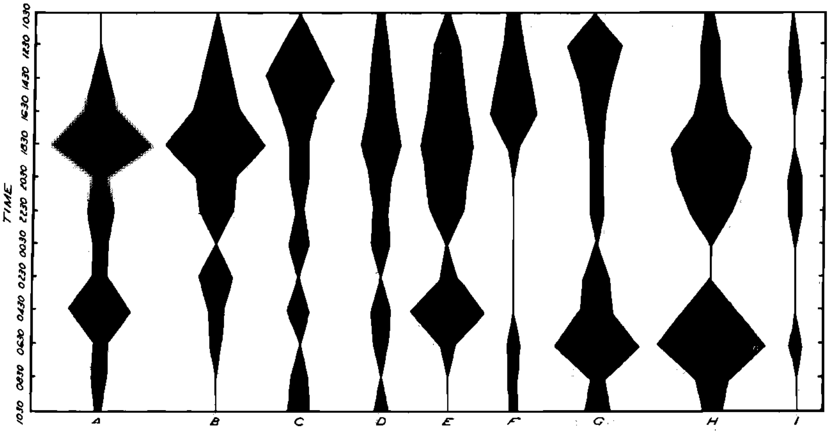


Fig. 5. Diurnal variation of zooplankton at 3.3 meters (see legend for Figure 3).

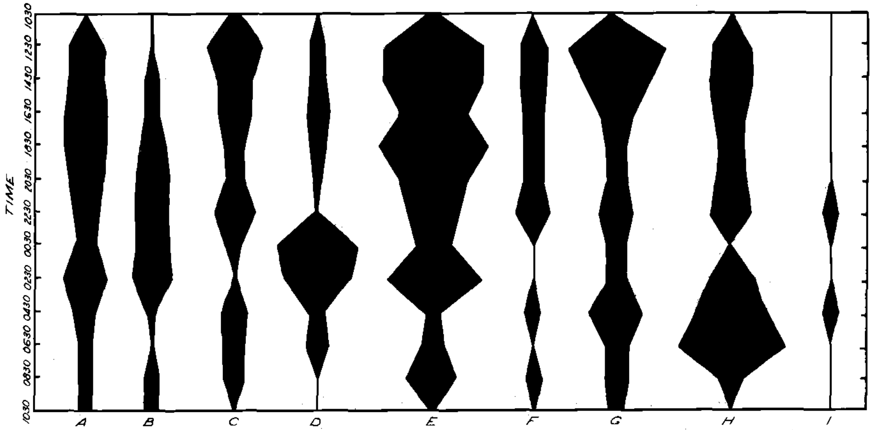


Fig. 6. Diurnal variation of zooplankton at 5 meters (see legend for Figure 3).

zooplankton only. Taxonomic determinations of Copepoda and Cladocera were made only up to the genus level. The Copepoda were represented by *Orthocyclops* sp., *Mesocyclops* sp., and *Diaptomus* sp. The Cladocera were represented by *Bosmina* sp., *Alonella* sp., and *Moina* sp. The Rotifera were represented by *Keratella cochlearis* and *Brachionus calyciflorus.*

Ceratium hirundinella occupied the surface water most of the time (Figures 3–6). It exhibited a downward migration from 6:30 to 8:30 P.M. and during this period occupied a depth of 1.3 meters.

The migratory behavior in the three species of Copepoda, *Orthocyclops* sp., *Mesocyclops* sp., and *Diaptomus* sp., was found to be the same. The populations seemed to occupy a depth of 1.3 meters for most of the period. During midday and late in the afternoon they seemed to migrate to greater depths. The nauplii behaved in the same manner.

The surface water was scarcely populated with *Moina micrura.* Although the migration was irregular, they seemed to avoid surface water. *Bosmina* sp. and *Alonella* sp. were recorded mostly in the deeper waters. *Bosmina* sp. was not recorded in the surface water during the early hours of the morning, 4:30 to 8:30 A.M. A depth of 1.3 meters seemed to be more favorable.

Keratella cochlearis and *Brachionus calyciflorus* were the two species of Rotifera recorded during the present investigation. Although the migratory behavior of these species was irregular, they seemed to occupy the surface water except at midnight and during midday.

Our conclusion is that Lake Gorewada is not deep enough for the zooplankton to exhibit a distinct migratory pattern.

Acknowledgments. This work was carried out when the senior author was at the Central Public Health Engineering Research Institute, Nagpur, India. The authors are thankful to the Director, Central Public Health Engineering Research Institute, for providing the research facilities and for his permission to publish the results of the investigation. The authors are thankful to Mrs. W. Kennedy for typing the manuscript.

REFERENCES

American Public Health Association, *Standard Methods for the Examination of Water, Sewage, and Industrial Wastes,* 10th ed., 834 pp., New York, 1955.

Atkins, W. R. G., and G. T. Harris, Seasonal changes in the water and heleoplankton of fresh water ponds, *Sci. Proc. Roy. Dublin Soc., 18,* 2–21, 1924.

Barlow, J. P., and J. W. Bishop, Phosphate regeneration by zooplankton in Cayuga lake, *Limnol. Oceanogr., 10,* suppl., 15–24, 1965.

Baxter, R. M., M. V. Prosser, J. F. Talling, and R. B. Wood, Stratification in tropical African lakes at moderate altitudes (1500 to 2000 meters), *Limnol. Oceanogr., 10,* 510–520, 1965.

Ganapati, S. V., Ecology of tropical waters, *Proc. Symp. Algol. 1959,* 200–218, 1960.

Hull, C. H. J., Oxygenation of Baltimore Harbor by planktonic algae, *J. Water Pollut. Contr. Fed., 35,* 587–606, 1964.

Hussainy, S. U., Plankton periodicity in Vehar Lake, *Environ. Health, 8,* 1966.

Hussainy, S. U., Studies on the limnology and primary production of a tropical lake, *Hydrobiologia, 30,* 335–352, 1967.

Hutchinson, G. E., *A Treatise on Limnology,* vol. 1, *Geography, Physics, and Chemistry,* John Wiley, New York, 1957.

Ohle, W., Bioactivity, production and energy utilization of lakes, *Limnol. Oceanogr.*, *1*, 139–140, 1956.

Sreenivasan, A., The limnology, primary production and fish production in a tropical pond, *Limnol. Oceanogr.*, *9*, 391–396, 1964.

Talling, J. F., Diurnal changes of stratification and photosynthesis in tropical waters, *Proc. Royal Soc., Ser. B*, *147*, 57–83, 1957.

Worthington, E. B., Observations on temperature, hydrogen ion concentration, and other physical conditions of Lakes Victoria, Albert, and Nyazas, *Int. Rev. Gesamten Hydrobiol.*, *13*, 279–287, 1930.

Limnological Studies of Ambazari Reservoir, Nagpur, India, in Relation to Water Quality

K. P. KRISHNAMOORTHI, ANURADHA GADKARI, AND M. K. ABDULAPPA
Central Public Health Engineering Research Institute, Nagpur, India

From a sanitary engineering viewpoint, limnological and hydrobiological studies of water bodies are undertaken to understand the raw water characteristics of drinking water sources to improve water treatment practices. The objects of the investigation undertaken at Ambazari Reservoir were (1) to study the raw water characteristics from a physicochemical viewpoint, the epibiota and the endobiota, the bottom fauna, and the planktonic organisms, communities, and associations and (2) to prepare a list of microfauna and macrofauna as well as benthic communities from this survey and from surveys of other water bodies of different degrees of pollution at Nagpur. The bacteriologic studies of the raw water were not done simultaneously because a detailed study on this water body was already available [*Rao and Parhad*, 1967].

This study deals at length with the physicochemical properties of the lake water, which is one of the sources of raw water for drinking purposes to the city of Nagpur, and includes comprehensive data collected during the different seasons for a period of nearly 2 years (February 1965 to January 1967).

MATERIALS AND METHODS

Collections were made at this reservoir once a fortnight or sometimes once a month. On the basis of the contour of the lake, three surface sampling points (A_1, A_2, and A_3) and one bottom sampling point (A_3B) were selected. The A_3 location is the raw-water intake point. Normally, the collections were made with the aid of an inflatable rubber boat (Zodiac) between 8:00 and 10:00 A.M. The samples were collected from the surface and the bottom for analyses for physicochemical properties, epibiota and endobiota, microplankton and macroplankton, and bottom fauna.

A Kemmerer water sampler (capacity 2 liters) was used to collect bottom water samples, and an Ekman dredge was used for bottom fauna. Plankton were collected with a bolting silk cloth net of 200 mesh. Two sets of plankton samples were collected. Only qualitative observations were recorded regarding phytoplankton. Zooplankton was quantitatively enumerated by both the Sedgwick-Rafter cell method and Utermohl's inverted plankton microscope. The physicochemical factors analyzed for surface and bottom samples were temperature, *p*H, dissolved oxygen (DO), carbonates, bicarbonates, total hardness (calcium and magnesium hardness), chlorides, oxygen-absorbed values (4 hr N/80 potassium permanganate), and biochemical oxygen demand (incubated at 20°C for 5 days). The temperature was recorded at the site, and the samples were transported to the laboratory as early as possible. All other chemical analyses were done according to *Standard Methods for the Examination of Water and Waste Waters Including Bottom Sediments and Sludges* [*American Public Health Association*, 1960].

Topography of the Lake

This reservoir is one of the sources of water supply to the city of Nagpur (population about 700,000). The lake, which is 6.4 km from the city, is about 330 meters above sea level and has a catchment area of 15.5 km^2 and a water-spread area of about 2.56 km^2. The water supply from this source is about 440 m^3/day. Although Nagpur has three water treatment plants, there is no treatment plant at Ambazari, and the only treatment given to the raw water is chlorination. The shoreline of the lake is wavy, and the side in which the raw-water intake point is situated has an embankment of cut stones and hard rock. The reservoir has a depth of about 7 meters in the middle and 5–7 meters at the intake point. The wave action in this water body is rather poor because of the comparatively small water-spread area. The reservoir supports some aquatic vegetation, partly submerged aquatic plants like *Hydrilla*, *Chara*, and *Hydrodictyon* and the filamentous algae *Spirogyra*. Some water is being pumped from this water body for an adjacent garden. This reservoir is strictly protected on most sides from sources of pollution.

OBSERVATIONS AND DISCUSSION

Physicochemical

Observations made on physicochemical characteristics of the Ambazari Reservoir for February 1965 to January 1967 are summarized as follows.

Temperature. There was no marked difference in temperature in the different stations (Figure 1). During the summer the atmospheric temperature was between 25° and 47.3°C, and the water temperature was between 22° and 31°C. The low temperatures during the summer may have been because the samples were collected in the early hours of the morning (8:00 to 9:00 A.M.). The bottom temperature (A_3B) was slightly higher than the surface water temperature, and this difference, which is a characteristic phenomenon of most of the tropical waters, was particularly evident during the summer months. An analysis of the diurnal variation study carried out in the same water body covering the different seasons in a year showed that the lake had a feeble thermal stratification during the summer.

During the rainy season the water temperature showed a slight increase, ranging from 26° to 33°C, in all stations. The maximum surface temperature of the whole observation period (33°C) was recorded from A_1 and A_2 in September 1965. The maximum bottom temperature (33.5°C) was recorded from A_3B in August 1965. During the winter the water temperature ranged from 20° to 30.5°C.

In general, throughout the seasons the reservoir water was almost homothermal. Low surface temperature and slightly higher bottom temperature were characteristic phenomena of most of the tropical waters. No thermal stratification was observed in any season except in summer when a feeble stratification occurred. Moreover, in shallow tropical waters, stratification during the day and convectional cooling at night are not very important.

pH, carbonates, and bicarbonates. Free carbon dioxide was not detected during the period of investigation except on rare occasions at midnight and during the early hours of the morning when it could be detected from the bottom samples of the lake water. During the period of observation the *p*H of the water was always >8, a complete absence of free carbon dioxide being indicated. The *p*H ranged from 8 to 8.95 without showing any marked seasonal or monthly variations. The bottom *p*H showed no marked

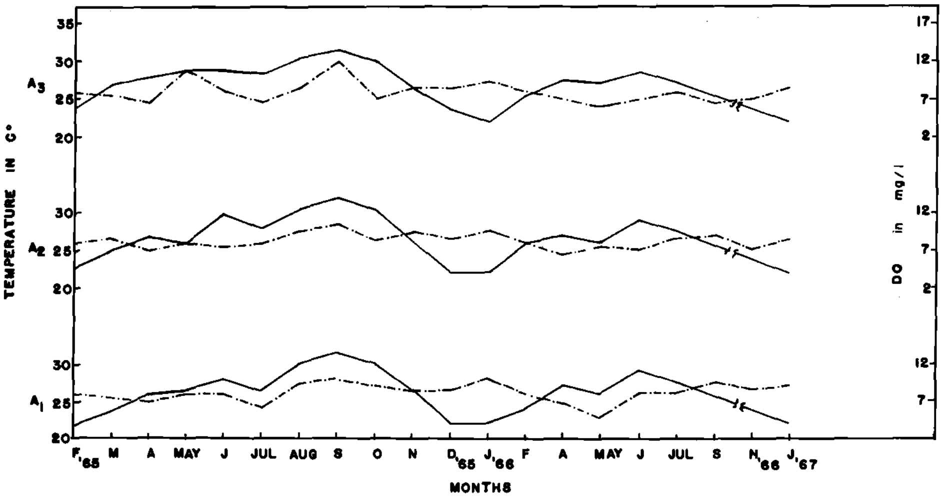


Fig. 1. Data for temperature (solid lines) and DO (dash-dot lines).

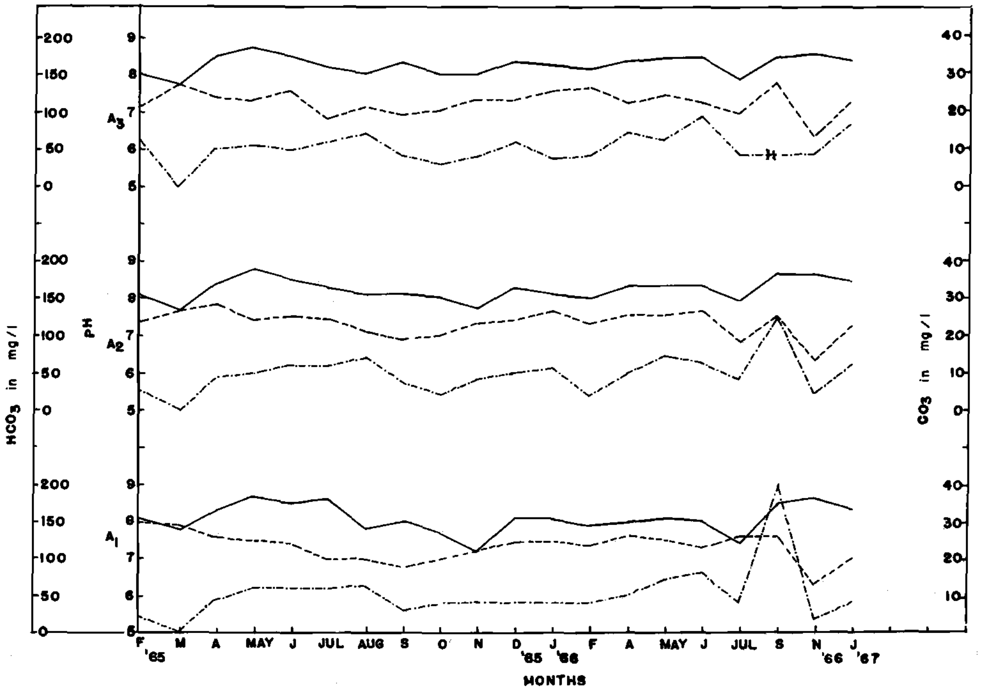


Fig. 2. Data for chlorides, where *p*H is represented by solid lines, CO_3 is represented by dash-dot lines, and HCO_3 is represented by dashed lines.

difference from that of the surface water. Carbonates and bicarbonates were detected in both surface and bottom samples. The concentration of carbonates for the surface water ranged from 4 to 20 mg/l, and that of bicarbonates ranged from 68 to 148 mg/l.

Figure 2 shows a positive correlation between the *p*H and the carbonate alkalinity of the surface water. There were no distinct relationships observed between *p*H and HCO_3 or CO_3 and HCO_3.

The absence of free carbon dioxide in the surface layer of the reservoir in all stations can be attributed to its removal by phytoplankton for photosynthesis. The presence of free carbon dioxide in feeble concentrations on rare occasions reflects the depletion of oxygen due to the excess respiratory processes of the organisms. The absence of free carbon dioxide or half-bound or bound carbon dioxide resulted in an increase in *p*H and also phenolphthalein alkalinity. Thus a positive correlation between *p*H and CO_3 alkalinity is obtained, this correlation being a characteristic phenomenon of most of the shallow tropical waters. The increase in bicarbonate alkalinity in the bottom layer may be due to tropholytic activity in the hypolimnion.

Dissolved oxygen. Figure 1 gives the DO concentration in milligrams per liter in the three sampling stations. The surface water of the reservoir was nearly saturated in all seasons. During the summer season in 1966 the oxygen concentration of the surface water ranged from 5.4 to 8.3 mg/l. Bottom samples ranged from 3.5 to 9.5 mg/l for all seasons and from 7 to 7.9 mg/l for 1966. During the rainy season the DO concentration of the surface water was almost above the saturation level, the range being 6.1 to 13.1 mg/l for 1965 and 6 to 11.1 mg/l for 1966. For 1965 and 1966 the bottom layer recorded 5.7–11 mg/l and 3.6–7.5 mg/l, respectively. During the winter season in all the stations the oxygen concentration was well above the saturation level, the range being 7.7 to 11.1 mg/l for 1965 and 7.1 to 11.1 mg/l for 1966. For 1965 and 1966 the bottom layer recorded 6.3 to 9.3 mg/l and 6.1 to 8.5 mg/l, respectively.

A high oxygen concentration in the surface layer and a low oxygen level in the bottom layer are indications of trophogenic activity in the

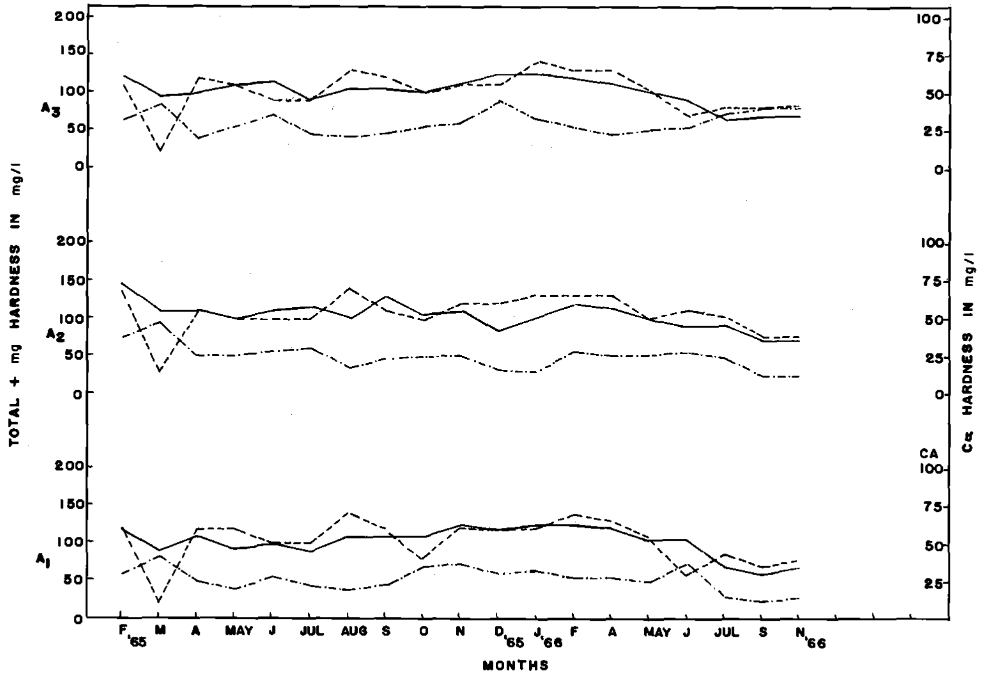


Fig. 3. Data for total (solid lines), calcium (dashed lines), and magnesium (dash-dot lines) hardness.

epilimnion and tropholytic activity in the hypolimnion. The maximum DO recorded during the observation period was 15.4 mg/l in May 1965. During the summer the water level in the lake goes down, and the shallow water that remains is mainly confined to the area around station A_3. This water is rich in nutrients owing to the decay of vegetation and is well exposed to sunlight, so that increased photosynthesis and in turn high oxygen levels result. Throughout the seasons, round-the-clock observations show that DO was always nearly at saturation levels except on a very few occasions at midnight in the bottom layers, where for a short time there was a depletion of DO. However, this depletion was not sufficient to be lethal to fish life and cause sudden fish mortalities. The concentration of DO in the bottom layer diminished during the summer season because of the many dead organisms in the process of decomposing.

Hardness. The hardness of surface water (Figure 3) is mainly due to carbonates of calcium and magnesium. The total hardness of the water ranged from 60 to 192 mg/l for calcium and from 8 to 80 mg/l for magnesium. There were no seasonal or monthly variations. Based on the data we can say that the water was moderately hard.

Chlorides. The chloride content (Figure 4) of the surface water was low, from 7 to 20 mg/l. There was no sharp rise in chloride content at any time during the period of investigation, and thus we can conclude that the water was free from pollution. There was no seasonal variation observed in the chloride content of the water.

Oxygen-absorbed values and biochemical oxygen demand (BOD). Oxygen-absorbed values indicate the amount of oxidizable organic matter in the lake. The values of Ambazari Reservoir were low, from 0.2 to 5.2 mg/l. There was no great seasonal or monthly variation in the oxygen-absorbed values observed in this water body. The BOD (incubated at 20°C for 5 days) of the lake water ranged from 5 to 10 mg/l. The low BOD and oxygen-absorbed values indicate that the water is free from organic pollution. Moreover, the low organic content in the water is an encouraging factor for its acceptability as potable water.

Biological

During the period of study, 12 species of protozoans, 10 species of rotifers, 10 species of oligochaetes, and 17 species of crustaceans composed of cladocerans, copepods, and ostracods were recorded. Among the macroinvertebrates, 10 species of mollusks composed mainly of pulmonate gastropods and a species of bivalve have been recorded in this reservoir. Among the insects the *Cuclicid trichoptera* and *C. chaoborus* larvae have been recorded quite frequently.

The bottom fauna are composed of the bloodworm larvae, namely, *Chironomus tendepediformis* and *C. tentans*. These two forms are not usually killed by the normal dose of chlorination, so that they get into the distribution system and often create problems from the esthetic viewpoint in the final drinking water. The public normally complains about the occurrence of these bloodworms in tap water during the end of the monsoon season and postmonsoon season, which incidentally coincides with the breeding season of chironomid flies. The nuisance of bloodworms in drinking water supplies is a global phenomenon, and many reports are available for water supplies throughout the world. So far, no definite conclusion can be drawn as to whether these larvae create any sort of health hazard by serving as vectors of different pathogens.

In addition, tubificid worms, *Limnodrilus hoffmeisteri*, are recorded in small numbers, and *Branchiura sowerbyi* and *Brachiodrilus* sp. have also been recorded. These forms normally indicate a high degree of organic pollution, but their qualitative occurrence cannot be directly attributed to such heavy pollution, although the quantity will beyond doubt indicate heavy organic pollution. Since organic decomposition is bound to go on occasionally in the bottom layer, few species have been recorded from the dredge sample. The bulk of the major plankton consisted of the crustaceans and rotifers, and many of the stalked ciliates were epizoic on crustaceans. Among the protozoans the dinoflagellate *Ceratium hirundinella* often occurred in large numbers and gave a musty odor to the water. The occurrence of *Ceratium* sp. and its relation to musty odor are well recognized in association with drinking water. Ten species of mollusks have been recorded, but no observation could be made on the choking of pipelines, although it is well established that *Corbicula*, *Lymnaea*, *Viviparus*, and *Indoplanorbis* choke different units of the water distribution system, including the water meters. This lack of choking can be attributed to the very small number of mollusks that occur in this lake. The qualitative occurrence of the phytoplankton indicates the presence of 25 different species of algae and diatoms. On a few occasions, blooms of blue green algae like *Microcystis* and *Spirulina* were observed. These blooms were never permanent.

The seasonal and horizontal distribution of protozoans did not follow any pattern. Except in February 1965 the protozoans were not significantly numerous in this reservoir. Since the epizoic forms were excluded from the bulk of the protozoans, only the remaining forms were taken into account for quantitation, and thus the protozoan population was low.

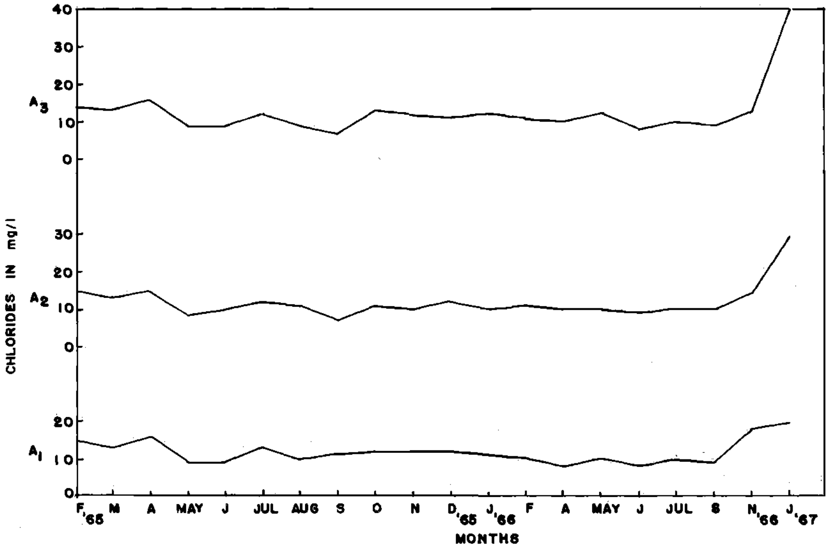


Fig. 4. Alkalinity data.

Among the rotifers, *Keratella tropica* showed a progressive increase in quantity during the summer period in all three stations during 1965. The other rotifers do not warrant any special comment from the quantitative data available.

The copepods in general showed an increase in quantity from September to December in the 2 study years, whereas the cladocerans were found in greater numbers during the other months of the year, especially in 1965. A better knowledge of the development of zooplankton in an oligotrophic lake is needed, and studies of the dynamics of crustacean population should be encouraged in order to understand the various nuisances that these forms are capable of creating in drinking water or water supplied to industry. The crustaceans that impart taste and odor to water are well known, and their bulk in the plankton adds to the organic material. The crustacean species escape into the water supply system and are trapped at several places in the distribution network. In India especially, since most of the waterworks operate an intermittent system, these forms cause a turbidity problem, and by decomposition in the water mains they affect the taste and odor of the water.

During the studies above, data were collected on the various microinvertebrates and macroinvertebrates associated with this type of oligotrophic water. These data were useful for comparing the forms obtained in mesosaprobic and polysaprobic waters, where simultaneous collections were made for biological data. These data also helped compare forms collected in running water. All these data were useful for compiling the saprobien system of organism classification for studying the water quality criteria from the biological viewpoint. The data available to us on this aspect are beyond the scope of this paper and will be published subsequently elsewhere.

Acknowledgments. The authors are very grateful to the Director, Central Public Health Engineering Research Institute, Nehru Marg, Nagpur, India, for working facilities and for permission to publish this paper.

REFERENCES

American Public Health Association, *Standard Methods for the Examination of Water and Waste Waters Including Bottom Sediments and Sludges,* 11th ed., New York, 1960.

Rao, N. U., and N. M. Parhad, Quantitative studies on the bacterial pollution of lake and river waters, *Environ. Health, 9*(1), 93–102, 1967.

Quality of Water of Man-Made Lakes in India

I. C. DOS M. PAIS-CUDDOU, N. C. RAWAL, AND K. R. AGGARWAL

Central Soil Mechanics Research Station
Central Water and Power Commission, New Delhi, India

The chemical analysis of river and reservoir water is assuming great importance in India because of the development of river valley projects, industrial and urban water supply, and so on. The data collected so far on the quality of river water have proved useful for the planning and development of irrigation and power projects in the country, but chemical and other properties of river water and their usefulness for industrial and domestic purposes also require full investigation. In the past in India, investigations of river water have been carried out only for use in irrigation. The work involved the determination of dissolved solids at the highest and lowest concentrations. Systematic chemical investigations of river and reservoir water in India were therefore undertaken for their judicious and scientific use in agriculture and industry, for drinking and domestic purposes, and so on.

WORK PROGRAM

River systems. The subcontinent of India is bounded by the Himalayas in the north and the Indian Ocean, consisting of the Bay of Bengal on the east and the Arabian Sea on the west, in the south. The great plain of India, which stretches across the foothills of the Himalayas, is formed by two great rivers, the Ganges and the Indus, and their tributaries. The Ganges River has major tributaries such as the Jamuna, Gumti, Sapt Kosi, Gandak, and Teesta in the north and the Chambal and Son in the south.

The Indus River rises from Kashmir in the north and has five important tributaries, the Jhelum, Chenab, Ravi, Beas, and Sutlej. In this paper the Ganges and the Indus and their tributaries are discussed under the northern and northeastern rivers.

In peninsular India the rivers rise from the Deccan plateau, which is of recent volcanic origin. The Western Ghats in the Deccan plateau experience a very high rainfall as a result of which two big long rivers, the Kistna and the Godavari, rise and flow eastward into the Bay of Bengal. Two fairly large rivers, the Tapti and the Narbada, flow west into the Gulf of Cambay in the Arabian Sea. The rivers of the Deccan plateau are discussed under the southern rivers.

Selection of river sites. The investigation of the northern and northeastern rivers covered the Indus River and its tributaries and the Ganges River and its tributaries. In addition, water of reservoirs such as Bhakra Dam on the Sutlej River and Rihand Dam on the Rihand River was also investigated. The selection of rivers and tributaries for water-sampling sites was made from the viewpoint of existing sediment and discharge observation sites. The details of sampling sites on the northern and northeastern rivers and reservoirs are given in Table 1.

The investigation of the southern rivers covered the peninsular rivers. In addition, water of reservoirs such as Maithon, Panchet, Shetrunji, and Tungabhadra was also included in the study. The details of the sampling sites of the southern rivers and reservoirs are given in Table 2.

Sampling and analysis. To make an accurate and systematic assessment of the quality of river water and its mineral content, representative water samples were collected once a month from the same location on the same day. The samples were collected with the help of a bottle sampler 15–20 cm below the water surface from the middle of the river, or from some other location along the cross section of the river, where the current was the fastest and the depth was the greatest. Water samples were collected in clean polythene bottles, labeled to show the name of the river, location, sampling date, and so on, and

TABLE 1. Sites on the Northern and Northeastern Rivers and Reservoirs That Were Sampled

River or Reservoir	Sampling Site
Indus	
Sutlej	Slapper Bridge
Beas	Pandoh
Ravi	Chamba
Giri	Jateon
Chenab	Kanthan
Jhelum	Baramulla
Ganges	
Ganges	Hardwar
	Kanpur
	Farakka
Jamuna	Tajewala headworks
	Okhla
Ramganga	Zira Rahimpur
Gumti	Maighat
Banas	Negaria
Chambal	Kota Barrage
Sapt Kosi	Barakhshetra
Gandak	Lalganj
	Hayaghat
Jaldhaka	road bridge on NH-31
Teesta	Anderson Bridge
Mahanadi	railway bridge broad gage
Mahi	
Mahi	Mahi Dam
Ajoy	
Ajoy	Nutunhat
Reservoirs	Bhakra
	Rihand

sent to the laboratory for analysis. For reservoirs, water samples were collected from the point of maximum depth.

All water samples were analyzed by standard methods for their total dissolved solids, conductivity, *p*H, cations (calcium, magnesium, sodium, potassium, and iron), and anions (carbonate, bicarbonate, chloride, sulfate, phosphate, and so on). The hardness of the water samples was also determined to assess their suitability for industrial purposes.

DISCUSSION OF TEST RESULTS

Total dissolved solids. Generally, water containing 150 ppm of total soluble salts is classified as being low in mineral content, water with 150–500 ppm of total soluble salts is moderate in mineral content, and water with 500–2000 ppm is high in mineral content. On the basis of this classification, water of all the northern rivers is either low or moderate in mineral content. The mineral content of water of northern rivers, i.e., the Sutlej, Giri, Jamuna at Okhla, Ganges at Kanpur and at Farakka, Ramganga, Gumti, Banas, and Chambal, remains moderate in all months of the year. In the water of the Mahi River the mineral content varies from moderate to high. In the Beas, Ravi, Jhelum, Chenab, Jamuna at Tajewala headworks, Ganges at Hardwar, Sapt Kosi, and Gandak rivers the soluble salts content varies from low to moderate in different months of the year. It remains low in the Ajoy, Jaldhaka, Teesta, and Mahanadi rivers and the Bhakra and Rihand reservoirs throughout the year.

For all southern rivers except the Mahi River at Sevalia, where the water in May is high in mineral content, the soluble salts content of the water is either low or moderate. Water of the Mandavi River at Sonai, Kali Nadi at Dundeli, and Maithon Reservoir is fairly low in mineral content during all the months of the year. In the Godavari, Zuari, and Cauvery rivers and the Panchet and Tungabhadra reservoirs the soluble salts content varies from low to moderate in different months of the year. The mineral content of water of the North Pennar, Ozat, and Tapti rivers and Shetrunji Reservoir is moderate throughout the year.

Reaction. The *p*H values <7.0 indicate an acidic reaction, and those >7.0 indicate an alkaline reaction. Water of all the northern rivers except the Jhelum and Ramganga is alkaline in reaction throughout the year. Water of the Jhelum and Ramganga is neutral in reaction (*p*H 7.0) during the months of February and September, respectively. In general, the *p*H of water of all the northern rivers varies widely. For many rivers the lowest values of *p*H are 7.1, 7.2, or 7.3, and the highest values are between 8.0 and 9.0.

TABLE 2. Sites on the Southern Rivers and Reservoirs That Were Sampled

River or Reservoir	Sampling Site
Cauvery	Grand Anicut
Godavari	Dowlaiswaram
North Pennar	Nellore
Tapti	Kathore
Ozat	Ozat weir
Kali Nadi	Dundeli
Zuari	Sanguem
Mandavi	Sonai
Reservoir sites	Tungabhadra (Mysore)
	Maithon (Damodar Valley Corporation)
	Panchet (Damodar Valley Corporation)
	Shetrunji (Gujarat)

For southern rivers the water is generally neutral to alkaline in reaction; the variation of *p*H in different months of the year is sufficiently wide. Water of the Godavari, North Pennar, Mandavi, Ozat, Tapti, and Kali Nadi rivers and the Panchet, Shetrunji, and Tungabhadra reservoirs is alkaline in reaction throughout the year. Water of Cauvery River and Maithon Reservoir is neutral to alkaline in reaction. Water of the Zuari River is acidic to alkaline in reaction.

Ionic composition. In all the northern rivers the predominant ions are calcium and bicarbonate. Next to these in decreasing order are the magnesium and sulfate ions. In the water of the Jamuna River the second place is occupied by sodium and chloride ions.

In most of the southern rivers the predominant ions are sodium and bicarbonate. In Maithon and Panchet reservoirs and Kali Nadi, calcium is the predominant cation instead of sodium. Next to sodium and bicarbonate in decreasing order are calcium and chloride except in Panchet Reservoir, where sulfate is the second predominant anion. Next in decreasing order are magnesium as cation and sulfate as anion.

SUITABILITY OF WATER FOR DIFFERENT PURPOSES

Irrigation. The suitability of water for irrigation is assessed from one or a combination of the six factors that follow: conductivity, content of soluble salts, nature of soil to be irrigated, drainage, type of crops, and climatic conditions. Electrical conductivity is one of the standard procedures for evaluating irrigation water for total dissolved solids. The U.S. Salinity Laboratory divides conductivity into six categories, and the quality rating of an irrigation water is determined from the sodium adsorption ratio and the conductivity.

According to the quality rating of irrigation water mentioned above, all the water of northern rivers falls in the C_1S_1 class (low salinity and low alkali hazard) or C_2S_1 class (moderate salinity and low alkali hazard). Water of the Beas, Chenab, Ganges at Hardwar, Sapt Kosi, Ajoy, Jaldhaka, Teesta, and Mahanadi rivers and the Sutlej and Rihand reservoirs remains in the C_1S_1 class throughout the year, whereas water of the Giri, Ganges at Farakka, Gumti, Banas, and Chambal rivers falls in the C_2S_1 class. Water of other rivers varies between C_1S_1 and C_2S_1 in different seasons of the year. Similarly, water of all the rivers in the southern region falls in the C_1S_1 or C_2S_1 class. Water of the Godavari, Mandavi, and Kali Nadi rivers and Maithon Reservoir remains in the C_1S_1 class throughout the year, and water of the North Pennar, Ozat, and Tapti rivers and Shetrunji Reservoir remains in the C_2S_1 class throughout the year. Water of the Zuari and Cauvery rivers and the Panchet and Tungabhadra reservoirs varies between C_1S_1 and C_2S_1 in different months of the year. In general, water of reservoirs and northern as well as southern rivers falls under the C_1S_1 and C_2S_1 classes and is considered suitable for irrigation for most of the soils and crops.

Drinking and domestic use. Water either low (total dissolved solids <150 ppm) or moderate (total dissolved solids 150–500 ppm) in mineral content is accepted for drinking and domestic use if it is also low in iron content, i.e., <1.5 ppm, and free from bacteriologic contamination and poisonous elements. As has been brought out in the test results, water of all the rivers except the Mahi (in the month of May) falls in low and moderate categories with respect to mineral content throughout the year. Also, water of all the rivers except Maithon and Panchet reservoirs is free of iron. Maithon and Panchet reservoirs have an iron content >1.5 ppm. This water should be treated suitably to stop bacteriologic contamination and to separate the undesirable suspended and insoluble matter before the water is used for drinking and cooking.

Industrial use. Soft water is more suitable for steam raising in boilers and for industrial use. Hard water forms an incrustation on the inner surface of boilers. This incrustation offers resistance to heat transfer. Also, hard water causes foaming and priming. Boilers using hard water will require frequent blowing down, and the water will also need treatment. Water quality requirements vary from industry to industry, and no generalization can be made regarding the suitability of water for industrial use. However, soft water is preferable in most of the industries.

The generally accepted classification of water with regard to hardness (in parts per million) is:

Soft	0–50
Moderately soft	50–100
Slightly hard	100–150
Moderately hard	150–200
Hard	200–300
Very hard	over 300

According to the classification above, water of the Beas, Ravi, Sapt Kosi, Ajoy, Jaldhaka, and Teesta rivers and the Bhakra and Rihand reservoirs falls in the soft to moderately soft categories and is not likely to create any serious problems for steam raising in boilers after minor treatment. There is a wide variation in the hardness of water of other rivers from month to month, and it changes from moderately soft to slightly hard and moderately hard. It may not be possible to use such water in boilers without treating the water intensively for demineralization and occasionally blowing down the boilers. Some of the water samples from the Jamuna, Ganges, and Gumti rivers fall in the category of hard water. Such water will require extra caution and intensive treatment for use in boilers.

Water of southern rivers, i.e., the Zuari, Mandavi, Kali Nadi, Godavari, and North Pennar rivers, and the Maithon, Panchet, Shetrunji, and Tungabhadra reservoirs falls in the soft and moderately soft categories and is considered suitable for use in boilers after minor treatment. However, there is a wide variation in the hardness of water of other southern rivers from month to month, and it changes from moderately soft to slightly hard and moderately hard.

Use in curing and preparing quality cement mortars and concrete. Excessive total dissolved solids and sulfate ions are considered objectionable in water to be used in the manufacture and curing of cement mortars and concrete. The river and reservoir water under consideration is either low or moderate in mineral content; i.e., the maximum concentration of total dissolved solids is 500 ppm in comparison with the permissible limit of 1000 ppm. Sulfate ions in the water samples are much lower than the permissible limit.

CONCLUSIONS

Analysis of the water of rivers and reservoirs shows that it varies in quality during different seasons and is also affected by industrial and town effluents. Its use for irrigation, drinking, and industrial purposes needs to be carefully considered, and adequate measures need to be taken against stream pollution.

There is very little variation in the water quality of major reservoirs like Bhakra and Rihand in different months of the year. For river water the concentration of dissolved solids is minimal in the monsoon months and maximal in the dry months. In the water of rivers such as the Jamuna and Ganges the concentration of salts increases in the lower reaches partly on account of dissolved salts from the soils and partly on account of disposal of sewage and industrial wastes into the rivers.

Acknowledgments. The authors are thankful to Shri S. K. Jain, Chairman, and Shri Y. K. Murti, member (Design and Research), Central Water and Power Commission, New Delhi, for their keen interest in the full exploitation of the water resources of this country for irrigation, drinking, domestic, and industrial uses and for encouragement in carrying out this work. The cooperation shown by the irrigation and power authorities of the various states in collecting water samples and dispatching them to the laboratory is also gratefully acknowledged. Data collected by the Central Water and Power Research Station, Poona, on the quality of southern rivers have been used in this paper, and due acknowledgment is made. The hard work of the staff of the Chemistry Division, Central Soil Mechanics Research Station, New Delhi, for the analysis of water samples is appreciated.

Limnological Basis for Modeling Reservoir Ecosystems

MILAN STRAŠKRABA

Hydrobiological Laboratory, Czechoslovak Academy of Sciences
Prague, Czechoslovakia

The aim of the study of reservoir ecosystems is to understand why particular conditions exist and why populations of organisms develop in a particular way. The term reservoir (i.e., impoundment or man-made lake) should be restricted to water bodies constructed by man. The importance of reservoirs for mankind and the fusion of practical and theoretical aspects during their study is obvious. To a theoretical limnologist the study of reservoir ecosystems offers a greater variety of conditions, the possibility of directed changes, and the organization of natural experiments. The scientific limnologist is led to accumulate more and more detailed data and to see the qualitative complexity of the structure of the ecosystem and the particularity of the examples studied. An engineer or applied limnologist is required to solve problems immediately by oversimplifying the quantitative expression of the behavior of the system and is looking for generality. The present degree of accumulation of data and abstraction of important relations and comparative bases on the one hand and the trend for both sufficiently accurate and widely applicable predictions on the other could induce the increasing convergence of the two approaches. If a common language is found, mutual understanding and use of results will grow.

ANALYSIS OF AQUATIC ECOSYSTEMS

The recent application of engineering techniques to the study of systems with complex interrelations also implies a close coöperation between limnologists and engineers in the use of mathematical language. Methods of systems analysis allow a limnologist to use the accumulated data for elucidating general trends, for quantitative comparisons, and for the quantitative interpretation of rather complex interactions. Results expressed as models are comprehensible to an engineer, and the limnologist is satisfied, since his results are being used immediately.

Figure 1 illustrates the stages of the analysis of aquatic ecosystems. The upper part of the flow diagram is the limnologist's participation; the bottom part is done on a computer with considerable participation by a mathematician. The trend is to understand at first the deterministic part of the relations. Obviously, the danger of obtaining false final results by neglecting at each step the evidently stochastic nature of the inputs could not be excluded.

The real aquatic ecosystem is divided into the water body and its surroundings, which include at least the surrounding landscape and atmosphere; in reservoirs the inflow and catchment area as well as the outflow and regulations by man are included. The first step of abstraction is the selection of adequate variables of the reality to be studied. Adequacy is the critical point, depending at this stage (verification being possible at the end of the procedure) on limnological experience and logical analysis of the objectives of the study. The goal of the next step of abstraction is to recognize and quantitatively formulate the main relations between variables measured by statistical techniques. The term limnological model is derived from economics literature [e.g., *Gál*, 1968; *Rychetnik*, 1968], where economics models precede the transfer into purely mathematical notation. Correspondingly, the limnological model should cover both the structure and the behavior of the system. Structure means the compartments of the model and their functional relations and feedbacks, in other words, the processes forming the skeleton of the system. Behavior means the quantitative expression of the input-output relations of the model.

O'Connor and Patten [1967] applied *Lewins*'

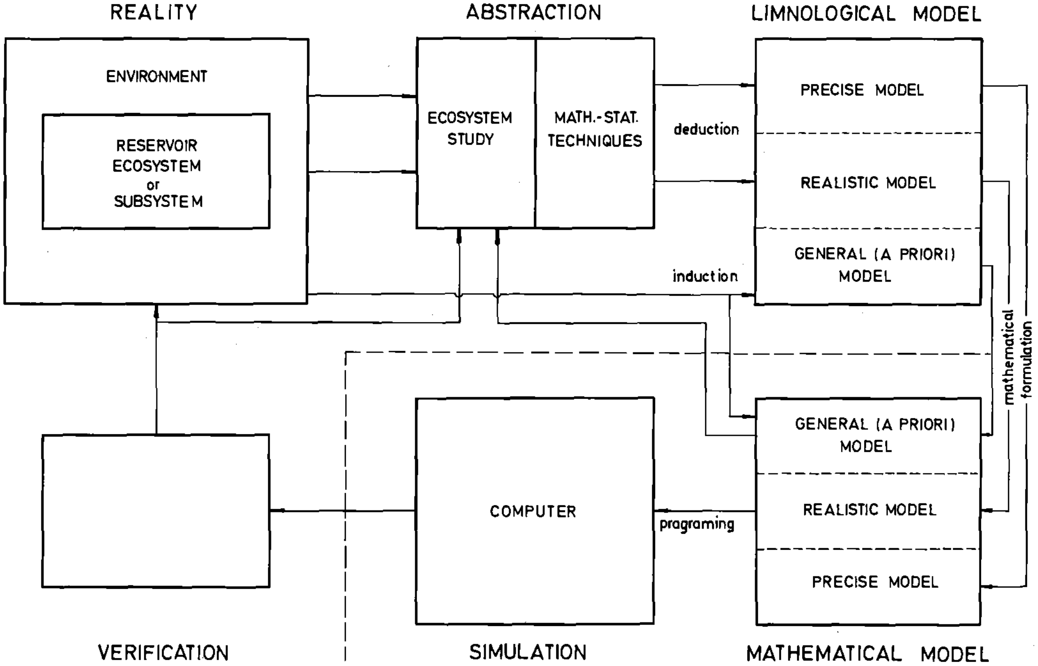


Fig. 1. Block diagram of the analysis of aquatic ecosystems.

[1966] classification of mathematical models to mathematical models of plankton productivity. Lewins' three types of models can be arranged according to decreasing information demand and increasing generality as follows: models sacrificing (1) generality to realism and precision, (2) precision to realism and generality, and (3) realism to generality and precision. (Lewins' types 1, 3, and 2 are called precise, realistic, and general a priori models below.) The philosophy of this classification stresses the incompleteness inherent in any model. The authors also stress the resulting usefulness of different kinds of models for different purposes.

In the application of the above gnostic classification to limnological models, precise models are those based largely on empirical deterministic relations between variables derived from detailed studies of single water bodies. They are optimally useful for numerical predictions of the reaction of the system and represent the obvious next step when quantitative limnological field data have been accumulated. How widely such a model can be applied for other conditions depends on how far the empirical relations (behavior of the model) reflect the mechanics involved (structure of the system).

The quantitative formulation of the realistic models is imprecise. In my opinion they are derived mainly from comparative investigations of water bodies. Many widely accepted limnological theories can easily be transferred into symbolic mathematical notation. The reality and also the degree of practical application of such theories as *Naumann*'s [1932] trophic concept, *Kolkwitz and Marsson*'s [1908] saproby, and others somewhat justify the failing attempts for numerical solutions, which are repeated with pigheadedness. The methodology of classical limnology was to run, by high abstraction, particular pathways through observations of many diversified water bodies. As a result classical models are unifactorial models of system behavior with no direct quantitative relation with the multifactorial nature or structure of the actual aquatic ecosystems. Until multifactorial models are designed, no hopes for adequate quantitative testing are justified.

General a priori models are based on simple mathematical formulas. They are either obtained directly by mathematical induction or induced from previous limnological observations of the ecosystems.

The classification of the three types according to gnoseology has drawbacks just as any classification does. For example, transitions between classes or models attributable to several classes are easily found. But more important, the three types can be considered historical steps toward achieving the maximum precision, optimum reality, and maximum generalization possible for the given purpose. According to the treatment of the mathematical plankton models by *O'Connor and Patten* [1967] the usual historical succession in this field has been from precise to general models. *Stumm and Stumm-Zollinger* [1968], *Szekielda* [1967, 1968], *Uhlmann* [1968], and *Vollenweider* [1969] followed in reverse the limits of validity of some general models to existing marine and freshwater ecosystems in attempts to obtain realistic models. Hypothetically, it should be possible to proceed from realistic structural models to precise models by considering the limiting conditions and multifactorial nature of the ecosystems. *O'Connor and Patten* [1967] stressed that realistic models have not been explored thoroughly in plankton ecology, and the same is true for reservoir limnology.

Perhaps, the gnoseology followed in this paper could be adequately classified as a progression from empirical studies of a few ecosystems and derived precise models toward attempts to distinguish the compatibility of the relations to comparative observations on several water bodies and derived realistic models. *Thomann* [1969] called for using all possible analytical techniques before proceeding to simulation. Surely, this deeply justified appeal deserves more than just being misused by the present author to cover his mathematical impotency.

APPLICATION TO RESERVOIRS

Before applying any limnological or oceanographic model (approach or method) to reservoirs, we should clarify the a priori limits of such a transfer because of the hydrologic differences between lakes and reservoirs.

In Figure 2, reservoirs from a geographically sufficient representative area for which data were easily available (the United States) are arranged in different size categories according to annual mean retention times (i.e., storage ratio or discharge-volume rate). Reservoirs with retention times >1 year, which are comparable to lakes in the sense of classical limnology, represent only ~20% of the reservoirs or ~40% of the large reservoirs (reservoirs $>1.000 \cdot 10^6$ m^3). The majority of reservoirs have retention times below this figure. Reservoirs with retention times <110 days represent almost one half of all reservoirs, and only in the large reservoirs do the figures drop to 20%.

Obviously, large modifications, if not other bases, will be necessary to cover reservoirs with shorter retention times. The search for an adequate basis is a major goal in this paper. Particularly helpful in this respect were the long-term data gathered during the Slapy Reservoir ecosystem study, made independently on the model approach. For the sake of brevity, direct data are mentioned here only in reviewing the basis for the models of reservoir ecosystems and subsystems and as reasons for the suggested additions.

The Slapy Reservoir is of medium size ($270 \cdot 10^6$ m^3), and the annual mean theoretical retention times ranged during the 10-year study from 24 to

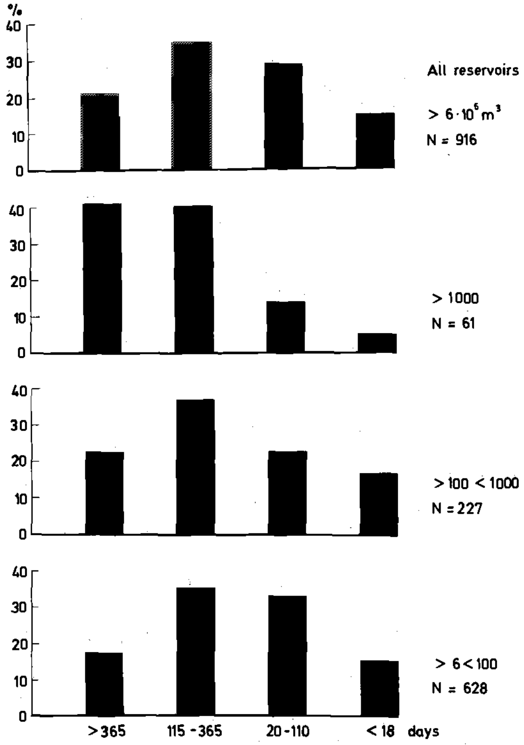


Fig. 2. Percent distribution of reservoirs in the United States with different size (in 10^6 m^3) according to the annual mean theoretical retention times in days based on data by *Martin and Hanson* [1966]. They set the lower size limit of a reservoir at about $6 \cdot 10^8$ m^3.

83 days (the mean being 38.5 days). Fifteen years ago Hrbáček designed intuitively a project of limnological study of reservoirs closely resembling the first steps of the present systems analysis. Two years of detailed hydrologic, physical limnological, chemical, microbiological, phytoplankton, zooplankton, and benthos studies [*Hrbáček and Straškraba,* 1966; *Hrbáček et al.,* 1966; *Hruška,* 1966, 1973; *Javornický et al.,* 1962; *Javornický,* 1966; *Straškraba and Hrbáček,* 1966] were conducted when a free river was flowing into the reservoir. During another 8-year study a similar reservoir (Orlík Reservoir with a volume of $720 \cdot 10^6$ m^3, observed retention times that ranged from 57 to 170 days, and a mean of 100 days) was operating close upstream. As a result the data for the Slapy Reservoir ecosystem are more suitable for systems analytical techniques than those for any other ecosystem in the country in which systems analysis originated. The method of distinguishing regular annual cycles and correlating their extremes was developed for evaluating relations between observed variables. The philosophy of this procedure is to avoid the drawbacks of a direct application of correlation and regression techniques to natural phenomena that result from the assumption that the independent variables are not randomly variable [*Eshett,* 1969; *Kozák,* 1968] and from complications with the seasonally changing correlation and regression coefficients (for temperatures see *McCombie* [1959] and *Moore* [1964]). An approximation of seasonal trends by harmonic analysis was preferred to the approximation by polynomials suggested by Eshett because of the direct usefulness of the modeling processes for deriving differential equations. Extreme values were interpreted as integrals of opposing processes for a particular preceding period. For extremes, correlation coefficients that were greater than correlations of all untreated data were obtained. High correlation coefficients are very useful for an adequate test of the hypotheses on the nature of relations and for predictions.

The structure of the Slapy Reservoir ecosystem as studied by a team of scientists [*Javornický and Komárková,* 1973; *Procházková et al.,* 1973; *Straškraba,* 1966, 1970; *Straškraba et al.,* 1973] is evident from Figure 3. Since the system is eutrophic, a few species are dominant, a characteristic that is favorable for study. Obviously, the part of the figure marked by a dotted line is relatively isolated from the rest and might be considered a subsystem and therefore be treated separately, but it must be understood to interpret the whole system.

SUBSYSTEM TEMPERATURE AND INTERNAL MIXING

The modeling of temperatures is of leading importance for the limnological modeling of reservoir ecosystems as a basic input affecting all chemical and biological processes and as a guide for proper physical structuring and a measure of mechanical transfer within the reservoir system. The two goals are achieved in present models by either the empirical sinusoidal approximation of the annual temperature cycle or the heat budget approach.

The approximation of temperatures by harmonic analysis is currently used as a basic input to hydrobiological models (*Davidson and Clymer* [1966] for the ocean, *Parker* [1968] for a reservoir, and *Karpov et al.* [1966], *Krogius et al.* [1969], and *Menshutkin and Umnov* [1970] for a lake). The application for air temperatures is included in mathematical textbooks [*Alger,* 1963]. *Ward* [1963] introduced the method to systematic studies of stream and reservoir temperatures. He showed high correlation coefficients of the observed values versus a simple sinusoidal curve calculated from monthly averages:

$$T = \bar{T} + a\,[\sin(x + b)] \qquad (1)$$

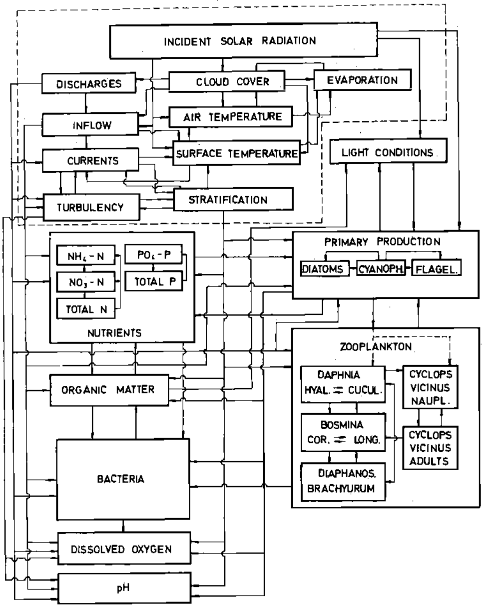


Fig. 3. Structure of the ecosystem of one particular eutrophic reservoir (Slapy Reservoir ecosystem) from *Straškraba* [1970].

where $\bar{T}$ is the annual mean temperature, a is the amplitude of the wave, x is the number of days from November 1 expressed in degrees, and b is the phase coefficient.

This simple curve holds for inflow temperatures and surface temperatures of reservoirs assumed to have no lateral heat transfer. For reasons shown below for reservoir and outflow temperatures the inclusion of the second harmonics is necessary for a proper approximation [*Straškraba and Javornický*, 1973]. No statistical techniques were used to test the significance of the higher harmonics, but no systematic effect was obtained by the inclusion of the third harmonics.

Evidently, the inclusion of much higher harmonics is necessary when daily cycles must be covered in addition to annual cycles. *Thomann* [1963, 1969] applied power spectrum analysis to water quality records in tidal streams. A source of references for the application of the technique to aquatic sciences is given by *Gunnerson* [1967].

Essentially, the approximation of temperature by harmonic analysis is included in oceanographic techniques (applied later for lake studies) for determining diffusion coefficients, these techniques being based on the time lag of temperature maximums in the deeper strata of a water mass [e.g., *Dutton and Bryson*, 1962, references]. For water bodies assumed to have no lateral heat transfer the depth distribution of temperature is given by

$$T = A_z e^{-2\pi(z/z_0)} \sin 2\pi \frac{t - (z/z_0)t_0}{t_0} \qquad (2)$$

where

A_z, diffusion coefficient;
z, depth of the surface;
z_0, depth of the bottom;
t, phase shift at depth z;
t_0, 365 days.

The approach based on energy transfer through a boundary between the atmosphere and the water can be applied accurately for prediction of highly turbulent water masses (such as streams and unstratified reservoirs). Recent methods of calculating different terms of the analytical heat budget equation from standard meteorological data and empirical equations are given by *Wright and Horrall* [1967] and, in Russian literature, *Nesina* [1967]. For the most recent oceanographic application, see *Seckel* [1970]. Important earlier reservoir applications are those by *Anderson* [1954], *Sauer and Anderson* [1956], *Raphael* [1962], and *Delay and Seaders* [1966].

Nielson [1967] pointed out that for application to stratified reservoirs present ideas should be expanded to include advective heat transfer by reservoir inflow and outflow. This line is followed under natural conditions by the Tennessee group [*Wunderlich and Elder*, 1968] and under laboratory conditions particularly by *Harleman and Huber* [1968] and *Brooks and Koh* [1968].

The basic assumptions of the graphic temperature model by *Wunderlich and Elder* [1968] are listed in the first column of Table 1. The assumptions reflect conditions in the prototype reservoir for this model, the Fontana Lake, which has a mean theoretical retention time of 150 days. The numerical model by *Orlob and Selna* [1968] is intended to be more widely applicable; nevertheless, most of the assumptions above are implied if not stated explicitly. The difficulties with understanding turbulent diffusion in reservoir conditions are avoided by using an effective diffusion coefficient obtained from field data on temperature profiles, discharges, and inflow temperatures. It will be shown elsewhere that diffusion coefficients are correlated with the mean depth in lakes. In a reservoir the complexity of currents, as shown in Figure 4, contributes to turbulent diffusion. In reservoirs with peaking operations, complicated daily changes in turbulence due to changes in currents have to be expected. A hydrodynamic solution of this complex situation is difficult if all these currents have to be included. Field observations suggest some guidelines to decide on the importance of particular currents.

Schräder [1958] showed in detail for reservoirs in Thüringer Wald that stratification conditions are affected by retention times. The same is implied in the empirical relations between the mean theoretical retention times and the annual mean difference of the reservoir inflow and outflow temperature derived by *Bratránek* [1953, 1961] from observations on Czechoslovak reservoirs.

Several years of relevant data on the temperature conditions of one reservoir (Slapy Reservoir) with annual mean theoretical retention times that varied in different years within broad limits were analyzed by *Straškraba et al.* [1973]. The data are particularly relevant to a quantitative study of the relations between retention times and thermics for two reasons. First, in part of the study period the reservoir was

TABLE 1. Comparison of the Main Assumption Used in the Temperature Model by *Wunderlich and Elder* [1968] and the Results of the Slapy Reservoir Ecosystem Study

Subject	Wunderlich and Elder Assumption	Slapy Reservoir Ecosystem Study	Evidence
Density of water	Dependent primarily on temperatures	Dependent primarily on temperatures	...
Thickness of the layer heated by solar energy	Constant (∿3 meters)	Function of retention time	Figure 6*d*
Heat transfer from the upper layer downward	Negligible	Important, function of retention time	Figure 6*b*
Temperature of the upper layer	Equilibrium temperature, approximation by analytical heat budget	Does not correspond to equilibrium temperature, cannot be approximated by analytical heat budget	Figure 8
Temperature of the inflow	Constant	Changing depending on the hydrologic differences between years	equation 3
Mixing of the inflow with reservoir water	No	Intensive, particularly in the backwater reach	...
Depth of the inflow stream jet	Constant, from year to year changing seasonally	Changing with retention time and seasonally	Figure 6*c*
Withdrawal layer	Limited by the upper and lower plane of intake	Changing with discharges and shape of intakes	*Smutek* [1955]
Water from the upper layer	Sinking gradually deeper	Sinking gradually deeper	...
Fall isotherms	Vertical lines from the surface to corresponding temperature levels	Vertical lines from the surface to corresponding temperature levels	...
Date of mixing	Constant	Function of retention time	...

fed by the bottom waters of a similar reservoir upstream. The effect of the discharges is given by summing up the influence of the two reservoirs. Second, the mixing of the inflow and reservoir water can be easily observed owing to the marked temperature difference between the cold inflow and the warm upper layers.

Figure 5 illustrates summer temperature profiles at comparable dates in successive years with different discharges. Evidently, when other factors are reduced to a minimum (the same reservoir with similar volumes of water), basic differences in both the absolute temperatures of different layers and the shape of temperature profiles occur. An analysis by the method of extremal correlations showed that the inflow temperatures (deepwater temperatures of the upstream reservoir slightly modified by a reregulation reservoir) are a function of the discharges. For illustration the April–July temperatures are

$$T_i(\mathrm{IV}-\mathrm{VII}) = -1.8 + 5.4 \log Q(\mathrm{IV}-\mathrm{VII}) \quad (3)$$

The annual course of air temperatures reflecting the heat budget of a water body when the lateral heat income is negligible correlates with the discharges (T_A, the maximum monthly mean, is equal to $22.8 - 3.32 \log Q(\mathrm{IV} - \mathrm{VII})$, $r = -0.776$; $T_A(\mathrm{I} - \mathrm{III}) = -11.6 + 5.74 \log Q(\mathrm{I} - \mathrm{III})$, $r = 0.980$). Rainy years have, on the average, much colder summers than sunny years, but cold winters are dry.

Figure 6 shows a few of the most critical correlations found between temperatures, stratification, and discharges. During the period when Slapy Reservoir is fed by the upstream reservoir, the maximum heat content of the reservoir (calculated on a birgean basis from temperature readings in the lower reach of the reservoir) (Figure 6*a*) increases less rapidly than the lateral heat inflow for the period of rising temperatures. The lateral heat inflow is calculated as a product of monthly mean discharges and inflow temperatures. (Birgean basis, distinct from forelian basis, is calculated per unit of volume below

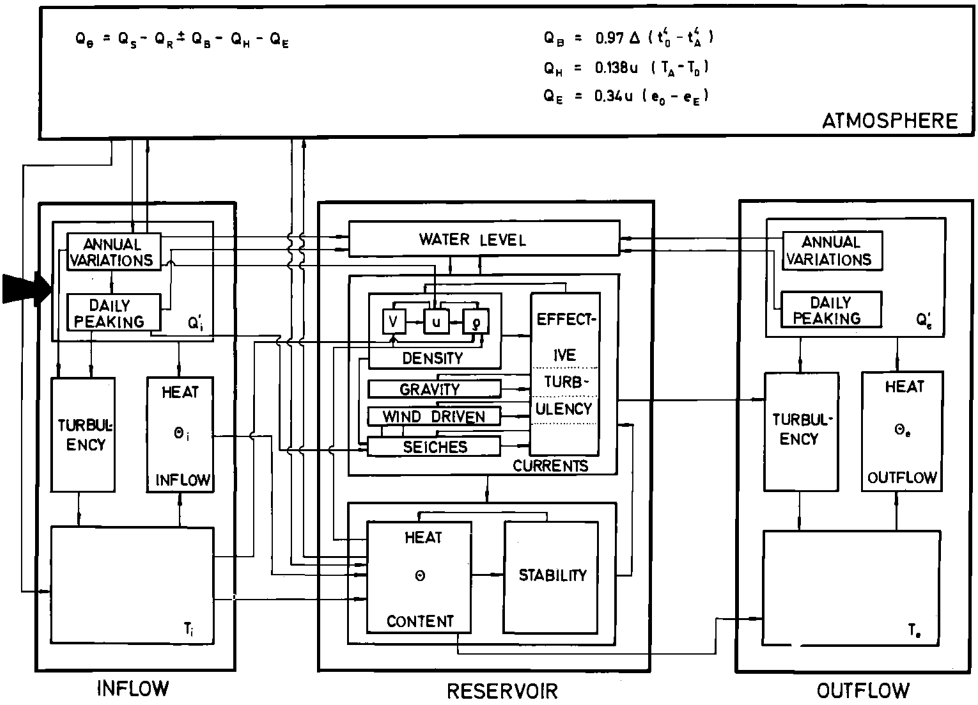


Fig. 4. Block diagram of the web of the thermal relations within a reservoir. The various currents in a reservoir are grouped in four main categories according to the driving force, seiches being separated because of mixed origin. Several characteristic currents can be named within the groups, e.g., among gravity currents the balancing currents in a particular depth from the dam upstream. Three main parameters of the currents to which the turbulence is related are indicated only for density currents (V being volume, u being velocity, and ρ being density). The analytical heat budget equation shows the heat transfer on the air-water interface. For details, see *Straškraba et al.* [1973].

unit of surface, i.e., corrected for layer volumes [see *Wright*, 1961].) A similar curve is obtained for deepwater temperatures that is decisive for the differences in the heat budget. The rising surface temperatures (Figure 6*b*) are a negative logarithmic function of the discharges for the period. The mean May–September depth of the theoretical inflow stream jet calculated simply as the depth of the reservoir corresponding to inflow temperature (Figure 6*c*) increases linearly from 12 meters at low discharges to 32 meters at high discharges. From May the depth of the theoretical stream jet increases progressively. The thickness of the well-mixed layer determined from late July or early August oxygen depth profiles (Figure 6*d*) increases linearly from 3 to 5 meters as mean summer discharges increase.

Regressions similar to those shown in Figure 6 are the basis for the idea of simultaneous stepwise changes of all the basic parameters of stratification when retention times are different. To il-

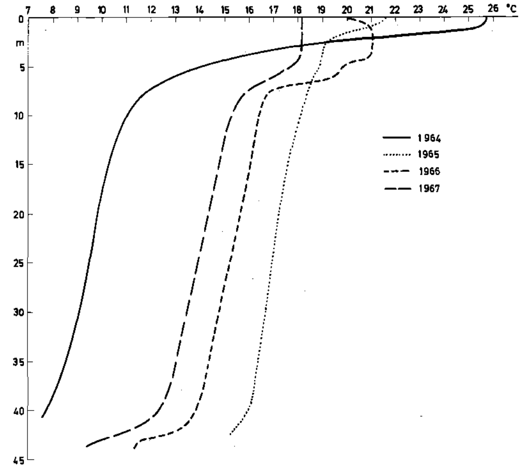


Fig. 5. Comparable summer plots of temperature against depth in Slapy Reservoir in successive years from thermistor readings.

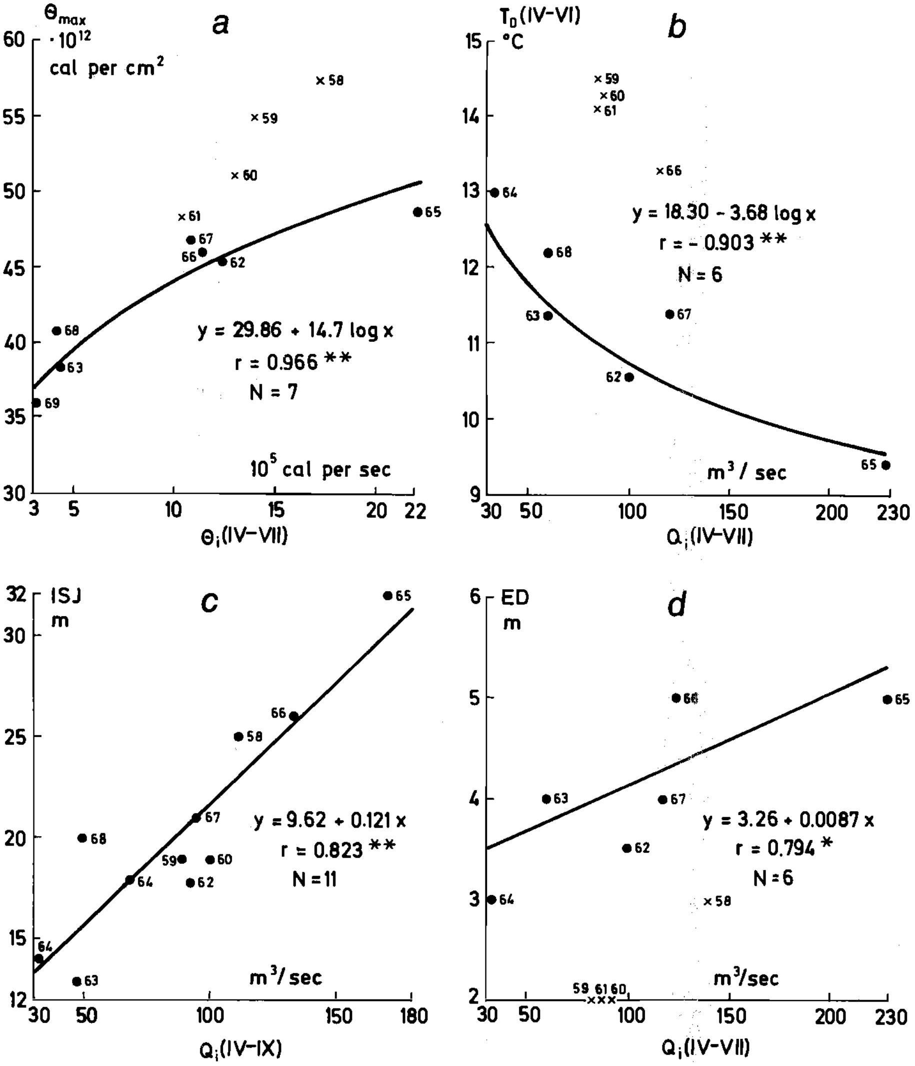


Fig. 6. Correlations between temperatures, stratification, and discharges in different years in Slapy Reservoir. (*a*) Maximum heat content (birgean basis) plotted against mean heat inflow for April–July. (*b*) Mean surface temperatures for April–June correlated with discharges for the period. (*c*) Depth of the mean theoretical inflow stream jet for May–September plotted against discharges for the period. (*d*) Thickness of the epilimnion in July–August plotted against discharges for April–July. Numbers at points indicate years. Crosses denote years not included in the regressions, particularly those before the upstream reservoir operated. This figure is modified from *Straškraba et al.* [1973].

lustrate simply this complex web of cause and effect pathways, highly schematized drawings generalizing the summer conditions during 3 selected years with mean theoretical retention times for the period when stratification develops (April–July) of about 15, 30, and 90 days are shown in Figure 7. The result of dynamic seasonal changes during such conditions is reflected in the different annual courses of temperatures approximated by harmonic analysis for two critical depths (surface and intake level) in Figure 8. In addition to the lower surface level and higher intake level temperatures in July at lower retention times (Figure 7), note the slower rise and retarded peak of the surface temperatures during low retention times. In deeper layers the peak is advanced, and temperatures are increased, much earlier autumnal homothermy resulting during low retention times. Winter temperatures are also highly different: the inversion evident during dry years results in the freezing of the reservoir surface, whereas in wet years water is almost homothermous below 2°C with no ice cover.

In a series of reservoirs such as that studied here this situation is striking and is easily analyzable. To a reduced extent it is valid for a solitary reservoir too. The relations shown between reservoir temperatures and discharges, particularly the negative logarithmic relations to deepwater temperatures, suggest a justification for devoting the early steps of reservoir hydrodynamics modeling to density currents as the most probable adequate approximation [*Smutek*, 1955; *Debler*, 1959; *Otsuboto and Fukushima*, 1959; *Levi*, 1959; *Jaske and Snyder*, 1967].

The findings above result in basic changes of the assumptions useful for a model of stratification conditions of reservoirs below some critical

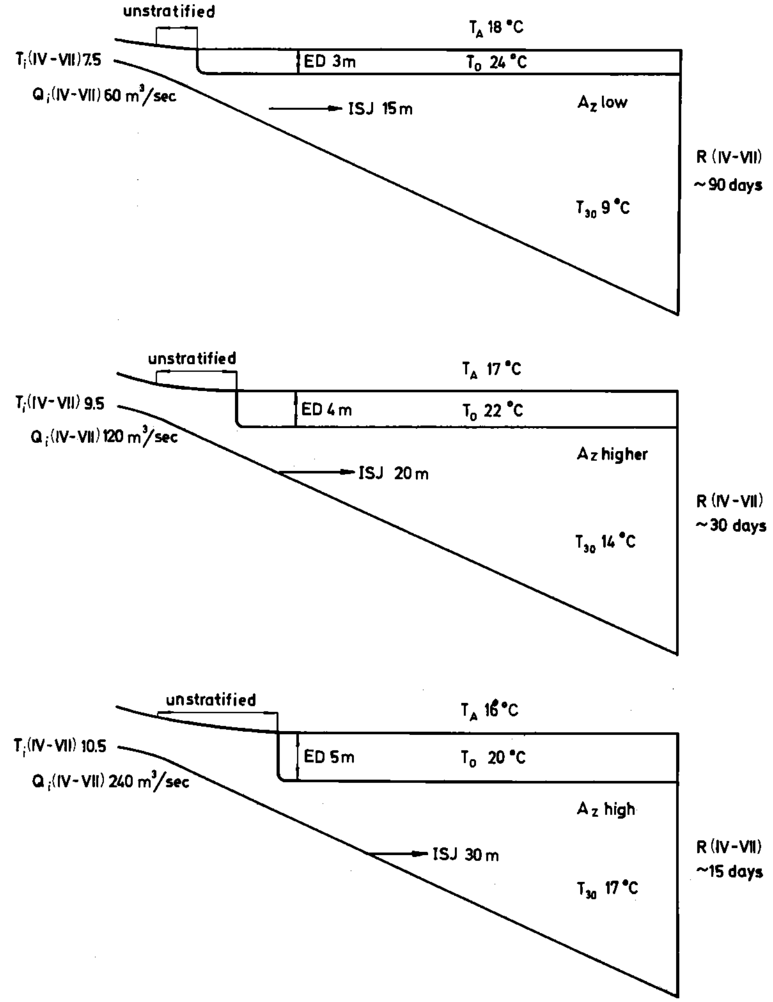


Fig. 7. Schematic representation of the summer stratification conditions in Slapy Reservoir during dry, medium, and wet years. The April-July mean temperature of the inflow is T_i (IV − VII); the mean July (August) temperatures of the air, surface level, and intake level are T_A, T_0, and T_{30}; the mean April-July discharge into the reservoir is Q_i(IV − VII); the depth of the epilimnion is *ED*; the May-September mean theoretical inflow stream jet (depth of the reservoir corresponding to the inflow temperature) is *ISJ*; and the coefficient of effective turbulence is A_z.

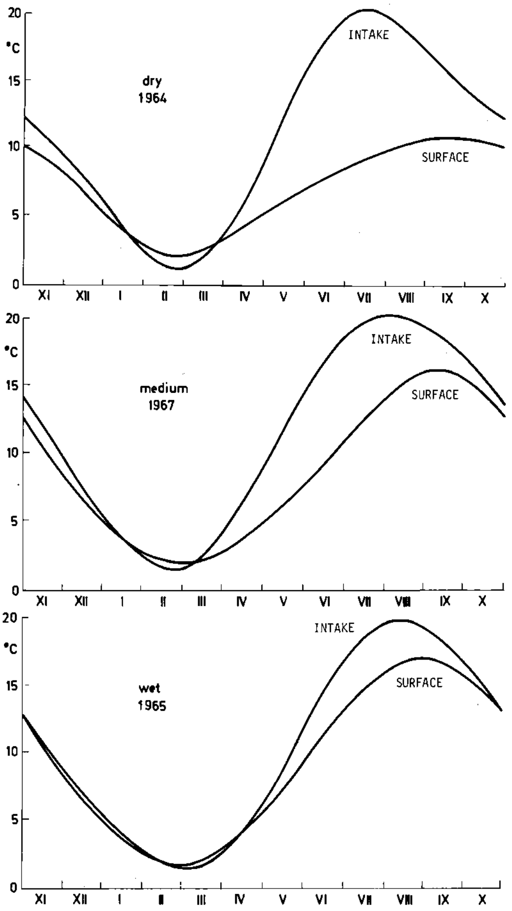


Fig. 8. Sinusoidal annual temperature curves for the surface level and intake level in Slapy Reservoir during a dry, medium, and wet year from November to October.

mean theoretical retention time. From present evidence the critical retention time will be somewhere <1 year, but the exact value has to be clarified. In the shortest possible way the assumptions are listed in the last column of Table 1. The suggestion of the corresponding physical structure of a temperate deep reservoir model is given in Figure 9. (An adequate classification of deep and shallow reservoirs will be $D < H$ and $D > H$, where D is the effective depth of mixing and H is the total depth. An empirical relation for D in a particular region, the Baltic lowland in northern Poland, was developed by *Patalas* [1968].) Figure 9*b* is the most general model, Figure 9*a* represents its derivative by $\lim_{\to 0}$ the backwater stretch, and Figure 9*c* represents its derivative by $\lim_{\to 0}$ the lower stretch. Several intermediate stages are possible.

Summarizing, I would like to stress that reservoirs are much more plastic systems than lakes. The direct unmodified application of deep-sea approaches via classical closed lake limnology is, to speak mildly, not adequate. The justification of speaking about epilimnion, hypolimnion, thermocline, stagnation, circulation, and heat budget, as defined, for example, in *Hutchinson* [1957], decreases to 0 when a change is made from stagnant reservoirs to those with shorter retention times [*Hrbáček and Straškraba*, 1966]. In using these terms, we must at least keep in mind their different nature or perhaps redefine them later on. An easy but far from optimal solution would be to create a new reservoir nomenclature.

Retention time appears to be a key for understanding reservoir limnology.

BASE FOR AN OXYGEN MODEL

According to a recent treatment [*O'Connor and DiToro*, 1968], models of the oxygen conditions

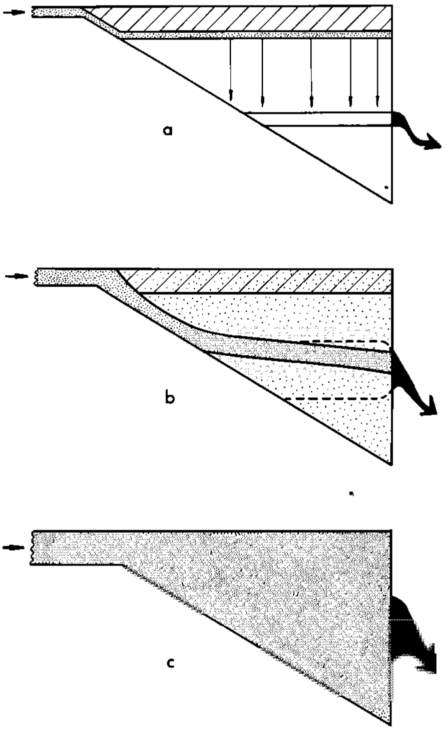


Fig. 9. One-dimensional idealization of the physical structure of hypothesized deep temperate reservoirs with different retention times.

in flowing waters are based on the Streeter and Phelps application of the equation of continuity or mass balance. Although the equations are appealing in their simplicity, numerous physical and biological processes severely limit their practical usefulness [*Frankel and Hansen*, 1968].

To reconsider briefly the applicability of this approach to reservoirs, two aspects are separated: (1) the hydrologic aspect, representing not only the distribution within the water body but also one major source (or sink) of oxygen that is exchanged with the atmosphere, and (2) the biological (biochemical) aspect, including the associated physical processes.

For shallow unstratified streams, classical objects of the engineering approach, the solution of the exchange rates with the atmosphere (in the absence of supersaturation equal to reaeration rates) is relatively well known [*Owens et al.*, 1964; *Thackston and Krenkel*, 1969]. The first application for deep unstratified slowly flowing rivers is of relatively recent date [*O'Connor and Dobbins*, 1956]. In a historical sequence to very slowly moving water masses, *Owens et al.* [1964] and *Znamenskii* [1965] suggested that the same approach should be applicable for stratified conditions, the depth of the thermocline being used instead of total depth for calculations of the reaeration coefficient. Calculations on this basis were made by *O'Connel and Thomas* [1965]. The difficulties with applying empirical hydrologic equations to reservoirs were stressed by *Kittrell* [1959]. *Nielson* [1967] suggested the derivation of the reaeration coefficient from hydrologic parameters in terms describing reservoir conditions by substituting the usual parameters of wind speed for flow velocity and effective mixing depth for total depth. No proof of the applicability is known to me, and I see a major drawback in the functional relation between wind speed and effective mixing depth in reservoirs and also in the additional effect of currents, as discussed previously.

The biological aspect was fairly simple in the original Streeter and Phelps model in connection with considering polluted streams as diluted sewage. Only the temperature-dependent oxygen consumption by bacteria was included, and the corresponding equation read

$$L_t = L_0 \cdot \exp(-kt) \qquad (4)$$

in the integrated form, where L_t was the concentration of biochemical oxygen demand (BOD) at time t, L_0 was the same at the beginning, and k was the depletion coefficient. Development of the concept resulted from independent limnological studies on clean waters [e.g., *Odum*, 1956]. The participation of the other members of the community metabolism was quantified. Systematic long-term studies on the biological sources and sinks of oxygen in streams were made by a group of English applied limnologists (summarized by *Owens et al.* [1964, 1969]). Recently, the list of important oxygen sources and sinks increased to 13 items [*Frankel and Hansen*, 1968], which can be grouped as listed in the appendix.

Evaluating oxygen conditions in particular reservoirs was attempted from two sides, a limnological side [*Wright*, 1961; *Parker*, 1968] and an engineering one [*Symons et al.*, 1967; *Wunderlich and Elder*, 1968]. The professions of Wright and Wunderlich and Elder clearly dictated the models used, but I see no professional or reservoir-bound reason why the first author should neglect advection and the second author should neglect turbulence. Nevertheless, according to the authors' reports, both models resulted in satisfactory agreement between measured and calculated values. *Wright*'s [1961, 1967] purpose was to obtain a measure of the phytoplankton oxygen production independent of the light and dark bottle technique for Canyon Ferry Lake (R = ~220 days). Therefore the very simplified model

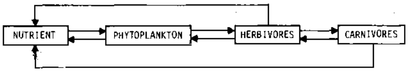
$$(dO_2/dt) = A_z(dO_2/dz) + R \qquad (5)$$

from *Hutchinson* [1957] was evaluated numerically, where A_z was the coefficient of vertical eddy diffusivity and R was the biological rate of change. The difference between the calculated and the observed rate of change in oxygen concentrations in deeper strata was assumed to be counterbalanced by diffusion from the equivalent oxygen production of the euphotic zone.

Wunderlich and Elder [1968] assumed during the first evaluation of the oxygen model for deeper strata of Fontana Lake (R = 150 days) that vertical eddy diffusion was negligible. The exponential decay law (4) was applied to changes in dissolved oxygen (DO). The organic loading of the advected water mass was neglected. Basically different depletion coefficients at similar temperatures were noted for waters of different nutrient contents.

The need to include phytoplankton photosynthesis and respiration as major oxygen sources and sinks is generally recognized in engineering studies of reservoirs [e.g., *Krenkel et al.*, 1968] and does not need to be explained here. The *O'Connel and Thomas* [1965] model used by *Symons et al.* [1967] is intended to cover the euphotic zone of a water body, where sedimentation is negligible. In addition to terms for reaeration and the exponential decay law for the DO deficit, symbolic terms covering phytoplankton photosynthesis and respiration in general were included.

More sophisticated models of the phytoplankton changes with time relevant to DO and water quality changes in reservoirs are those derived from marine observations as reviewed by *Patten* [1968]. All actually bear traces of the ingenuity of Riley (particularly *Riley et al.* [1949]), who in 1946 included the principles of feedback before it was generally recognized in cybernetics:



The qualitative formulation of the models includes, following *Patten* [1968]: $dB/dt = [f_1$ (influx of producer biomass) $+ f_2$ (photosynthesis) $+ f_3$ (influx of higher trophic level biomass) $+ f_4$ (autotrophic and heterotrophic growth)] $- [f_5$ (respiration) $+ f_6$ (grazing) $+ f_7$ (efflux of biomass from all trophic levels)].

Terms f_1 and f_7 are equivalent to the hydrologic term for redistribution of mass within the water body in the appendix. Active migrations of phytoplankters are neglected. Term f_4 is covered in essence in the engineering models by the exponential decay law. In connection with a low organic matter content this term is grossly neglected in marine studies and limnological models. Phytoplankton photosynthesis (f_2) is assumed to depend on one limiting nutrient, light, temperature, and algal standing crop, and these are included in the models. *Nielson* [1967] suggested that for application to reservoirs this relation be modeled by a statistical empirical equation similar to that applied for estuaries and rivers by *Bailey* [1967]. In generalized notation this can be written as

$$dP/dt = (k_1 I k_2 N k_3 T)B \qquad (6)$$

where I is the light intensity, N is the critical nutrient, T is the temperature, and k_i are the empirically derived coefficients.

Parker [1968] simulated phytoplankton photosynthesis in the epilimnion of Kootenay Lake, a reservoir on the U.S.-Canadian border ($R = \sim 150$ days). In addition to terms f_2, f_5, and f_7 above the population of the major zooplankton consumer was included. Limnological observations and experiments [e.g., *Hrbáček et al.*, 1961] demonstrated a high feedback from the fish population structure to zooplankton and phytoplankton metabolism via species composition. *Hrbáček* [1965, 1969] demonstrated the direct relevancy of the fish population structure to the DO content of standing waters.

The review above of the application of both the engineering models and the limnological models to reservoirs shows that no verification of the basic assumptions is obtained. Progress in this respect is to be expected from advanced field studies.

The main factors of oxygen variations have been analyzed by the method of extremal correlations and regressions during the Slapy Reservoir ecosystem study. Two aspects were followed: the regular annual variations and the relation of these variations to changes in retention times (discharges). Figure 10 represents the mean of several years of DO variations at the surface and intake levels based on moving averages [*Straškraba et al.*, 1973]. The peaks and drops indicated in the figure occur every year, but the numerical values are different. Similar shapes were obtained for other Czechoslovak reservoirs, and evidence from several published records suggests that trinodal curves are widely distributed.

Application of a similar technique to data by *Procházková et al.* [1973] revealed regular annual cycles for variables presumably related to DO variations (Figure 10). Secchi disk transparency reflects the light conditions. Gross phytoplankton production expressed in grams of DO produced below a unit of surface was obtained directly from oxygen readings in suspended light and dark bottles. The values closest to natural bacterial respiration rates are considered to be those obtained in filtered water during 24 hours under reservoir temperatures. Phosphate phosphorus was recognized as the major limiting nutrient for phytoplankton production (nitrogen limitation being recognized at times). The validity of zooplankton respiration

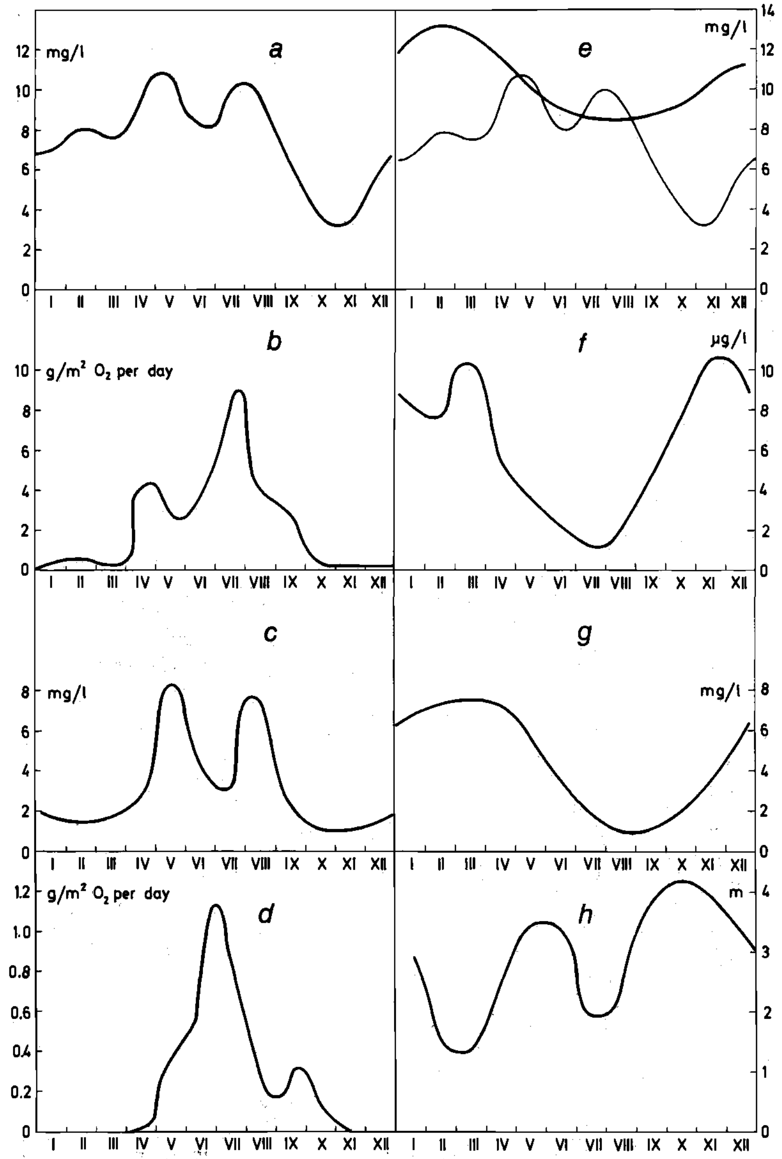
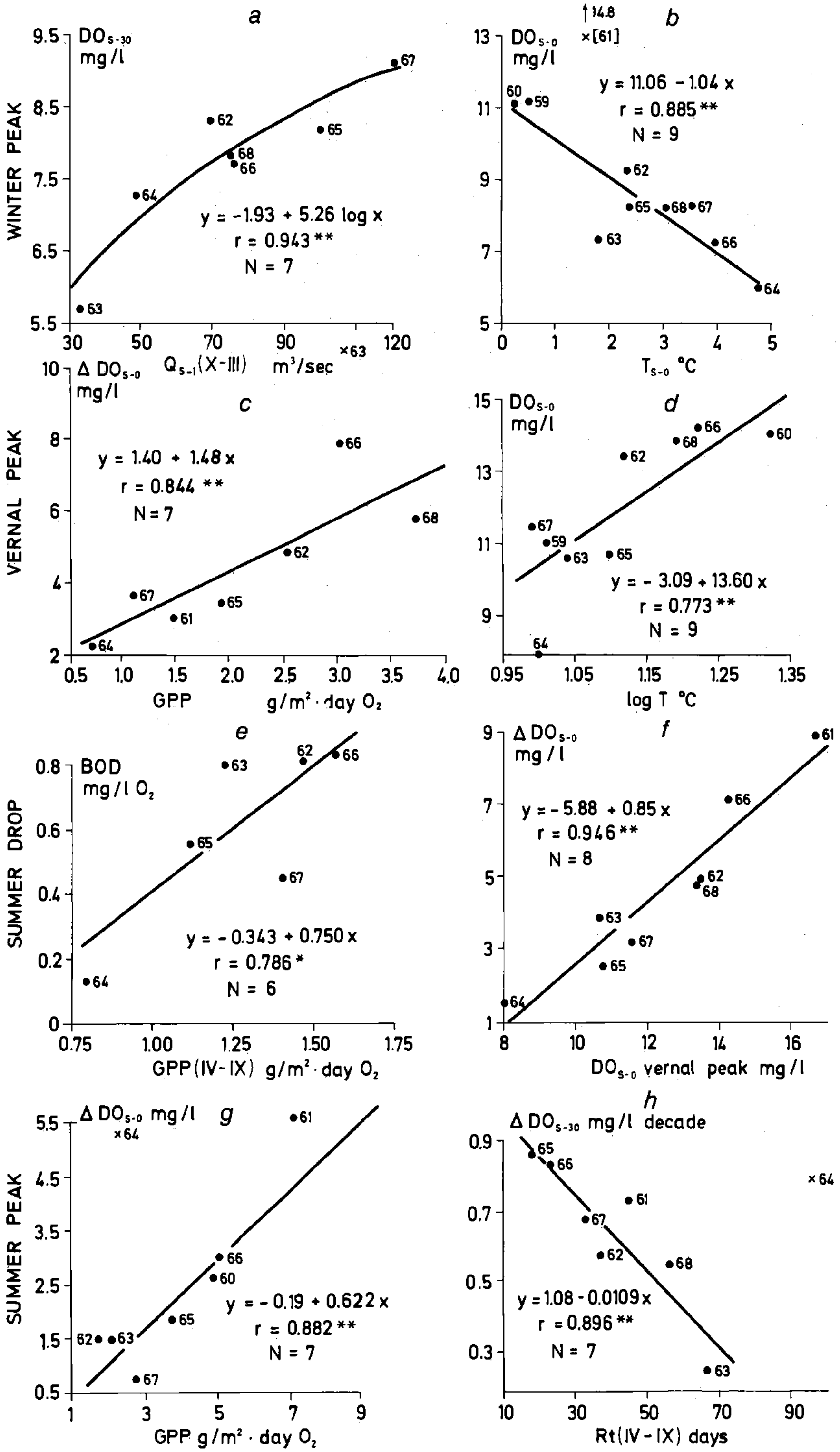


Fig. 10. Mean seasonal cycles of DO and related variables in Slapy Reservoir from January to December 1962 to 1968: (*a*) DO concentration at the surface, (*b*) gross phytoplankton production, (*c*) BOD_1 at the surface temperature, (*d*) total zooplankton respiration during 1963 modified from *Straškraba* [1966], (*e*) saturation value of the DO at the surface, the thin line repeating Figure 10*a* for direct comparison with the figures below, (*f*) phosphate phosphorus concentration at the surface, (*g*) DO concentration at the intake level, and (*h*) transparency during 1967.

values is not comparable with that of the other curves, since the values are based on 1-year data [*Straškraba*, 1966]. Indirect evidence from regular filtrator and predator standing crop data indicates that the order of magnitude but not the shape is representative.

A direct inspection of the curves suggests that several possible interrelations between the phenomena have to be examined. The winter oxygen peak coincides with the highest saturation value, and the vernal and summer oxygen peaks coincide with pulses of phytoplankton produc-


a
WINTER PEAK
DOs-30 mg/l
y = -1.93 + 5.26 log x
r = 0.943 **
N = 7
Qs-1(X-III) m³/sec
×63
b
↑14.8 ×[61]
DOs-0 mg/l
y = 11.06 - 1.04 x
r = 0.885 **
N = 9
Ts-0 °C
c
VERNAL PEAK
Δ DOs-0 mg/l
y = 1.40 + 1.48 x
r = 0.844 **
N = 7
GPP g/m² · day O₂
d
DOs-0 mg/l
y = - 3.09 + 13.60 x
r = 0.773 **
N = 9
log T °C
e
SUMMER DROP
BOD mg/l O₂
y = - 0.343 + 0.750 x
r = 0.786 *
N = 6
GPP (IV-IX) g/m² · day O₂
f
Δ DOs-0 mg/l
y = -5.88 + 0.85 x
r = 0.946 **
N = 8
DOs-0 vernal peak mg/l
g
SUMMER PEAK
Δ DOs-0 mg/l
×64
y = - 0.19 + 0.622 x
r = 0.882 **
N = 7
GPP g/m² · day O₂
h
Δ DOs-30 mg/l decade
×64
y = 1.08 - 0.0109 x
r = 0.896 **
N = 7
Rt(IV-IX) days

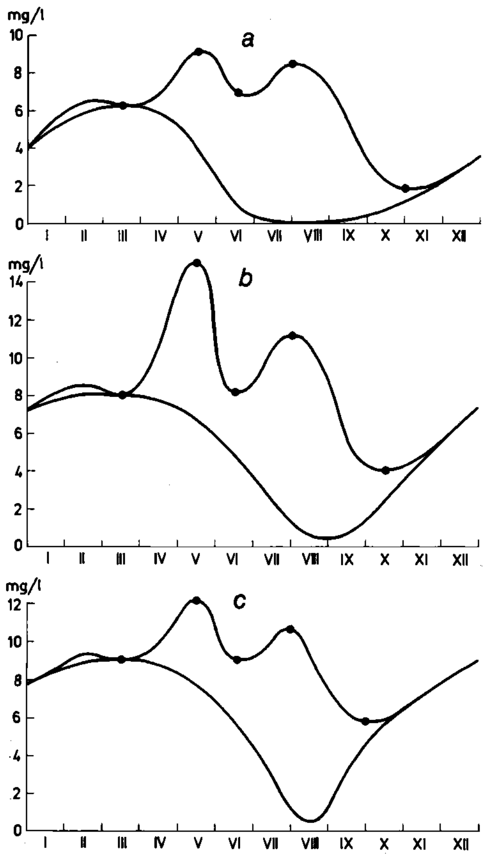


Fig. 12. Graphic simulation of the surface (trinodal) and intake level (uninodal) DO curves for Slapy Reservoir from January to December: (*a*) conditions during a dry year, the April–July mean theoretical retention time being about 90 days, (*b*) conditions during a medium year, the April–July mean theoretical retention time being about 30 days, and (*c*) conditions during a wet year, the April–July mean theoretical retention time being about 15 days.

tion. The BOD variations follow the two peaks of photosynthesis, both being seasonally slightly postponed. The shift is in the intervals between samplings and hence is affected by considerable bias but is nevertheless significant. The relation of these peaks to the decomposition of organic matter produced during photosynthesis is suggested. The maximum amount of phosphate phosphorus occurs in the period of no photosynthetic activity and at the winter oxygen peak. Not only is the minimum amount of phosphate phosphorus coincident with the summer phytoplankton pulse, but a break in the rate of uptake is observed during the spring phytoplankton peak. The maximum amount of zooplankton respiration coincides with a drop in phytoplankton. The summer minimum of transparency coincides with the phytoplankton pulse.

Results of an analysis of some of the suggested relations are summarized in Figure 11 (for a description, see *Straškraba et al.* [1973]). The idealized surface and intake level DO curves resulting from the approach above for retentions of about 15, 30, and 90 days (identical with those characterized in Figures 7 and 8) are shown in Figure 12. The surface dots are derived from regressions in Figure 11, and the curve is a graphic simulation of the mean shape derived in Figure 10.

CONCLUSIONS

Coupling the review of the existing models to suggestions resulting from the Slapy Reservoir ecosystem study, I must first stress that engineering and limnological approaches can be considered supplementary in many respects. In reser-

---

Fig. 11. Extremal correlations for DO and related variables in Slapy Reservoir. (*a*) The DO concentration during the winter peak at intake level plotted against the mean discharges from the previous October to March. (*b*) The DO concentration during the winter peak at the surface plotted against the surface temperature at the time of the peak; 61 is not included in the calculations owing to the exceptionally high amount of DO connected with filling the upstream reservoir. (*c*) The DO increase from vernal drop to vernal peak plotted against the gross phytoplankton production below a unit of surface; 63 is not included in the calculations. (*d*) The surface DO content during the vernal peak plotted against the log temperature at the surface during the vernal peak. (*e*) The April–September mean BOD (1 day at the reservoir surface temperature) plotted against the mean gross primary production for the same period (modified from *Procházková et al.* [1973]). (*f*) The surface DO decrease from vernal peak to summer drop plotted against the surface DO concentration during the vernal peak. (*g*) The surface DO increase from summer drop to summer peak plotted against the gross primary production; 64 is not included in the calculations owing to the exceptionally high surface concentration connected with the extremely shallow epilimnion. (*h*) The rate of DO decrease from the April value to a concentration of 1 mg/l at the intake level plotted against the mean April–September theoretical retention times; 64 is not included in the calculations. This figure is modified from *Straškraba et al.* [1973] unless another source is stated.

voirs, physical processes and decomposition of organic matter are coupled with phytoplankton production and its use.

For a proper application of models from other environments and as a base for reservoir ecosystem models the following should be considered.

1. The proper physical structuring of the reservoir model (discussed in the section on temperature) is important. Changes in DO associated with the backwater reaches of reservoirs were discussed particularly by *Krenkel et al.* [1968]. The proportion of oxygen transferred advectively increases greatly as retention times decrease, but turbulent transfer also increases.

2. Parameters of the models for reservoirs are shown to vary as a function of retention times. The biological changes associated with the direct physical effects show the dependence of the variables on retention times.

3. The understanding of the relation of phytoplankton photosynthesis and respiration to nutrients, light, and temperature is necessary not only because phytoplankton photosynthesis and respiration are important sources and sinks of oxygen but also because, in addition to organic matter advected, phytoplankton production is an additional important source. The organic matter produced in this way is immediately decomposed.

4. Historically, the evidence for significant feedback between variables of the ecosystem increases. In addition to the feedbacks recognized earlier and those implicit in (2) and (3), at least two highly important ones should be included. Not only is zooplankton respiration at times an important DO sink, but also the consumption of phytoplankton may at times exceed its production. Carnivores and zooplankton induce considerable changes in the phytoplankton composition and associated production and respiration rates. Surprisingly, the high feedback mechanism is not obvious per se, nor is it obvious in all the recent oceanographic models (as shown by *Patten* [1968]) or in all the recent limnological models (cf. the Lake Dalneye ecosystem model [*Karpov et al.*, 1966; *Krogius et al.*, 1969; *Menshutkin and Umnov*, 1970]).

5. Regular seasonal changes of limnological variables are recognized in reservoirs. Inclusion of the seasonality in the models increases their precision highly. The approximation of seasonal curves by harmonic analysis points to the differentiation of variables by time. Before a full understanding of the cyclicity for all variables is obtained, the approximated curves can be used as input for the predictive models. Extreme periods of peaks and drops result from a domination of one particular process. The values reached can be interpreted as integrals of the processes for the periods between successive extremes. Thus the phase shift of the corresponding extremes of interrelated variables can be included in the analysis.

6. In the present models the effect on the processes indicative of water quality changes of associations other than planktonic is neglected. Speculatively, the effect of the mud-water interface and associated organisms should be higher in reservoirs than in lakes in connection with the increased turbulence. This effect cannot be neglected, particularly in the backwater reaches, which have increased sedimentation rates. The effect of increased contact phenomena due to ebullition of gases from bottom sediments should be considered. No estimate is available about the participation of production and use by organisms on solid surfaces of the reservoir slopes. Macrophytes can usually be considered absent in deep temperate usually fluctuating reservoirs, but under certain circumstances this assumption may not be valid.

APPENDIX: LIST OF PROCESSES CONSIDERED IN RECENT MODELS FOR DO CHANGES IN RIVERS

I. Hydrologic processes
    A. Reaeration
        1. Turbulent mixing
        2. Effect of suspended and dissolved matter
    B. Distribution within the rivers
        1. Turbulent mixing
        2. Longitudinal dispersion
        3. Effect of channel configuration, weirs, and so on
    C. Local runoff
II. Biochemical processes: Decomposition of organic matter (variability of k_1 during nitrification stage)
III. Higher biocenosis processes
    A. Phytoplankton
        1. Photosynthesis
        2. Respiration
    B. Macrophyta
        1. Photosynthesis
        2. Respiration
    C. Benthos (respiration)

IV. Sediment processes
  A. Sedimentation of organic matter
  B. Adsorption of organic matter by sediments
  C. Resuspension of deposits
  D. Diffusion of oxygen into sediments
  E. Diffusion of oxygen from sediments
  F. Purging action of gases rising from bottom

Considered are daily variations of flow, temperature, BOD, photosynthesis, and respiration.

REFERENCES

Alger, P. L., *Mathematics for Science and Engineering*, McGraw-Hill, New York, 1963.

Anderson, E. R., Energy budget studies in water loss investigations, Lake Hefner Studies, *U.S. Geol. Surv. Prof. Pap., 269*, 1-158, 1954.

Bailey, T. E., Measurement and detection of eutrophication, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng., 93*, 121-132, 1967.

Bratránek, A., Vliv tepelného režimu vody v nádržích na změnu teploty vytékající vody (English summary), *Vod. Hospod., 3*, 350-357, 1953.

Bratránek, A., The course ot temperature in rivers and its changes by the water management (in Czech with English summary), *VÚV Práce a Studie, 101*, 1-97, 1961.

Brooks, N. H., and R. C. Y. Koh, Selective withdrawal from density-stratified reservoirs, Proceedings of Special Conference on Effects of Reservoirs on Water Quality, *Tech. Rep. 17*, pp. 169-214, Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Davidson, R. S., and A. B. Clymer, The desirability and applicability of simulating ecosystems, *Ann. N. Y. Acad. Sci., 128*, 790-794, 1966.

Debler, W. R., Stratified flow into a line sink, *J. Mech. Eng. Div. Amer. Soc. Civil Eng., 85*, 50-65, 1959.

Delay, W. H., and J. Seaders, Predicting temperatures in rivers and reservoirs, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng., 92*, 115-135, 1966.

Dutton, J. A., and R. A. Bryson, Heat flux in Lake Mendota, *Limnol. Oceanogr., 7*, 80-97, 1962.

Eshett, A., An analytical tool for a statistical model, *Verh. Int. Ver. Limnol., 17*, 497-501, 1969.

Frankel, R. J., and W. W. Hansen, Biological and physical responses in a freshwater dissolved oxygen model, in *Advances in Water Quality Improvement, Water Resources Symposium*, vol. 1, edited by E. F. Gloyna and W. W. Eckenfelder, pp. 126-140, University of Texas Press, Austin, 1968.

Gál, T., *Úvod do Lineárního Programování (Introduction to Linear Programming)*, pp. 5-12, Státní Zemědělské Nakladatelství, Prague, 1968.

Gunnerson, C. G., Optimizing sampling intervals, in *Water and Air Resource Management*, pp. 115-140, IBM Data Processing Division, White Plains, N.Y., 1967.

Harleman, D. R. F., and W. C. Huber, Laboratory studies on thermal stratification in reservoirs, Proceedings of Special Conference on Effects of Reservoirs on Water Quality, *Tech. Rep. 17*, pp. 73-95, Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Hrbáček, J., Beziehungen zwischen Nährstoffgehalt, Organismenproduktion und Wasserqualität in Talsperren, *Wiss. Z. Karl Marx Univ. Leipzig, 14*, 265-273, 1965.

Hrbáček, J., Relation of productivity phenomena to the water quality criteria in ponds and reservoirs, in *Advances in Water Pollution Research, Proceedings 4th International Conference*, pp. 717-724, Pergamon, New York, 1969.

Hrbáček, J., and M. Straškraba, Horizontal and vertical distribution of temperature, oxygen, *p*H and water movements in Slapy Reservoir (1958-1960), *Hydrobiol. Stud.. 1*, 7-40, 1966.

Hrbáček, J., M. Dvořáková, V. Kořínek, and L. Procházková, Demonstration of the effect of the fish stock on the species composition of zooplankton and the intensity of metabolism of the whole plankton association, *Verh. Int. Ver. Limnol., 14*, 192-195, 1961.

Hrbáček, J., L. Procházková, and V. Straškrabová-Prokešová, The relationship between the chemical characteristics of the Vltava River and Slapy Reservoir with an appendix: Chemical budget for Slapy Reservoir, *Hydrobiol. Stud., 1*, 41-84, 1966.

Hruška, V., The changes of benthos in Slapy Reservoir after establishing Orlík Reservoir and their influence upon the fish stock, *Verh. Int. Ver. Limnol., 16*, 741-746, 1966.

Hruška, V., The changes of benthos in Slapy Reservoir in the years 1960-1961, *Hydrobiol. Stud., 2*, 213-247, 1973.

Hutchinson, G. E., *A Treatise on Limnology*, vol. 1, *Geography, Physics, and Chemistry*, pp. 466-478, John Wiley, New York, 1957.

Jaske, R. T., and G. R. Snyder, Density flow regime of Franklin D. Roosevelt Lake, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng., 93*, 15-28, 1967.

Javornický, P., Seasonal dynamics of the phytoplankton of Slapy Reservoir 1958-1960, *Hydrobiol. Stud., 1*, 155-163, 1966.

Javornický, P., and J. Komárková, Evolution of several parameters of plankton primary productivity in Slapy Reservoir during 1960-1967 and their correlations with ecological factors, *Hydrobiol. Stud., 2*, 155-211, 1973.

Javornický, P., J. Komárek, and J. Růžička, The phytoplankton of the water reservoir of Slapy during 1958-1960, *Technol. Water, 6*, 349-387, Inst. of Chem. Technol., Prague, 1962.

Karpov, V. E., F. V. Krogius, E. M. Krokhin, and V. V. Menshutkin, A model of the ichthyocenosis of Lake Dalneye realised on an electronic computer, *Verh. Int. Ver. Limnol., 16*, 1095-1102, 1966.

Kittrell, F. W., Effect of impoundment on dissolved oxygen resources, *Sewage Ind. Wastes, 31*, 1065-1078, 1959.

Kolkwitz, R., and M. Marsson, Örologie der pflanzlichen Saprobien, *Ber. Deut. Bot. Ges.*, *26*, 505–519, 1908.

Kozák, J., Meření rytmičnosti pomocí Fourrierových řad (Measurement of rhythmicity by means of Fourier expansion), *Statistika*, 76–80, 1968.

Krenkel, P. A., E. L. Thackston, and F. L. Parker, The influence of impoundments on waste assimilative capacity, Proceedings of Special Conference on Effects of Reservoirs on Water Quality, *Tech. Rep. 17*, pp. 1–39, Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Krogius, F. V., E. M. Krochin, I. I. Kurenkov, and V. V. Menshutkin, Model ekologicheskoi sistemy ozera Dalnego (A model of ecological system of the Lake Dalneye), *Gidrobiol. Zh.*, *5*, 14–22, 1969.

Levi, I. I., Theory of underflows in storage reservoirs, in *Proceedings of the 8th Congress of the International Association for Hydraulic Research*, vol. 2, pp. 1–26, United Nations Educational, Scientific and Cultural Organization, Paris, 1959.

Lewins, R., The strategy of model building in population biology, *Amer. Sci.*, *54*, 421–431, 1966.

Martin, R. O. R., and R. L. Hanson, Reservoirs in the United States, *U.S. Geol. Surv. Water Supply Pap.*, *1838*, 1–114, 1966.

McCombie, A. M., Some relations between air temperatures and the surface water temperatures of lakes, *Limnol. Oceanogr.*, *4*, 252–258, 1959.

Menshutkin, V. V., and A. A. Umnov, Matematicheskaya model prosteyshei vodnoi ekologicheskoi sistemy (A mathematical model of a simple ecosystem), *Gidrobiol. Zh.*, *6*, 28–35, 1970.

Moore, A. M., Correlation and analysis of water-temperature data for Oregon streams, *U.S. Geol. Surv. Prof. Pap.*, *501D*, 185–189, 1964.

Naumann, E., *Grundlinien der Experimentellen Planktonforschung*, Schweizerhartsche Verlagshandlung, Stuttgart, 1932.

Nesina, L. V.. Raschod sostavlyayushchich teplovogo balansa proyektiruyemich vodoyemov (Calculation of the heat budget terms for newly built reservoirs), *Tr. Gos. Gidrol. Observ.*, *206*, 31–37, 1967.

Nielson, L. J., Evaluation of pre-impoundment conditions for prediction of stored water quality, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, Jr., pp. 153–168, American Fisheries Society, Washington, D. C., 1967.

O'Connel, R. L., and N. A. Thomas, Effect of benthic algae on stream dissolved oxygen, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *91*, 1–16, 1965.

O'Connor, D. J., and D. M. DiToro, Analysis of the dissolved oxygen variation in a flowing stream, in *Advances in Water Quality Improvement, Water Resources Symposium*, vol. 1, edited by E. F. Gloyna and W. W. Eckenfelder, pp. 96–102, University of Texas Press, Austin, 1968.

O'Connor, D. J., and W. E. Dobbins, Mechanism of reaeration in natural streams, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *82*, 1–30, 1956.

O'Connor, J. S., and B. C. Patten, Mathematical models of plankton productivity, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, Jr., pp. 207–228, American Fisheries Society, Washington, D. C., 1967.

Odum, H. T., Primary production in flowing waters, *Limnol. Oceanogr.*, *1*, 102–117, 1956.

Orlob, G. T., and L. G. Selna, Mathematical simulation of thermal stratification in deep impoundments, in Proceedings of Special Conference on Effects of Reservoirs on Water Quality, *Tech. Rep. 17*, pp. 121–162, Dep. of Environ. and Water Resour. Eng., Vanderbilt Univ., Nashville, Tenn., 1968.

Otsuboto, K., and H. Fukushima, Density currents in a river mouth with a small tidal range, in *Proceedings of the 8th Congress of the International Association for Hydraulic Research*, vol. 2, pp. 1–25, United Nations Educational, Scientific and Cultural Organization, Paris, 1959.

Owens, M., R. W. Edwards, and J. W. Gibbs, Some reaeration studies in streams, *Int., J. Water Pollut.*, *8*, 469–486, 1964.

Owens, M., G. Knowles, and A. Clark, The prediction of the distribution of dissolved oxygen in rivers, in *Advances in Water Pollution Research, Proceedings 4th International Conference*, pp. 125–137, Pergamon, New York, 1969.

Parker, R. A., Simulation of an aquatic ecosystem, *Biometrics*, *24*, 803–821, 1968.

Patalas, K., Landschaft und Klima als Faktoren der Massenproduktion von Algen, *Fortschr. Wasserchem. Ihrer Grenzgeb.*, *8*, 21–30, 1968.

Patten, B. C., Mathematical models of plankton production, *Int. Rev. Gesamten Hydrobiol.*, *53*, 357–408, 1968.

Procházková, L., V. Straškrabová, and J. Popovský, Changes of some chemical constituents and bacterial numbers in Slapy Reservoir during eight years, *Hydrobiol. Stud.*, *2*, 83–154, 1973.

Raphael, J. M., Prediction of temperature in rivers and reservoirs, *J. Power Div. Amer. Soc. Civil Eng.*, *88*, 157–181, 1962.

Riley, G. A., H. Stommel, and O. F. Bumpus, Quantitative ecology of the plankton of the western North Atlantic, *Bull. Bingham Oceanogr. Coll.*, *12*, 1–169, 1949.

Rychetník, L., J. Zelinka, and V. Pelzbauerová, *Sbírka Příkladů z Lineárního Programování (Exercises of Linear Programming)*, Statni Nakladatelstvi Technicke Literatury, Bratislava, 1968.

Sauer, J. F. T., and E. R. Anderson, The heat budget of a body of water of varying volume, *Limnol. Oceanogr.*, *1*, 247–257, 1956.

Schräder, T., Thermische Verhältnisse in Talsperren, *Gewässer Abwässer*, *21*, 68–88, 1959.

Seckel, G. R., The trade wind zone oceanography pilot study, 8, Sea-level meteorological properties and heat exchange processes July 1963 to June 1965, *U.S. Fish Wildl. Serv. Spec. Sci. Rep. Fish.*, *612*, 1970.

Smutek, R., Flow of fluid layers of different temperature (in Czech with English summary), *Rozpr. Cesk. Akad. Ved Rada Tech. Ved*, *65*, 1–49, 1955.

Straškraba, M., Interrelations of zooplankton and phytoplankton in the Slapy and Klíčava reservoirs, *Verh. Int. Ver. Limnol.*, *16*, 719–726, 1966.

Straškraba, M., Base for a model of the Slapy Reservoir ecosystem, in *Productivity Problems of Freshwater*, United Nations Educational, Scientific and Cultural Organization and the International Biological Program, Warsaw, 1970.

Straškraba, M., and J. Hrbáček, Net-plankton cycle in Slapy Reservoir during 1958-1960, *Hydrobiol. Stud.*, *1*, 113-153, 1966.

Straškraba, M., and P. Javornický, Limnology of two re-regulation reservoirs in Czechoslovakia, *Hydrobiol. Stud.*, *2*, 249-316, 1973.

Straškraba, M., J. Hrbáček, and P. Javornický, Effect of an upstream reservoir on stratification conditions in Slapy Reservoir, *Hydrobiol. Stud.*, *2*, 7-82, 1973.

Stumm, W., and E. Stumm-Zollinger, Chemische Processe in natürlichen Gewässern, *Chimia*, *22*, 325-337, 1968.

Symons, J. M., W. H. Irwin, R. M. Clark, and G. G. Robeck, Management and measurement of DO in impoundments, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *93*, 181-209, 1967.

Szekielda, K. H., Modellrechnungen für die freigesetzte Energie bei der Oxydation organischen Materials in Seewasser, *Deut. Hydrogr. Z.*, *20*, 265-269, 1967.

Szekielda, K. H., Ein chemisches Modell für den Auf- und Abbau organisches Materials und dessen Anwendung in der offenen See, *J. Cons. Cons. Perma. Int. Explor. Mer*, *32*, 180-187, 1968.

Thackston, E., and A. Krenkel, Reaeration prediction in natural streams, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *95*, 65-94, 1969.

Thomann, R. V., Mathematical model for dissolved oxygen, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *89*, 1-30, 1963.

Thomann, R. V., Systems analysis and simulation in water quality management, in *Water and Air Resource Management*, pp. 223-233, IBM Data Processing Division, White Plains, N. Y., 1967.

Uhlmann, D., Der Einfluss der Verweilzeit des Wassers auf die Massenentwicklung von Planktonalgen, *Fortschr. Wasserchem. Ihrer Grenzgeb.*, *8*, 32-47, 1968.

Vollenweider, R. A., Möglichkeiten und Grenzen elementarer Modelle der Stoffbilanz von Seen, *Arch. Hydrobiol.*, *66*, 1-36, 1969.

Ward, J. C., Annual variation of stream water temperature, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *89*, 1-16, 1963.

Wright, J. C., The limnology of Canyon Ferry Reservoir, 4, The estimation of primary production from physical limnological data, *Limnol. Oceanogr.*, *6*, 330-337, 1961.

Wright, J. C., Effect of impoundments on productivity, water chemistry and heat budgets of rivers, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, Jr., pp. 188-199, American Fisheries Society, Washington, D. C., 1967.

Wright, J. C., and R. M. Horrall, Heat budget studies on the Madison River, Yellowstone National Park, *Limnol. Oceanogr.*, *12*, 578-583, 1967.

Wunderlich, W. O., and R. A. Elder, Reservoir modeling for thermal stratification conditions, paper presented at 63rd National Meeting, Amer. Inst. of Chem. Eng., St. Louis, Mo., Feb. 19-23, 1968.

Znamenskii, V. A., Prostranstvennoe modelirovanie režima vodoemov dlja izučenija ich sanitarnogo sostojanija (Three-dimensional modelling of water quality in reservoirs for sanitary purposes), in *Nauchnye Doklady po Voprosam Samoochisheheniya Vodoemov*, pp. 188-189, Tallinskii Polytechnicheskii Institut, Riga, 1965.

Thermal Structure of the Artificial Reservoir

TADASHI ARAI

Department of Geography, Risshyo University, Tokyo, Japan

Artificial reservoirs change the hydrologic, physical, and chemical properties of the original river water. The hydrologic change is caused mainly by the operation of reservoir control. The most fundamental physical and chemical change is the change in water temperature. Temperature changes the habitats of river animals and plants and also affects the water supply in the river basin, e.g., the irrigation, waterworks, and industrial water. In addition, since the reservoir itself is a huge mass of inland water, its limnological and hydrologic properties must be researched. For these and many other reasons, studies of the water temperature in the reservoir, the mechanism that governs the vertical distribution of water temperature, and the estimation of the temperature of water flowing from the reservoir and its control are needed.

Investigations of the thermal and hydrologic structures of reservoir water are needed for this study. The heat budget at the water surface and the distribution of physical quantities in the reservoir are regarded as two main aspects of the system that transfers energy from the air to the reservoir water. Heat budget considerations may distinguish the main factors that contribute to the distribution of water temperature. Investigations of the distribution of physical quantities in the reservoir may explain the heat redistribution mechanism of the lake.

The characteristics of the water temperature of a reservoir are completely different from those of natural lakes. The most important feature in the water balance relations of the reservoir is the complex movement of the water mass. A change in water level is more complicated in a reservoir than in a natural lake. Thus it may be assumed that advective heat transfer and vertical movement of the water mass can play important roles in the distribution of water temperature in an artificial reservoir. Advective heat transfer exceeds the heat supply from the water surface in many reservoirs. Thus water and heat budgets in an artificial reservoir show considerably different characteristics from those in natural lakes.

Thermal characteristics of the artificial reservoir are divided into two types according to the hydrologic condition. The water of the first type has a long travel time, so that a remarkable thermal stratification is created in the summer season. The water of the second type has a short travel time, and the thermal stratification is weak in comparison with that of the first type. Differences in heat balance are produced by the above-mentioned hydrologic conditions because advective heat is greatly affected by the amount of discharge and the water travel time in the reservoir.

In general, advective heat from an inflowing and outflowing water mass occupies a large part in the heat balance process of an artificial reservoir. The heat redistribution process in the water column differs with hydrologic condition as well as surface heat balance.

Heat and water balances for two representative reservoirs were calculated. The first is Tagokura Reservoir, which has a long water travel time, and the second is Sakuma Reservoir, which has a short water travel time in comparison to its volume. Heat balance and heat redistribution in the reservoirs were analyzed. In both reservoirs, advection occupies a large part in the heat balance process. Evaporation reaches its maximum in late autumn, and the temperature of the outflowing water reaches its maximum in November. Since Sakuma Reservoir discharges >300 m^3/sec of water in about 10 days of travel time, its advective heat is extremely great. The thermal stratification is very weak in this reservoir, and the isothermal layer extends from the surface to 80 meters below the surface.

The important hydrologic characteristic of the reservoir is the complex movement of the water mass, which causes the increment of vertical and advective heat transfer. Because advection occupies a large part in the heat budget of the reservoir, the movement and exchange of the water mass govern its vertical temperature profile. The magnitude of the exchange is illustrated by the turbulent diffusivity.

To carry out the general comparison of the diffusivity coefficient in the reservoir, the equation of heat balance in water that is assumed to be completely free from direct effects of surface heating is represented by

$$c\rho \int u \frac{\partial \theta}{\partial X} dZ = c\rho K\left(\frac{\partial \theta}{\partial Z}\bigg|_{Z1} - \frac{\partial \theta}{\partial Z}\bigg|_{Z2}\right)$$

The results of the calculation for several reservoirs are shown in Figure 1 in comparison with the results derived from the mixing length theory and from the heat storage calculation. As these coefficients are assumed to vary in relation to the stability of the flow, the order of magnitude of Richardson's number is also shown in this figure. The numerical value of the coefficient lies between the order of 10^0 and 10^1 and therefore surely exceeds the value for a natural lake.

In natural lakes, several results on eddy diffusivity were obtained on the basis of the analysis of heat balance or change in water temperature. According to these results the coefficient does not exceed the order of magnitude of 10^{-1} in lakes in Japan. Vertical heat transfer in a natural lake is governed mainly by the vertical eddy diffusion and the water mixing associated with the internal wave. The process of heat transfer is more complicated in the artificial reservoir than in the natural lake because many other heat transfer mechanisms exist in the reservoir.

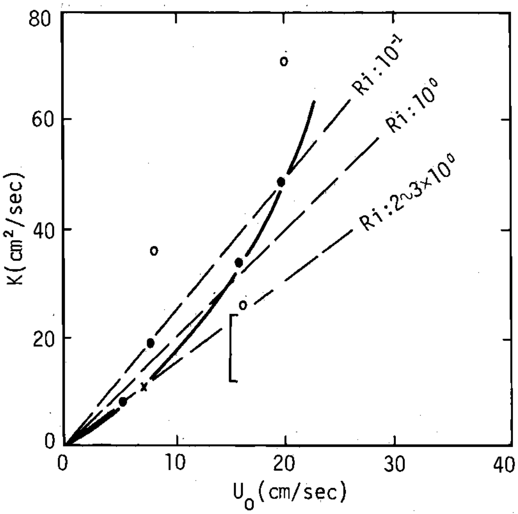


Fig. 1. Relation between diffusivity coefficient K and maximum velocity in the reservoir. The solid dots represent Tagokura Reservoir, the open dots represent the coefficient for Tagokura Reservoir obtained by the mixing length method, the cross represents the coefficient at Miwa Reservoir obtained by the heat storage method, and the bracket represents Sakuma Reservoir.

Because advective heat transfer and vertical water mixing exert important influences on the distribution of water temperature in the reservoir, the temperature in the summer season in the deep layer of the reservoir becomes higher than that of a natural lake at the same depth.

Water temperature in the deep layer of a deep lake in the temperate climatic zone is about 4°C, whereas that in the deep layer of an artificial reservoir is >4°C at the same level under the same climatic and morphologic conditions. Table 1 shows the comparison between water temperatures in deep layers in several lakes and those in reservoirs. Water temperatures approach 10°C at the 70- or 80-meter layer in midsummer in some reservoirs. This warmwater mass may be created in early summer when the heat is allowed to move to the deep layer because the advective heat flux shows a strong positive value and the thermal stratification remains relatively weak. When the discharge of the reservoir is large enough in comparison to its capacity, the water temperature of the reservoir is largely controlled by the inflowing water mass.

The distribution of water temperature in a reservoir is governed by its hydrologic properties, which are divided into two types. The criterion for the classification is the ratio, amount of advective heat transfer to net change of heat storage. Advective flux increases in proportion to the increase in discharge, as is explained in the analysis of the Sakuma Reservoir. Another example is the analysis of the Tagokura Reservoir in which a comparatively large net change of heat storage was obtained. It is difficult to obtain an accurate criterion for the classification of reservoirs, but the following approximate value may be applicable.

In the middle and high latitudes, where temperate lakes prevail, reservoirs can be divided thermally into two types by using two parameters. These parameters are calculated by using the volume V, surface area S, and discharge

TABLE 1. Comparisons of Water Temperature in Natural Lakes and Artificial Reservoirs

	Temperature, °C		
	Depth, 15 meters	Depth, 30 meters	Depth, 70 to 80 meters
Natural lakes			
Lake Towada	10	6	4
Lake Tōya	10	6	4
Lake Chūzenji	10	6	4
Lake Tazawa	12	7	4
Artificial reservoirs			
Tagokura (1960)	14	13	10
Tagokura (1961)	15	12	8
Tagokura (1962)	11	9	6
Tagokura (1963)	11	9	6
Okutadami (1962)	13	12	6
Okutadami (1963)	11	8	5
Sakuma (1958)	25	10	10

q of the reservoir and take the forms S/q and V/q. For a summer climate in Japan the following values of the parameters may be regarded as the boundary for the classification between large capacity (i.e., strong thermal stratification with a long water travel time) and small capacity (i.e., isothermal profile with a short water travel time) reservoirs: $S/q \simeq 0.1 \times 10^6$ sec/m and $V/q \simeq 3$ or 4×10^6 sec. Note that this method gives only a rough aid to the classification of reservoirs.

Several results of observations show that thermal stratification vanishes for a summer climate when the flow velocity in the reservoir exceeds about 20 cm/sec because heat is distributed to all water layers by strong mixing at that water velocity.

The construction of the drainage mouth greatly affects the distribution of water temperature in all reservoirs. The vertical distance between the water surface and the drainage mouth varies according to the change in water level in reservoirs that are not equipped with a surface drainage mouth. The analysis of water temperature must be made with regard to the reservoir control.

The analyses and discussions in this report have been made mainly by considering a summer climate in the middle latitude. In a tropical climate, there is only weak thermal stratification in the lakes. In addition, in the tropical zone the temperature of the river water approximates the temperature of the surface water of the lakes, and so the thermal stratification in a reservoir may be very weak.

Selective Withdrawal from Man-Made Lakes

JOHN L. GRACE, JR.

U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi 39180

Effective planning, design, management, and operation of one or more man-made lakes for optimum conservation and use of regional water and related resources for many purposes involves, among others, the problems of predicting, monitoring, and controlling the thermal and chemical quality of impounded water and releases through spillways, powerhouses, and outlet works. An evaluation of the effectiveness of various structures in selectively withdrawing releases from various levels of stratified reservoirs is urgently needed for multipurpose projects that have specific thermal and chemical release requirements for existing and future needs.

The desire to release quality water requires monitoring the characteristics of reservoir water and knowing the flow pattern to be expected in the immediate and upstream vicinity of various regulating structures. Therefore a determination of the effect on withdrawal of the size, shape, and spacing of multilevel openings is desired to permit prediction and control of the stratum of the reservoir from which releases are made and selection of effective locations for fixed monitoring stations. An evaluation of the effectiveness of submerged skimming weirs and walls or thermal barriers in preventing the intrusion of either cold or warm water into powerhouse intakes and single-level outlet works is also of primary concern.

During 1966 the U.S. Army Corps of Engineers initiated laboratory research at the Waterways Experiment Station to determine the characteristics of withdrawal zones resulting from release of flows from randomly stratified reservoirs through orifices and over weirs for developing means of predicting and controlling the quality of water discharged through various regulating structures. Stratification was generated in experimental facilities by means of differentials in both temperature and dissolved salt concentration. Density distributions were determined from temperatures and salinities measured with thermistors and conductivity probes. Velocity distributions were obtained by dropping dye particles into the flow and photographing the resulting streaks with movie cameras.

Generalized expressions describing the limits of the withdrawal zone and the distribution of velocities therein were developed from analyses of the velocity and density distribution data. Means for evaluating those conditions where the free surface and/or bottom boundary dictate the upper and/or lower limits of the withdrawal zone were also determined. Since the velocity distribution to be anticipated for any given density distribution upstream of an orifice or weir can be predicted, the weighted average technique can be applied to predict the value of any water quality parameter of the outflow for which a profile in the reservoir is known. (This paper is a summary of material presented by *Bohan and Grace* [1969, 1973] and *Grace* [1971].)

REFERENCES

Bohan, J. P., and J. L. Grace, Jr., Mechanics of flow from stratified reservoirs in the interest of water quality, *Tech. Rep. H-69-10*, Hydraul. Lab., U.S. Army Eng. Waterways Exp. Sta., Vicksburg, Miss., 1969.

Bohan, J. P., and J. L. Grace, Jr., Selective withdrawal from man-made lakes, *Tech. Rep. H-73-4*, Hydraul. Lab., U.S. Army Eng. Waterways Exp. Sta., Vicksburg, Miss., 1973.

Grace, J. L., Jr., Selective withdrawal characteristics of weirs, *Tech. Rep. H-71-4*, Hydraul. Lab., U.S. Army Eng. Waterways Exp. Sta., Vicksburg, Miss., 1971.

Influence of Reservoir Discharge Location on the Water Quality, Biology, and Sport Fisheries of Reservoirs and Tail Waters

RICHARD H. STROUD AND ROBERT G. MARTIN
Sport Fishing Institute, Washington, D. C. 20005

PERSPECTIVE

In 1958, Congress further amended [*U.S. Congress*, 1958, p. 564] the previously amended [*U.S. Congress*, 1946] Fish and Wildlife Coordination Act [*U.S. Congress*, 1934]. The amended act required that, before new water projects could be undertaken, federal construction agencies or federal licensees had first to

> . . . consult with the United States Fish and Wildlife Service, Department of the Interior, and with the head of the agency exercising administration over the [fish and] wildlife resources of the particular State wherein the impoundment, diversion, or other control facility is to be constructed, with a view to the conservation of [fish and] wildlife resources by preventing loss of and damage to such resources as well as providing for the development and improvement thereof in connection with such water-resource development.

The new authority to provide for enhancement of fish and wildlife resource potential, as contrasted to the earlier limited authority for mere mitigation of losses, was the realization of a goal long sought by many concerned conservationists including key personnel in the Environmental Branch of the U.S. Army Corps of Engineers. Consequently, the conservationists immediately sought to implement the new authority in various ways. One of the first of the related proposals was that systems of multilevel outlets be incorporated at U.S. Army Corps of Engineers dams to permit selective discharge regulation. The ostensible purpose was to restore water temperatures in downstream river sections to their values prior to impoundment to preserve warmwater fish populations there.

Questions immediately arose as to both the adequacy of the scientific basis for making specific recommendations for the regulation of key water quality factors in dam tail waters and the wisdom of possible deliberate sacrifice through such single-objective manipulation of potential biological production within the affected upstream reservoir pool. Underscoring these questions was the emergence among fishery scientists of two sharply divided schools of thought about the influence of epilimnial and hypolimnial water discharge regimes on fish production of reservoirs, neither tenet having sufficient evidence to support it clearly.

Finally, it seemed imperative to develop an improved scientific basis for better prediction of the results to be expected from the application of alternative recommendations. Such information would be particularly pertinent to the U.S. Army Corps of Engineers in view of its extensive involvement in reservoir planning and construction. It has completed 252 reservoir projects, an additional 71 reservoirs are under construction, and 117 reservoir projects are authorized but not started. Large impoundments have a potential adverse effect through thermal stratification, deoxygenation of deep water, and concentration of metallic compounds in solution on the quality of downstream flow. The quality of impounded water is subject to constant change by inflow, wave action, eutrophication, climatic variations, and changes in many other environmental factors. Multilevel outlets have been installed for selective discharge regulation at 20 dams operated by the corps without a full understanding of the effect of discharge regulation on water quality and water uses both in the reservoir and downstream.

The Sport Fishing Institute is responsible for the overall planning, coordination, and reporting of results and recommendations for water quality control operations. The institute is also responsible for the planning, administration, coordination, and reporting of any investigations performed by cooperating state conservation departments, universities, or other research institutions as subcontractors for this research project as well as for the evaluation of final project reports.

Research subcontracts have been executed with four responsible and qualified agencies and institutions to carry out the investigations necessary to implement the objectives of this study. These subcontracts have been further complemented by three formal memorandums of understanding negotiated with pertinent state and federal agencies and by informal agreements with 23 state agencies.

FINDINGS

Exploratory statistical studies (subcontract DACW31-67-C-0083-S1 with Dr. James E. Dunn, Mathematics Department, University of Arkansas) were initiated in 1967 to examine the relationship between hypolimnial oxygen distribution and reservoir outlet location, storage ratio, and dissolved solids. Oxygen-temperature profiles were recorded for 103 reservoirs in 23 states from historical data obtained by an extensive literature search and from administrative reports supplied by cooperating state agencies. The profiles represented data obtained from the deepest areas of the reservoirs during the period of most severe hypolimnial oxygen depletion in late summer and fall. These historical data were augmented in 1968 by the synoptic collection of more precise oxygen-temperature profiles and supporting physicochemical data from 57 stratified reservoirs by specially dispatched teams from 20 cooperating state fishery agencies. The oxygen-temperature profiles were obtained from areas of maximum reservoir depth in all instances. Maximum depth, thermocline depth, and the midpoint depth of the outlet facility were recorded synoptically by the investigators. Dissolved solids, storage ratios, and mean reservoir depths were secured from records maintained by the National Reservoir Research Program, Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior. After compilation the data were forwarded to Dr. Dunn for statistical treatment and analysis.

Statistical analysis of the data compiled in 1967 from historical records indicated that the location of the reservoir outlet influenced the distribution of the dissolved oxygen in the hypolimnion of stratified reservoirs during the period of intense stratification in late summer and fall. The probability of the presence of at least 4 ppm dissolved oxygen below the thermocline of stratified reservoirs was significantly greater for hypolimnial (low-level) outlets (0.79) than for epilimnial (high-level) outlets (0.29) at the 5% level of significance. No significant difference was observed in the oxygen regimes of reservoirs with metalimnial discharge (0.77) and those of reservoirs with hypolimnial discharge (0.79). Thus, for all practical purposes, hypolimnial and metalimnial discharge may be considered one entity.

The relationship described in the preliminary survey of the historical oxygen-temperature profiles analyzed in 1967, indicating a positive correlation between the outlet depth and the concentration of oxygen in the hypolimnion, was corroborated and strengthened by the analysis of the more precise synoptically collected data obtained in 1968.

Simple and partial correlations between the several criterion functions (dependent variables) and the predictor variables (independent variables, i.e., storage ratio, dissolved solids, and outlet depth) were determined. The universal result was that neither the storage ratio nor the dissolved solids showed any significant degree of correlation to any of the three criterion functions, whereas the outlet depth was strongly positively correlated to all three criterion functions, i.e., the greater the outlet depth, the greater the proportion of depth below the thermocline occupied by any of the three specified dissolved oxygen levels; the greater the outlet depth, the greater the proportion of maximum depth occupied by all the specified dissolved oxygen levels; and the greater the outlet depth, the greater the proportion of mean depth occupied by any of the three dissolved oxygen levels. The correlations involving the third criterion function for mean depth were not as high as those involving the first two functions, as might be expected, since the data for mean depth were not newly collected and hence were not closely representative of the conditions in the reservoir at the time of sampling.

Supplemental data from 130 large reservoirs, made available to the Institute by the cooperating National Reservoir Research Program, were also analyzed by Dr. Dunn under our computer service subcontract as directed by institute personnel. The results further indicated that a significant correlation (0.31) existed between high standing fish crops and hypolimnial (low-level) outlet location in flood control, irrigation, and water supply reservoirs. A separate analysis of this relationship according to the two basic types of water regimes that characterize hydropower reservoirs was inconclusive.

These collective statistical findings suggest that outlet location can indeed exert substantial influence on water quality and biological productivity within large stratified reservoirs. At the very least they tend to confirm the validity of the overall experimental design under which the project is being conducted. Thus they lend preliminary support to the basic research premise that significant biological and water quality differences occur under opposing epilimnial (high-level) and hypolimnial (low-level) discharge regimes. These parameters may be viewed then as the critical conditions that must prevail substantially in the research design.

LARGE RESERVOIR STUDIES

Subcontracts DACW31-67-C-0083-3 with the Kentucky Department of Fish and Wildlife Resources and DACW31-67-C-0083-4 with Western Kentucky University provide for comprehensive biological and water quality investigations at the two U.S. Army Corps of Engineers flood control reservoirs and tail waters in south central Kentucky under opposing discharge regimes. Multilevel discharge ports incorporated in the design of the dams at both reservoirs allow discretionary selective discharge from either the hypolimnion or the epilimnion, an essential prerequisite of the research design. Barren River Lake, a 4047-ha impoundment, was operated with a hypolimnial discharge in 1968 and 1969, while Nolin Lake, 2347 ha, was operated with an epilimnial discharge. These discharge regimes were reversed in the winter of 1969, and for 2 additional years (1970 and 1971) the reservoirs were to be operated under opposing discharge regimes.

Fish population, water quality, and angling harvest data are being collected by the Kentucky Department of Fish and Wildlife Resources. Western Kentucky University is responsible for plankton, periphyton aufwuchs, benthos, mineral nutrient, and dissolved organic matter determinations. Annual population estimations of the pelagic fish fractions in both reservoirs are being carried out and made available to the project by the National Reservoir Research Program under the terms of a memorandum of understanding negotiated by the institute with the Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior. Data for the estimations are obtained by a mid-water trawl sampling program designed and conducted by members of the South Central Reservoir Research Team, National Reservoir Research Program, in consultation with Dr. Dunn.

Water quality. Water quality in the hypolimnions of both Barren River (hypolimnial discharge) and Nolin (epilimnial discharge) lakes during the period of summer and fall stratification was profoundly affected by the quantity and quality of inflowing tributaries. This point is illustrated by the examination of oxygen profiles from the reservoirs in 1968 and 1969 (Table 1). In 1968, considered a normal runoff year on the Nolin Lake watershed, the average percent of maximum reservoir depth containing at least 4 mg/l of dissolved oxygen during the period of maximum stratification (June 1 through October 16) was only 21.5%. In 1969, an abnormally dry year, this increased to 56.9%.

An extremely heavy rainfall on the Barren River watershed increased the reservoir level some 5.8 meters by June 30, 1969. This resulted in the protracted storage (6 weeks) of the high oxygen demand floodwater and the subsequent reduction in dissolved hypolimnial oxygen values. Normal seasonal pool elevation was not achieved until August 14, 1969. High manganese and iron concentrations, which contributed further to the deterioration of water quality, were noted in the hypolimnion in association with the surcharge of floodwater. Had this flood occurred under an epilimnial discharge regime, oxygen reductions in the hypolimnion probably would have been much more severe and extended over a longer period of time. Under an epilimnial discharge regime the high-quality surface water would have been evacuated first, the effect being an extension of the storage period and a concurrent reduction in dissolved oxygen values throughout the reservoir.

Although the investigation was not intended to compare water quality characteristics of the two reservoirs, it is interesting to note the differences in dissolved oxygen distribution at Barren River and Nolin lakes during the summer and fall of 1968, when more or less average runoff conditions prevailed on both watersheds. Dissolved oxygen values were more favorable in Barren River Lake, which was operated under a hypolimnial discharge regime (36.5% of the max-

TABLE 1. Depth and Percent of Maximum Reservoir Depth Containing at Least 4 Milligrams per Liter of Dissolved Oxygen at Main Pool Stations near Dams at Barren River and Nolin Lakes, April to November 1968 and 1969

Barren River Lake, 1968			Barren River Lake, 1969			Nolin Lake, 1968			Nolin Lake, 1969		
Date	Depth, meters	Percent	Date	Depth, meters	Percent	Date	Depth, meters	Percent	Date	Depth, meters	Percent
4/11	maximum	100	4/16	maximum	100.0	4/16	maximum	100	4/18	maximum	100.0
4/22	maximum	100									
5/7	maximum	100	5/8	maximum	100.0	5/14	19.82	70	5/7	maximum	100.0
			5/19	18.29	80.0				5/27	maximum	100.0
6/4	9.15	35.3	6/5	13.72	60.8	6/12	15.24	43.2	6/3	maximum	100.0
6/19	7.62	31.0	6/26	9.15	32.3	6/24	3.11	10.8	6/23*	maximum	100.0
7/9	6.10	27.0	7/10	4.57	16.6	7/2	4.57	16.1	7/8*	24.38	86.6
7/18	6.10	27.0	7/24	4.57	17.9	7/16	6.10	21.3	7/22*	21.34	75.3
7/23	6.10	27.0	7/31	6.10	25.0	7/31	4.57	16.1			
8/6	6.10	27.0	8/13	7.62	33.3	8/7	4.57	16.1	8/15*	18.29	64.5
8/15	6.10	27.0	8/20	9.15	41.1	8/20	4.57	16.1	8/26	7.62	26.9
8/22	6.10	27.0	8/29	4.57	20.5	8/26	6.10	21.3			
9/9	7.62	33.8	9/10	9.15	41.1	9/11	3.11	10.8	9/8	7.62	26.9
9/16	9.15	41.4				9/27	4.57	16.3	9/22	7.62	27.2
9/24	10.71	47.3									
10/16	10.71	48.6	10/8	1.52	6.9	10/17	6.10	22.2	10/22	9.15	34.1
10/28	15.24	75.0	10/15	0.00	0.0	10/30	12.19	48.2	10/31	7.62	27.5
			10/28	maximum	100						
11/26	maximum	100.0	11/16	maximum	100.0	11/3	maximum	100	11/9	maximum	100.0

The maximum depth at Barren River Lake is 22.56 meters at a seasonal pool elevation of 168.29 meters. The maximum depth at Nolin Lake is 28.35 meters at a seasonal pool elevation of 157.01 meters. The average percents of maximum reservoir depth containing at least 4 mg/l of dissolved oxygen from June 1 through October were 36.5 and 33.0% for 1968 and 1969, respectively, for Barren River Lake and 21.5 and 56.9% for 1968 and 1969, respectively, for Nolin Lake.

*Less than 4.0 mg/l of dissolved oxygen between 7.62 and 13.72 meters.

imum reservoir depth occupied by at least 4 mg/l of dissolved oxygen), than in Nolin Lake, which was operated under an epilimnial discharge regime (only 21.5%). Thus a considerably greater volume of Barren River Lake than of Nolin Lake was available to plankton, benthos, and fish populations.

An informal agreement was negotiated with the Tennessee Valley Authority Engineering Laboratory to determine the reservoir strata that were contributing to the discharge from both Barren River and Nolin lakes. Field investigations were conducted August 12–25, 1969, by Tennessee Valley Authority Engineering Laboratory personnel using their unique deep water isotopic analyzer.

As is noted in Table 2, the discharge from Barren River Lake, operated under a hypolimnial discharge regime, emanated essentially from the bottom strata. The thickness of the strata ranged from 7.3 to 14.8 meters upward from the reservoir bottom. All determinations except one were made at the greater than normal discharge rates necessary to evacuate stored floodwater (occasioned by the previously mentioned heavy June rainfall). The other determination was made on August 25 at a near-normal discharge rate of 7.36 m^3/sec. It exhibited a withdrawal layer 8.4 meters thick, extending upward from the reservoir bottom. The top of the withdrawal layer was 14.2 meters below the reservoir surface, well within the hypolimnion.

A single determination was obtained at Nolin Lake on August 21, 1969. The withdrawal layer extended downward from the surface to a depth of 5.2 meters, well within the prescribed epilimnial reservoir strata.

Fish population sampling. Estimates of standing fish crops were obtained from Barren River and Nolin lakes in 1968 and 1969 by means of standard cove rotenone sampling techniques. Four coves totaling 5.12 ha were sampled each year in Barren River Lake. Four coves totaling 4.52 ha were sampled in Nolin Lake in 1968, and five coves totaling 5.33 ha were sampled there in 1969. In Barren River Lake, operating with a hypolimnial discharge during both years, the standing fish crop increased some 76% over the 2-year period, from 247 kg/ha in 1968 to 434 kg/ha in 1969. Nolin Lake, operating with an epilimnial discharge during this same period, experienced a 26% reduction in standing fish crop over the 2-

year period, from 596 kg/ha in 1968 to 439 kg/ha in 1969. This suggestion of a positive correlation of hypolimnial discharge regimes and a negative correlation of epilimnial discharge regimes with standing fish crops was to be evaluated further during the succeeding 2-year period (1970–1971), when the discharge regimes were to be reversed.

The pelagic fractions of the fish population of the reservoir are represented principally by young-of-the-year gizzard shad. Estimates were made of their biomass in both reservoirs during 1968 and 1969 by personnel of the South Central Reservoir Research Program using mid-water trawl techniques. Approximately 45 hauls, distributed vertically through successively deeper 2.4-meter strata, were made at each reservoir. The gizzard shad population in Barren River Lake increased substantially from an estimated 7.7 kg/ha in 1968 to 15.1 kg/ha in 1969. The gizzard shad population in Nolin Lake, on the other hand, declined drastically from 7.8 kg/ha in 1968 to only 2.1 kg/ha in 1969.

It is noteworthy that the increase in the gizzard shad population in Barren River Lake and the corresponding decline in Nolin Lake in 1969 closely parallel the patterns that the first population trends exhibited according to the cove rotenone samples noted previously.

Plankton sampling. Conventional pump sampling techniques were used to sample the plankton populations at both Barren River and Nolin lakes in 1969. Samples were obtained every 3 weeks from April through September at each of three stations representing the lower main pool, mid-reservoir, and upper-reservoir areas. Each time, 400-liter samples were obtained from the surface and at 3.0-meter vertical intervals down to and including 12 meters, depth permitting. Three vertical series were taken in the main pool area, two in the mid-reservoir area, and one in the upper-reservoir area. Standard techniques were followed in enumerating and weighing the samples.

Swanson automatic plankton samplers installed in the reservoir outlets sampled the plankton discharged from each reservoir. Four randomly distributed 15-min samples were automatically taken each 24-hour period, filtered, and preserved with formalin. Weekly composite samples representing 7570 liters of filtered water were used for the qualitative analyses and enumeration of zooplankton in the reservoir effluent.

A monthly summary of the number per liter of crustacean plankton (copepods and cladocerans) recovered from the lower main pool reservoir station near the dam by pump sampling and from the discharge outlet by Swanson automatic plankton samplers was made. The ratio of plankton abundance (number per liter) to the volume of effluent was similar in both reservoirs during the spring and early summer. These ratios averaged 0.46 in April, 1.4 in May, and 2.3 in June at Barren River Lake and 0.5 in April,

TABLE 2. Determination of Reservoir Withdrawal Strata Based on Deepwater Isotopic Analyzer Measurements

Date	Measuring Location from Left Bank, meters	Discharge, m^3/sec	Reservoir Bottom, meters*	Withdrawal Layer: Bottom of Layer, meters*	Withdrawal Layer: Top of Layer, meters*	Withdrawal Layer: Thickness, meters
			Barren River Lake			
8/12/69	67.06	784.46	23.17	23.17	9.91	13.26
8/13/69	67.06	781.63	23.17	23.17	8.38	14.78
8/13/69	329.18	781.63	17.68	15.70	8.38	7.32
8/14/69	65.53	402.14	23.17	23.17	14.33	8.84
8/15/69	65.53	402.14	22.87	22.87	8.53	14.33
8/15/69	329.18	402.14	17.07	17.07	5.33	11.73
8/20/69	67.06	529.58	23.48	21.18	10.06	11.13
8/25/69	121.92	73.63	22.57	22.57	14.17	8.38
			Nolin Lake			
8/21/69	at center of channel	152.93	26.22	5.18	surface	5.18

*Meters below water surface.

1.4 in May, and 2.1 in June at Nolin Lake. However, as stratification became progressively more severe in July, August, and September, crustacean abundance in the discharge from Barren River Lake, operated under a hypolimnial discharge regime, was drastically reduced. The reservoir effluent ratio at Barren River Lake decreased to 0.044 in July, 0.058 in August, and 0.011 in September. Conversely, the ratio at Nolin Lake, operating with an epilimnial discharge, was 0.29 in August and rose to 0.4 in September, 5 and 36 times higher than the ratios at Barren River Lake. This comparison suggests that during the late summer and fall stratification periods a much greater plankton loss occurs in the presence of epilimnial discharges than in the presence of hypolimnial discharges. The implication of these preliminary findings that the location of the reservoir outlet might substantially affect the rate of loss of important fish food organisms from reservoirs was to be explored in more detail in the 1970–1971 investigations.

Creel census. Nonuniform probability surveys of anglers' catches were conducted at Barren River and Nolin lakes and tail waters between March 1 and October 31 in both 1968 and 1969. Prior creel survey data were used in assigning probability values. Conservation officers of the Kentucky Department of Fish and Wildlife Resources, all of whom had previous training and experience in catch survey work, served as census clerks. The surveys were designed according to the recommendations of Dr. Don W. Hayne of the Southeastern Cooperative Fish and Game Statistics Project, Institute of Statistics, North Carolina State University.

Fish success (fish catch per hour) was almost 3 times as high at Barren River Lake, 1.6 and 1.5 fish per hour in 1968 and 1969, as it was in both years at Nolin Lake, 0.6 fish per hour. The fish harvest from Barren River Lake amounted to 13.45 kg/ha in 1966 and 8.2 kg/ha in 1969; the fish harvest from Nolin Lake amounted to 11.2 kg/ha in 1968 and 9.8 kg/ha in 1969. Fishing pressure was comparatively low at Barren River Lake, 9 and 4 angler hours per hectare in 1968 and 1969; it was 20 hours per hectare in 1968 and 17 hours per hectare in 1969 at Nolin Lake.

Fishing pressure and harvest were many times higher at the Barren River Lake tail water than at the Nolin Lake tail water in both years. The Barren River Lake tail water supported 4137 angler hours per hectare in 1968 and 2242 hours per hectare in 1969 with a harvest of 2976 kg of fish per hectare in 1968 and 4961 kg per hectare in 1969. Nolin Lake tail water anglers fished 1072 hours per hectare in 1968 and 437 hours per hectare in 1969 with a corresponding harvest of 1032 kg of fish per hectare in 1968 and 328 kg of fish per hectare in 1969. The number of fish creeled per hour ranged from 1.0 to 2.0 in the Barren River Lake tail water and from 1.2 to 0.7 in the Nolin Lake tail water in 1968 and 1969.

MINIATURIZED RESERVOIR STUDIES

Subcontract DACW31-67-C-0083-2 with the University of Georgia provides for the collection and analysis of water quality, fish population, periphyton aufwuchs, plankton, benthos, and fish harvest data under opposing epilimnial (high-level) and hypolimnial (low-level) discharge regimes from the drainable 36.4-ha Lake Russell and its tail water, a recreation reservoir located in the Chattahoochee National Forest. Formal memorandums of understanding were negotiated by the Sport Fishing Institute with the U.S. Forest Service and the Georgia State Game and Fish Commission to ensure local cooperation in conducting the research and to provide for assistance with creel census, lake drainage, and fish-stocking activities. The reservoir was operated with a hypolimnial discharge during 1968 and 1969. After the completion of a 2-year period of base line data collection the lake was drained in the fall of 1969, and the standing fish crop was enumerated. After the lake was refilled and restocked, the reservoir overflow was reversed to an epilimnial discharge for 1970 and 1971 operation. The same physicochemical and biological parameters were to be monitored during the ensuing 2 years, the lake was to be redrained in the fall of 1971 for the determination of the standing fish crop, and comparisons were to be made with the data obtained under the earlier 2-year period of contrasting hypolimnial discharge.

Water quality. Weekly oxygen, temperature, alkalinity, hardness, *p*H, and dissolved solid determinations were made in the tail water and in three reservoir stations representative of the main pool, mid-reservoir, and upper-reservoir areas from April through October and twice monthly for the remaining months in 1968 and 1969. Monthly samples were obtained for more detailed analysis of major elements.

The original plan called for the reservoir to be

TABLE 3. Oxygen-Temperature Profiles at Lake Russell from Main Pool Station near Dam, June to September 1968 and 1969

Depth in 1968, meters	6/7*		6/24		7/9		7/23		8/6		8/19		9/4		9/24	
	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l
0	27	7.5	27.5	9.6	26.0	10.2	29.5	10.2	30.0	9.8	30.5	9.0	26.0	12.6	24.5	9.2
1			27.5	9.6	26.0	9.9	28.5	10.6	29.5	9.5	30.5	7.0	25.0	11.6	24.0	9.1
2			27.0	9.9	26.0	9.8	28.0	10.5	29.0	9.8	29.5	8.0	25.0	11.2	23.5	9.3
3	20.0	8.5	24.0	11.2	26.0	9.6	27.0	12.4	28.0	10.7	29.0	9.0	24.0	10.5	23.5	9.1
4			21.0	9.8	25.0	9.1	25.5	12.9	27.0	12.0	29.0	9.0	24.0	10.1	23.0	9.4
5			16.0	13.0	21.5	8.9	24.0	6.4	25.5	7.3	27.5	9.0	24.0	8.5	23.0	9.2
6	11.5	9.2	13.0	12.1	18.0	11.0	22.0	6.7	23.5	2.4	26.5	4.0	23.5	7.5	22.5	7.9
7			11.5	10.4	15.0	11.2	20.0	7.8	22.5	3.6	25.5	1.0	23.0	4.4	22.5	7.5
8			10.5	7.2	12.5	11.1	17.0	10.9	20.0	5.7	24.5	2.0	22.5	1.1	22.0	7.3
9	9	8.0	9.5	6.6	12.0	9.9	16.0	10.6	19.0	7.0	23.5	3.0	22.0	0.4	22.0	6.3
10	9	4.5	9.5	4.1	11.5	7.8					23.5		20.0	0.3	21.5	5.8
Tail water	27.5	6.7	10.0	5.6	11.5	12.0	13.5	9.7	17.0	10.3	18.0	6.0	19.5	7.6	21.0	7.7

Depth in 1969, meters	6/3		6/24		7/8		7/25		8/8		8/21		9/4		9/27	
	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l	T, °C	O_2, mg/l
0	26.5	5.8	28.0	7.3	32.0	6.8	31.0	6.8	29.0	6.6	28.0	6.8	28.0	7.2	24.0	7.4
1									28.0	6.7						
1.5	25.5	5.9	28.0	7.3	30.0	6.9	30.0	6.8	28.0	6.7	28.0	6.8	27.5	7.0	24.0	7.4
2									28.0	6.6						
3	25.0	6.1	28.0	7.3	30.0	6.8	29.5	6.8	28.0	6.6	27.5	6.7	27.5	5.8	23.0	7.4
4									27.5	6.4						
4.5	21.5	6.7	25.0	8.2	27.0	8.2	29.0	7.5	27.5	6.2	27.0	6.3	27.0	5.4	23.0	7.0
5									27.5	6.1						
6	19.5	6.8	23.0	7.8	26.0	8.0	27.0	6.3	27.0	5.5	26.5	5.3	26.5	4.4	23.0	6.5
7									26.5	5.0						
7.5	17.5	6.0	21.0	7.4	23.0	7.8	25.0	7.0	26.0	5.2	26.0	4.6	26.0	3.8	23.0	6.3
8									26.0	4.6						
9	16.5	5.1	18.5	6.1	21.0	5.6	23.0	5.7	25.0	3.4	25.5	4.0	25.5	3.6	22.0	6.1
Tail water	17.0	6.4	18.5	6.2	20.0	6.2	20.0	6.6	22.5	5.0	25.5	4.2	24.0	3.4	20.5	6.4

*Discharge regime changed from epilimnial to hypolimnial.

TABLE 4. Standing Fish Crop at Lake Russell as Estimated from Three Cove Rotenone Samples Taken in September 1969 Compared to the Complete Fish Population Inventory Obtained by Reservoir Drainage in November 1969

Species	Drainage, kg/ha	Cove Rotenone, kg/ha
Largemouth bass	6.73	10.87
Black crappie	12.78	14.57
Bluegill*	28.47	28.02
Channel catfish	0.45	0.67
Bullhead†	3.25	4.93
Golden shiner	2.58	1.46
Total	54.25	60.53

*Includes redear sunfish, green sunfish, and redbreast sunfish.

†Includes brown bullhead and yellow bullhead.

operated with an epilimnial discharge during the first 2 years of the project, 1968 and 1969. However, an early malfunction of the discharge mechanism necessitated a reversal of the original schedule. Effective June 7, the discharge regime was shifted to the hypolimnion for the rest of 1968 and for 1969.

Thermal stratification was first detected in March, and the fall overturn occurred by mid-September each year. Stratification was more pronounced in June 1968 than in 1969, doubtless owing to the influence of the epilimnial discharge in effect in the early months of 1968 (Table 3). Likewise, hypolimnial and tail water temperatures remained lower in 1968 than in 1969 until late September.

Oxygen-temperature profiles obtained at 1-meter intervals from the main pool station near the dam indicated the presence of ample dissolved oxygen concentrations at all depths in 1969 during the summer and fall stratification period. All dissolved oxygen determinations were >4 mg/l in the reservoir and tail water with the exception of concentrations of 3.8 and 3.6 mg/l at 7.5 and 9.0 meters, respectively, on August 4, 1969. Dissolved oxygen values in 1968 were >4 mg/l except for a 2-week period in late August and early September, when oxygen deficiencies developed below 6 meters. With these minor exceptions, the reservoir contained sufficient dissolved oxygen at all depths to maintain an adequate biota of fish, plankton, benthos, and aufwuchs throughout the 2-year study period. All other chemical parameters, such as alkalinity, *p*H, hardness, iron, manganese, and so on, fell within acceptable limits.

Fish population sampling. Three cove rotenone samples totaling 1.2 ha were collected in September 1969, prior to reservoir drainage; complete enumeration of the fish population occurred at drainage in November 1969. Table 4 presents the standing fish crop as estimated from the cove rotenone samples compared to the weight of fish recovered after complete reservoir drainage. Combined data for the three cove samples yielded a standing crop estimate of 60.5 kg/ha. This compared favorably with the 54.2 kg/ha actually recovered during the complete drainage of this 36.4-ha reservoir. The standing crop and the relative abundance of major species from both the drainage and the cove rotenone sample data were in reasonably close agreement and thereby indicated that cove rotenone sampling adequately reflected the actual population level of the reservoir.

Gill net sampling of the fish population was undertaken during months of potential reservoir stratification, i.e., July, August, and September, to determine the effects of a hypolimnial discharge regime on the depth distribution of the fish population. These depth distribution studies were carried out by means of four overnight sets of paired 25-, 38-, and 50-cm bar mesh nylon gill nets (91 by 2 meters). Results indicated that several species of fish were randomly distributed as to depth and thereby demonstrated that the fish population used the entire reservoir volume from top to bottom (Table 5).

Benthos sampling. Benthos were collected by Peterson dredge on August 5, 1969, and were supplemented by artificial substrate samplers installed August 6 and retrieved September 3, 1969. Three dredge samples were obtained at 3-meter intervals from top to bottom (9 meters). Artificial substrate samples were obtained from 3, 6, and 9 meters. Numbers of individuals were determined for each sample by major taxonomic groupings and total dry weights (at 105°C). Since oligochaetes seldom were recovered in one piece, the counts were made for total numbers, both with and without oligochaetes. Benthos were found at all reservoir depths in both the Peterson dredge and artificial substrate samplers. The number of organisms, minus oligochaetes, collected per dredge sample averaged 23.5 near

TABLE 5. Depth Distribution of Fishes in Lake Russell in July (J), August (A), and September (S) 1969

Depth, meters	Largemouth Bass			Black Crappie			Bluegill*			Catfish†			Rainbow Trout			Total		
	J	A	S	J	A	S	J	A	S	J	A	S	J	A	S	J	A	S
0 to 1.52	2	3	6				3	1	2		2	2				5	6	10
1.52 to 3.04	2		2	1		1	1	1		2	1	2				6	2	5
3.04 to 4.56		1	1				4	2		3	2	1				7	5	2
4.56 to 6.08		1	2				1	4	1	3	1		1			5	6	3
6.08 to 7.60		2	1				1	2			2	1	1			2	6	2
7.60 to 9.12		1	1		1	1			3	4		1	1		1	5	2	7
9.12 to 10.64		1	1	1	3			1		3			3	1		7	6	1

*Includes redear sunfish, green sunfish, and redbreast sunfish.
†Includes channel catfish, brown bullhead, and yellow bullhead.

the surface, 8.6 at 3 meters, 5.3 at 6 meters, and 4.7 at 9 meters, the maximum reservoir depth. Artificial substrate samples averaged 43.5, 23.0, and 21.5 organisms at 3, 6, and 9 meters, respectively, and thereby indicated that suitable water quality prevailed at all depths to support benthic populations.

Periphyton aufwuchs sampling. Periphyton aufwuchs were sampled in both 1968 and 1969 by using 12.5-cm plexiglass plates measuring 60 by 20 cm suspended at 2-meter intervals from 1 meter below the surface to the maximum depth of 9 meters. A 0.2-m^2 section of each plate was marked off for quantitative determinations (dry weight in milligrams). The 1968 plates were installed September 18 and recovered November 2 after being in place 45 days. The 1969 sampling period extended a maximum of 48 days from July 17 to September 2, well within the period of maximum thermal stratification. Findings in both years indicated that water quality conditions were adequate to support aufwuchs communities at all depths. In 1968 the dry weight of aufwuchs ranged from 696 mg/0.2 m^2 at 1 meter to 82 mg/0.2 m^2 at 9 meters. In 1969 it ranged from 1159 mg/0.2 m^2 at 1 meter to 65 mg/0.2 m^2 at 9 meters.

REFERENCES

U.S. Congress, Fish and Wildlife Coordination Act, 73rd Congress, 2nd Session, March 10, 1934.
U.S. Congress, Fish and Wildlife Coordination Act, *Public Law 79-732*, as amended, 79th Congress, 2nd Session, Aug. 14, 1946.
U.S. Congress, Fish and Wildlife Coordination Act, *Public Law 85-624*, as amended, 85th Congress, 2nd Session, Aug. 12, 1958.

Reservoir Water Quality Control

MARK ANTHONY AND GLENN DRUMMOND

U.S. Army Engineer Division, Ohio River, Cincinnati, Ohio 45201

With the exception of the Tennessee River the Corps of Engineers has extensive water resource development and management responsibilities in the Ohio River basin. Overall development and management objectives include flood control, navigation, water supply, hydropower, flow augmentation, water quality control, recreation, and fish and wildlife. These objectives are being met by meshing the operation of 56 tributary storage reservoirs. In addition, large systems of lock and dam structures maintain navigation pools or channels along the main stem and larger tributaries. Many of the navigation pools are significant in terms of water supply and hydropower.

The Ohio River is formed by the confluence of the Allegheny and Monongahela rivers at Pittsburgh, Pennsylvania. It flows 1580 river km to the west to join the Mississippi River at Cairo, Illinois. The basin drains 528,000 km^2 and lies within four major physiographic divisions: the valley and ridge province, the Appalachian plateau, the interior low plateau, and the central lowlands. The topography is quite diversified and is graduated between the mountains to the east and the low plateaus to the west.

Most of the basin is underlain with two basic groupings of sedimentary rocks: coal measures and a series of calcareous sediments. The coal measures form the Appalachian plateau in the eastern third of the basin and underlie parts of the central lowlands to the west. They consist of a great series of sandstones and shales containing many important coal beds. The calcareous rocks, consisting of limestones and shales, underlie a broad belt in the central part of the basin. Much of the drainage to the north of the Ohio River below Portsmouth, Ohio, has been glaciated.

The climate of the basin is temperate. Rainfall and runoff tend to be high in winter and spring and low in summer. Average annual precipitation varies from 129.5 cm at the southwestern boundary to 109.2 cm in the extreme northeast and from 154.4 cm in the extreme southeast to 94.0 cm in the northwest. Storms have occurred with precipitation averaging 16.51 cm in 48 hours over 95,800 km^2. On the other hand, monthly rainfalls averaging as low as 4.32 cm have persisted for 6 months at a time over much of the basin. The average annual discharge furnishes about 60% of the Mississippi River flow at the point of confluence and about 45% of the flow at New Orleans, Louisiana.

Approximately one third of the area is used for intensive agriculture. Livestock, corn, soybeans, small grain, and tobacco are the chief products. Rich natural resources, including coal, oil, natural gas, limestone, fire clay, and lumber, help to support an extensive and varied industry. The production of steel, glass, distillery products, chemicals, rubber, paper, automobiles, and electrical machinery is significant on a national scale.

All these diverse watershed activities and a population of about 20 million (1970) represent a spectrum of extensive and often critical demands on water resource needs and uses. One of the most important of these demands is the requirement for reservoir discharge for low-flow augmentation to maintain the in-stream assimilation of thousands of tons of domestic, industrial, mining, and other types of wastes. Even if tertiary waste treatment becomes universal, this requirement will continue to be a perpetual water management problem in this basin.

The need for flow augmentation is partially met by the routine operation of the reservoir system in meeting flood control and navigation objectives. Regulated release of summer storm runoff and of storage specifically provided for low-flow augmentation can at times constitute as much as two thirds of the total flow in parts of the main stem. The reduction of reservoir pool levels in late summer and early fall also offsets the most critical low-flow problems. In addition, special storage for specific water quality problems is provided in some reservoirs.

The problem of protecting the quality of reservoir storage and discharge has become increasingly critical. Rapid commercial development and increasing population have generated an intense dependence on reservoir storage as well as a degradation of reservoir inflows. Although progress is being made toward pollution control at the source, this will resolve only part of the overall problem.

Typically, the reservoirs in this basin are thermally stratified. Usually, there is sufficient organic loading to result in oxygen depletion below the thermocline. Sedimentation has not been a significant problem to date, but it might be for a few proposed reservoirs. There are several other factors or conditions that are common in many of the reservoirs; e.g., in the coal regions, sulfuric acid, sulfates, iron, and manganese tend to be universal problems.

In spite of many similarities, each of the 56 existing reservoirs tends to be unique in one or more water quality factors. These differences may constitute significant problems in understanding the cause and effect relationships of chemical and biological reactions as well as the operation of reservoirs. Relationships involving the size and shape of the impoundment, the watershed area, and the topographic, geologic, hydrologic, and land use characteristics are obvious and predictable. For example, the storage in a small reservoir is extremely vulnerable to acid mine wastes unless it is highly buffered. Elsewhere, the factors are too subtle, or so many variables are involved that measurement, correlation, and prediction are difficult. For example, reservoir inflow will seek a level of identical density, which could be above, within, or below the thermocline. The reactions that occur then may vary drastically depending on the presence or absence of oxygen, the water temperature, the materials in solution or suspension, and the kinds and numbers of organisms present.

The initial reservoirs in this basin were provided with only bottom discharge. Biologists eventually pointed out that a radical change to the downstream aquatic environment was being brought about by discharges of cold water into a previously warmwater stream. Other detrimental effects were also brought to light. As a result, attempts were made to achieve greater flexibility for reservoir discharge control. A series of structures were built with low-flow bypass arrangements permitting discharge from various pool elevations. The Corps of Engineers has been extensively involved in evaluating and in seeking to improve this capability.

Preimpoundment water quality surveys are now essential to provide design criteria for selective withdrawal structures and guidelines for reservoir regulation in terms of water quality requirements. Heat budget analysis and prediction of temperature characteristics provide the basis for the design criteria and for the evaluation of the relationship of storage to tail water temperature objectives. It is believed that correlations and predictions of other parameters can be refined and integrated in the design and operating approaches.

Although thermal stratification has been studied in the oceans and in natural freshwater lakes for many years, only recently has attention been given to man-made reservoirs with the thought of controlling the quality of stored and released water. It was observed that thermal gradients in impoundments differed noticeably from those in natural lakes. In fact, impoundments having similar volumes and surface areas and located in close proximity to each other differ significantly.

Although the sources of energy and the mechanisms responsible for thermal stratification are the same in both instances, the difference lies in the effect of net advection in terms of energy and mass. The ratio of inflow and outflow volume to storage varies over a wide range for man-made reservoirs, whereas it is generally an insignificant factor in natural lakes. Water entering a stratified impoundment or lake can spread over the surface or occupy a discrete layer at a level of neutral buoyancy according to its temperature-density relationship. Outflow from a natural lake occurs at the surface, whereas the outlet structure of a man-made reservoir may allow withdrawal from any level. Low-level discharge results in the downward displacement of the warm upper layers, which causes a more gradual thermal gradient than that found in the classic lake profile.

Because of the temperature-density relationship a well-defined thermal gradient serves as a highly flexible diaphragm separating the epilimnion from the hypolimnion. Although the corresponding density gradient is small in magnitude, it is sufficient to form a barrier to the vertical transfer of thermal energy.

In addition to being an energy barrier the density gradient effectively isolates the hypolimnion storage from the surface reaeration process. If there is even a moderate amount of organic matter suspended in the lower levels, oxygen depletion is swift once the transfer of dissolved oxygen is blocked. As the dissolved oxygen concentration nears total depletion, facultative and anaerobic microorganisms proliferate in and above the mud-water interface. Some use mineral oxides, sulfates, and more complex inorganic compounds as a source of energy, whereas others decompose organic matter. The mineral compounds are thus reduced to their more soluble state, whereas the waste products of the decomposition process include carbon dioxide, hydrogen sulfide, and methane. Part of the dissolved carbon dioxide dissociates to form a weak acid. This dissociation lowers the *p*H, a more favorable environment for the solution of the reduced forms of iron, manganese, and sulfur compounds thus being created.

To achieve optimal control of such factors, two areas of activity are being expanded to improve the design and operation of selective withdrawal structures. Laboratory investigations of density currents have been conducted to develop techniques for analyzing the features of the withdrawal zone. Mathematical models are also being used to simulate the thermal characteristics of impoundments.

Density currents, long familiar to oceanographers, are being studied with hydraulic models. These studies are yielding information pertaining to the vertical dimensions of the withdrawal zone, the velocity distribution within the zone, and the relationship of the shape and location of the intake port to these factors. Prototype verification has been difficult because of the small velocities involved. However, by integrating the computed velocity profile and prorating density according to the discharge distribution, one can determine the density of the outflowing water. These values are in very close agreement with observed release temperatures.

The basinwide environmental impact of a reservoir system is not the only aspect of water management that is difficult to depict. There is a tendency to oversimplify grossly day-to-day operating problems, hydrologic procedures, and the involved decision-making process.

The extent of meteorological variance and the limited reliability of rainfall and runoff predictions necessitate careful daily analysis. Summer storms may produce intense rainfall over one or a series of reservoir watersheds. Rainfall generated by hurricanes and tropical storms is an additional and most imposing threat in the basin. Drought provides another set of complications in terms of evaluating current conditions and the consequences of judgment decisions.

An equally demanding aspect is the consideration of priorities and alternatives involving the various requirements and uses of reservoir storage. It is impossible to avoid incompatibility between water use interests, and the conflict is usually intensified during hydrologic extremes. These conflicts may involve strictly local versus regional interests, such as desires for stable pool levels versus downstream needs for discharge. On the other hand, national interests may be involved if the problem involves a power shortage or consequential flood damages. In spite of all the available logic based on safety factors, economic guidelines, and the hard facts of hydrologic reality, resolution may be difficult.

A Big Lake Cooling System

DANUTA JURAK

State Hydrological and Meteorological Institute, Warsaw, Poland

ZDZISLAW KACZMAREK

Warsaw Technical University, Warsaw, Poland

When we discuss man-made lakes, we usually have in mind the artificial reservoirs constructed for hydroenergetic needs, flood control, water supply, and so on. Sometimes, however, the influence of human activity on natural lakes can cause such essential changes in their regimes that a body of water representing completely different hydrologic features, especially hydrophysical and hydrochemical ones, is actually created. Studies of such an altered natural body can have importance from the engineering and natural environment protection point of view. In this paper we present the results of studies on the group of lakes that is part of the cooling system of two thermal power stations, which have a total capacity of about 1800 Mw. According to the available data it is one of the largest systems of this kind in Europe. The relatively small depth of these lakes, their characteristic feature, enables the mixing of waters. The conclusions are applicable to other lakes having similar characteristics and similar climatic conditions. The studies were conducted during 1968–1970 by a group of Polish specialists with the assistance of the United Nations Development Program, the World Health Organization acting as the executive agency.

KONIN LAKES

The five lakes studied are presented in Figure 1 and described in Table 1. By way of further simplification we will mark these lakes with the letters S, L, W, P, and G. Lakes S, L, and W are tunnel valley lakes and are characterized by a long narrow syncline. Lakes P and G are shallow morainic lakes of relatively large surfaces and very small depths. The surface of the Konin Lakes basin is small, only 411 km^2. Because basin precipitation is not large and evapotranspiration is rather high, the natural inflow to these lakes is insignificant, and to a considerable degree it evaporates from the water surface.

Figure 1 also shows the locations of two thermal power stations, which have capacities of 1200 Mw and 600 Mw, respectively. Both stations work on the basis of an external cooling system, the fundamental element of which is the Konin Lakes. The total water intake by these two stations from lakes P and G averages about 70 m^3/sec. After the water is heated about 7°–8°C, it is discharged into the lakes by a complicated system of channels. The fact that during 11 days the lakes take in 66 million m^3 of water, i.e., as much as the total volume of the Konin Lakes, emphasizes the quantity of water intakes and discharges.

The Konin Lakes are situated in the central part of Poland. The mean annual air temperature is 8.2°C; the amplitude of monthly values oscillates from −2.3° (January) to 18.3°C (July). The relative air humidity is about 70% during the summertime and about 85% during the wintertime. The mean annual precipitation amounts to 540 mm in the Konin region.

PURPOSE AND METHODS OF STUDY

The main purpose of the studies has been to determine the values of the energy balance components of lakes with artificial heat advection and to compare these values to the natural conditions. The analysis of the thermal relations in the lakes in the cooling system has been one of the tasks because the water temperature plays an important role concerning both the effective work of the thermal power station and the biocenosis of lakes. The determination of the

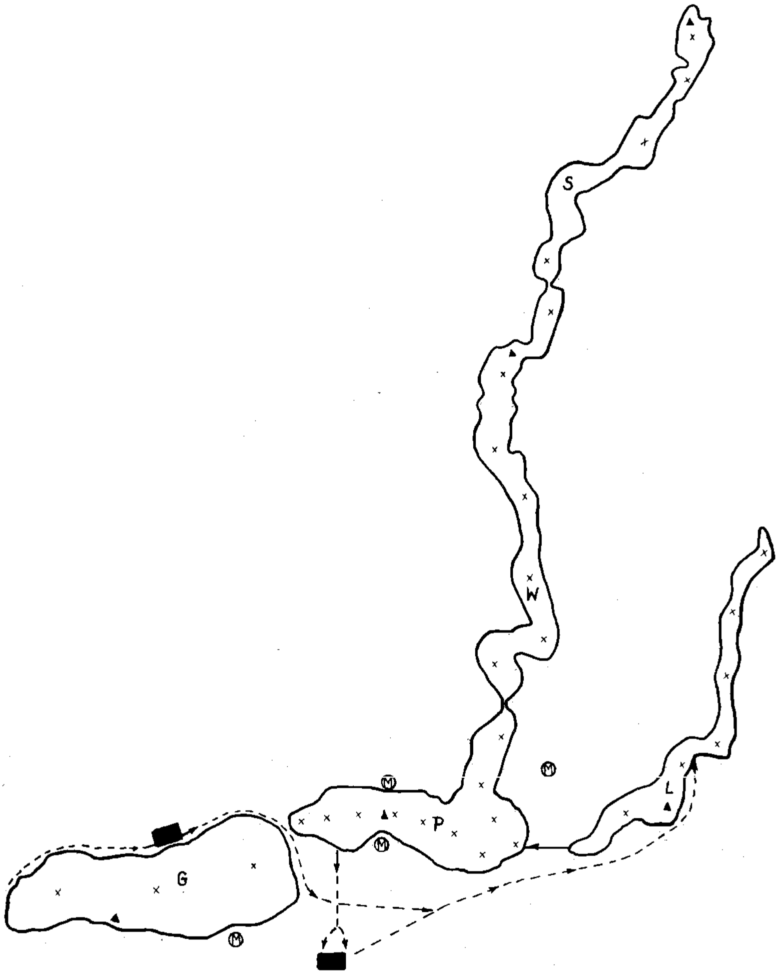


Fig. 1. Konin Lakes. A circled M represents a meteorological station, solid triangles represent evaporimetric stations, crosses represent vertical profiles of water temperature, solid rectangles represent thermal power stations, and dashed lines represent discharge and intake channels.

changes in the temperature and humidity of air masses flowing in over the lakes has been an additional task. These changes result from the influence of the water surface on the turbulence processes in the lower layer of the atmosphere.

These studies have been considered experimental. They have taken into consideration the theoretical relationships among the individual elements of the energy balance, the meteorological conditions, and the characteristics of the water surface. The measurement network is composed of several observation posts situated around the lakes as well as several floating stations for evaporation measurements and measurements of the hydrometeorological elements. The locations of the most important observation posts have been presented in Figure 1. They were equipped with modern apparatus to measure the components of radiational balance and meteorological parameters.

As has been mentioned previously, the main purpose of the studies was the determination of the energy balance components of the lakes, which can be simplified to the formula:

$$Q_f + Q_v - Q_e - Q_h = \Delta B \qquad (1)$$

in which

Q_f, radiation balance of the water surface considering the short- and long-wave radiation incident to the water surface and reflected from it;

Q_v, heat advection calculated as the difference between the heat coming into and that taken from the lake as a result of natural flows as

TABLE 1. Certain Morphometric Features of the Konin Lakes

Lake	Symbol	Surface, m^2 in thousands	Length, meters	Mean Width, meters	Mean Depth, meters	Volume, m^3 in thousands	Morphologic Type
Ślesińskie	S	1512.5	4385	338	7.4	12,742.3	tunnel valley
Licheńskie	L	1462.5	5525	278	5.7	8,348.4	tunnel valley
Wąsowsko-Mikorzyńskie	W	2225.0	6620	370	11.9	28,865.7	tunnel valley
Pątnowskie	P	2770.5	3685	752	2.6	7,155.9	morainic
Gosławskie	G	4380.0	3980	1049	2.1	9,159.2	morainic

well as intakes and discharges from the thermal power station;

Q_e, total heat used for the evaporation process including heat carried away as a result of the water decrease caused by evaporation, that is, $Q_e = \zeta_w E(L + c_w T_0)$, where E is the evaporation value, ζ_w and c_w are the water density and the specific water heat, and L is latent evaporation heat;

Q_h, heat taken from or coming into the lake as a result of the convection process, calculated here on the basis of evaporation value and Bowen's relation, that is, $Q_h = \zeta_w LER_b$;

ΔB, increase or decrease of heat in lake in the given balance period.

All elements of the energy balance have been determined on the basis of the methods presented by the *World Meteorological Organization* [1966].

The results of the calculations have been checked by comparing both sides of (1) or by comparing the evaporation calculated from the altered equation of the balance to the results of measurements.

$$E = \frac{Q_f + Q_v - \Delta B}{\zeta_w(L + c_w T_0 + LR_b)} \tag{2}$$

The evaporation was measured by evaporimeter GGi-3000, certain alterations being taken into account [*World Meteorological Organization*, 1966].

Note that during the period of measurement lake L has been loaded with considerable quantities of thermal energy from the thermal power station, whereas lake S (of similar morphometric conditions) has not been included in the cooling system. This situation, one lake under the influence of human activity and the other under natural conditions, created especially convenient and unique conditions for comparing the energy balance components. Therefore we shall concentrate in the next section on only these two lakes. Additional data representing the thermal conditions and the influence of the thermal water discharges on these conditions will also be presented.

The problem of the transformation of the temperature and humidity of air flowing in over the reservoir will not be dealt with at length. During the studies of the Konin Lakes the usefulness of the theoretical models of *Sutton* [1953] and *Timofeev* [1963] has been verified. These models permit calculation of the temperature T and humidity e values over any point of the lake provided the following data are available: the initial conditions, i.e., the temperature and humidity of the lakeshore and the water surface temperature, and the parameters characterizing the turbulence processes in the lower layer of the atmosphere. These studies have been aimed at determining the possibility of forecasting microclimate changes in the planned reservoir region or changes resulting from artificial thermal changes of the existing lake. Formulas from *Sutton* [1963] and *Timofeev* [1963] have been the basis for such forecasting:

$$e(x, z) = e_1 + (e_0 - e_1)F(L, n) \tag{3}$$

$$T(x, z) = T_1 + (T_0 - T_1)F_1(L, n) \tag{4}$$

in which

$T(x, z)$, air temperature at height z and distance x from the lakeshore;

$e(x, z)$, air humidity at height z and distance x from the lakeshore;

T_1, air temperature over land;

e_1, air humidity over land;

T_0, temperature of the water surface;

e_0, saturation water vapor pressure at temperature T_0;

$F(L, n)$ and $F_1(L, n)$, incomplete gamma functions depending on x and air turbulence.

The results of these studies are presented here on the basis of *Kasprzycka* [1970].

ENERGY BALANCE OF LAKES S AND L

Now we will present the results of the studies on the energy balance of lakes S and L for the

TABLE 2. Values of the Thermal Balance Components of Lakes S and L from November 1968 to October 1969

Component, cal cm^{-2} day^{-1}	Lake	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Yearly Mean
Q_f	S	-23.3	-31.4	-35.6	14.8	49.3	265.9	242.3	326.5	329.8	186.4	148.8	53.4	127.2
Q_f	L	-90.9	-135.8	-104.5	-73.9	13.2	106.2	182.6	244.8	273.6	132.6	73.6	-41.0	48.4
Q_v	S	0	0	0	0	0	0	0	0	0	0	0	0	0
Q_v	L	461.2	492.8	497.0	486.3	544.5	507.4	509.2	509.0	608.9	470.2	692.0	376.2	512.9
Q_e	S	60.0	6.0	6.0	15.5	16.4	71.5	150.2	209.2	263.6	222.3	161.9	87.4	105.8
Q_e	L	265.4	228.1	180.6	245.5	238.6	319.7	480.4	530.4	620.3	594.1	542.1	323.0	380.7
Q_h	S	16.5	8.0	9.0	21.3	16.2	85.6	11.1	42.6	-1.2	15.9	29.8	31.8	23.9
Q_h	L	176.0	228.9	202.6	263.6	229.5	158.6	138.3	144.4	133.6	167.2	180.4	147.7	180.9

TABLE 3. Comparison of the Measured Evaporation Values *E* and Those Calculated by (3) from November 1968 to October 1969

Lake	Method	Nov.	Dec.	Jan.	Feb.	March	April	Total Dec. to April	May	June	July	Aug.	Sept.	Oct.	Total Nov. to Oct.
S	calculated	35.9	...	...	...	...	...	65.8	76.8	90.0	144.9	121.0	98.0	41.6	674.0
S	measured	31.4	...	...	...	...	...	57.9*	83.9	103.8	134.5	113.4	83.5	45.0	653.4
L	calculated	136.4	111.9	95.9	112.9	120.4	159.9	...	240.7	260.3	310.2	309.7	288.0	152.3	2298.6
L	measured	132.1	117.0	93.1	104.7	123.0	159.0	...	245.3	261.8	315.0	302.2	267.9	166.4	2287.5

Values are given in millimeters.
*Calculated by *Konstantinov*'s [1968] method (3).

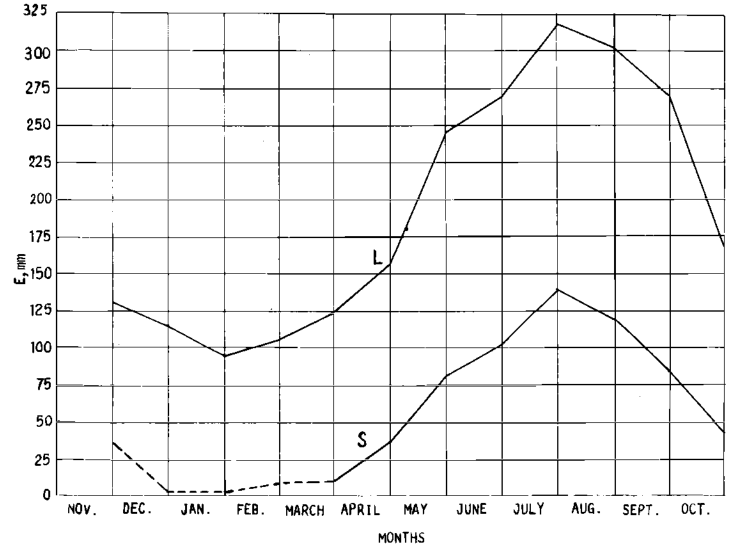


Fig. 2. Evaporation values for lakes S and L.

hydrologic year 1968–1969. These lakes were chosen because one has been under natural conditions and the other has been loaded with considerable quantities of thermal energy from the thermal power station. This year was chosen because all the required measurement data were available and it was a year of relatively high air temperatures during the summertime.

The monthly values of the energy balance components [*Jurak,* 1972] for both lakes and their differences are presented in Table 2. For the whole period, $Q_v = 0$ for lake S. For lake L the mean annual value of this element has been very high, 512.9 cal cm^{-2} day^{-1}, and has caused considerable changes of all the remaining components. The verification of the calculations, based on a comparison of the measured evaporation value and that calculated by (2), has been given in Table 3. The accordance can be recognized as satisfactory.

The analysis of the values given in Tables 2 and 3 permits us to draw several conclusions. The values for the radiation balance Q_f are higher during the whole year for lake S than for lake L as a result of the difference in the long-wave radiation of water, which is considerably larger for lake L than for lake S because the water surface temperature of lake L is higher. It is necessary to pay attention to great differences in the evaporation values E and heat energy values Q_e for both lakes. These differences are particularly high during the wintertime; e.g., $E_L/E_S > 30$ in certain months. For the whole year the values of evaporation amount to $E_L = 2288$ mm and $E_S = 653$ mm, as shown on Figure 2; the E_S value is typical for the natural lakes in the central part of Poland. The same relationship applies to values of Q_e. A comparison of the values of Q_h shows that the heat energy conducted from the lake as a result of convection processes is larger

TABLE 4. Temperature Values for Lakes S and L from November 1968 to October 1969

Thermal Characteristics of S and L	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.
Mean temperature*												
S	6.48	3.69	3.57	3.69	4.00	6.52	11.51	15.07	16.78	15.44	13.67	10.11
L	13.72	10.37	8.31	8.19	8.99	16.40	21.96	24.62	26.39	24.40	22.52	17.39
Temperature for 40-cm depth												
S	6.8	...	...	...	...	...	14.7	18.3	18.9	19.5	16.2	11.2
L	14.9	10.8	8.2	9.2	9.1	15.6	23.2	25.8	27.8	26.5	24.2	18.7

*Approximate values.

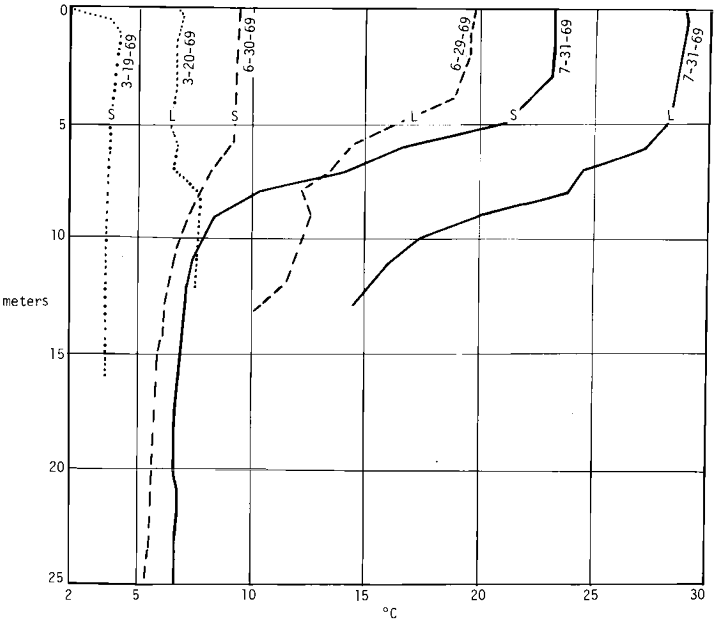


Fig. 3. Vertical distributions of water temperature in lakes S and L.

for lake L, loaded with thermal water discharges, than for lake S. The differences, however, are smaller than they are for Q_e, and, because of the periodic decrease of the water and air temperature gradient, there are periodic oscillations of the relationship Q_{hL}/Q_{hS}.

So the additional advection of heat energy from the thermal power station changes the energy balance of the lake considerably. These changes are revealed especially during the wintertime and are characterized by a most significant discordance between the natural regime of the meteorological elements and the high water temperature of the lake. High thermal gradients formed over the surface of such a lake change the stability conditions of the layer of the atmosphere next to the water and also stimulate heat energy exchange processes between the water surface and the atmosphere. Accordingly, in winter as well as summer, lakes that are in similar climatic conditions have great cooling possibilities and can be used effectively for this purpose. The additional heat advection also causes essential changes in the thermal conditions of the lake. This problem will be discussed later.

TABLE 5. Comparison of the Quantity of Algae Species in Lakes S and L

Name	S	L
Chlorophyceae	19	85
Bacillariophyceae	52	74
Cyanophyceae	5	20
Euglenophyceae	8	11
Dinophyceae	4	2
Chrysophyceae	2	2
Xanthophyceae	0	1
Total	90	195

THERMAL CONDITIONS IN LAKES S AND L

The mean monthly values of the water temperature for both lakes have been given in Table 4 on the basis of *Jurak* [1972] for the whole water mass in the lake and for the standard 40-cm depth. As is expected, the temperatures are considerably higher in lake L than in lake S. From May to October in both lakes the epilimnion, 5-8 meters deep, has been formed; the differences in water temperature in this layer oscillate from 6° to 10°C in the same period. Several examples of the vertical temperature distribution in lakes L and S are given in Figure 3. The total cooling effect of the Konin Lakes system expressed as the difference between the water temperature of the discharge and that of the intake has averaged about 8° to 10°C. This can be considered satisfactory from the point of view of the needs of the thermal power station.

TABLE 6. Values of T and e for the Land and Lake P

Hydrometeorological Element	May 11 to 20, 1969			August 11 to 20, 1969			October 11 to 20, 1969		
	7:47* A.M.	12:47 P.M.	8:47 P.M.	7:47 A.M.	12:47 P.M.	8:47 P.M.	7:47 A.M.	12:47 P.M.	8:47 P.M.
T_1, °C	12.8	18.3	12.8	14.5	19.5	16.5	5.1	12.6	8.8
e_1, mb	11.4	11.7	13.2	14.2	14.4	15.4	8.7	11.1	11.6
T_0, °C	20.2	20.8	20.5	22.5	23.0	23.1	15.5	16.0	15.8
$T(x)$, °C									
Lake†	13.8	18.8	15.4	15.5	20.1	17.7	6.3	13.0	9.8
Land§	13.6	18.7	15.2	15.4	20.0	17.5	6.2	12.9	9.7
$e(x)$, mb									
Lake†	12.4	13.3	14.5	15.5	16.0	16.9	9.4	11.7	11.9
Land§	12.6	15.3	14.4	15.6	16.3	16.8	9.6	11.6	11.8

*Official time.
†Values calculated by (3) and (4).
§Values measured at the meteorological station.

The increase of water temperature in the lake affects the biological processes occurring in the aquatic environment. The investigations on this influence require systematic observations over the years, and they are being continued on the Konin Lakes area at present (and so are measurements of the energy balance components). As the preliminary results published by *Baskiel et al.* [1967] indicate, the increase in temperature has caused considerable changes in the phytoplankton, consisting of an increase of algae production and an increase of the number of algae species. The comparison of their quantities in the spring and summer for lake S (under natural conditions) and lake L is given in Table 5. The preliminary results of the studies indicate also that during the period of the highest temperatures the zooplankton production in lake L was 4 times higher than that in lake S; the changes in its species composition of lake L were insignificant. The investigations being conducted at present aim at the determination of the influence of the water temperature increase on the intensification of fish breeding for fishery needs and also at the extent of this influence.

CHANGES IN AIR TEMPERATURE AND HUMIDITY OVER LAKES

It is well known that every big body of water causes changes in the microclimatic conditions above the water surface and also in its surroundings. To determine these changes for heat energy advection to the lake, experimental and theoretical studies were conducted during 1966–1970 in the Konin Lakes area, especially on lake P. Lake P has been chosen because of its larger dimensions (width) in relation to lakes S and L. The values of temperature T and humidity e over the land and over the lake 500 meters from the bank are given in Table 6. The values over the lake have been calculated by (3) and (4). To save space, the table is limited to the values mentioned above for several characteristic periods in the hydrologic year 1968–1969.

The results of the studies indicate that the changes of air temperature and humidity have not been particularly important, probably because the lakes under study do not have very large surfaces. It is obvious that the differences of temperature and humidity over the land and over the lake increase as the differences of air temperature and water surface temperature T_0 in the lake increase.

Acknowledgments. The authors wish to express their gratitude to the authors of the Projekt Polska 26 report and to the technical staff and consultants of the World Health Organization, Professor P. A. Krenkel in particular.

REFERENCES

Baskiel, T., L. Horosiewicz, K. Patalas, and J. Zawisza, Próba oceny wpływu zrzutów wód podgrzanych na ichtiofaunę i kierunki produkcji rybackiej, J. G. K., Poznań, 1967.

Jurak, D., Bilans cieplny jezior i jego zmiany pod wpływem zrzutów wod podgrzanych, *Pr. Pol. Hydrol. Meteorol. Inst., 107,* 1972.

Kasprzycka, E., Metoda obliczania transformacji masy powietrza naplywającego na zbiornik wody o średniej wielkości, *Pr. Pol. Hydrol. Meteorol. Inst.*, *99*, 1970.

Konstantinov, A. R., *Isparenje v Prirode*, Gidromietizdat, Leningrad, 1968.

Sutton, O. G., *Micrometeorology*, pp. 303-354, McGraw-Hill, New York, 1953.

Timofeev, M. P., *Meteorologičeskij Režim Vodoemov*, pp. 20–95, Gidromietizdat, Leningrad, 1963.

World Meteorological Organization, Measurement and estimation of evaporation and evapotranspiration, *Tech. Note 83*, pp. 65–75, Geneva, 1966.

Eutrophication of Small Reservoirs in the Great Plains

GARY L. HERGENRADER

Department of Zoology, University of Nebraska, Lincoln, Nebraska 68508

MARK J. HAMMER

Department of Civil Engineering, University of Nebraska, Lincoln, Nebraska 68508

The Great Plains region does not have a large number of natural lakes. However, many reservoirs have been constructed in recent years by the Soil Conservation Service, the Bureau of Reclamation, and the U.S. Army Corps of Engineers for flood control and soil conservation. Many of these impoundments have facilities such as boat ramps, bathhouses, sand beaches, and campsites to provide a measure of water-based recreation for residents of the area. Yet, the demand for additional recreational waters by the general public continues unabated. More and more of the costs for new dam construction are being charged to recreational benefits, both because it is recognized that reservoirs constructed to provide water recreation constitute justifiable expenditures of public funds and also because the total benefits that can accrue from additional land treatment are declining as an increasing percent of the land area receives modern soil conservation and flood control practices.

Unfortunately, as laudable as efforts to secure additional recreational waters in the Great Plains may be, it appears that many of the small reservoirs, present and future, will be troubled by excessive and rapid eutrophication, resulting in deterioration of their recreational uses after a few years of existence. The naturally fertile soils of the region, the widespread application of fertilizers to agricultural lands, and the development of the livestock-feeding industry can all contribute to high nutrient loads in runoff water. It is natural that reservoirs impounding nutrient-rich water should be productive and have the potential to generate nuisances, which interfere with projected recreational uses.

The Salt Valley watershed district in eastern Nebraska contains 10 sizable reservoirs constructed by the U.S. Army Corps of Engineers for flood control with recreational facilities developed by the state of Nebraska. Hunting, fishing, swimming, boating, hiking, picnicking, and camping are all popular activities provided by these facilities. The reservoirs are located within a 32-km radius of Lincoln, Nebraska, and range in age from 3 to 8 years. Several of them are already exceedingly eutrophic and exhibit many of the symptoms of advanced eutrophication.

In the summer of 1968 limnological studies of five of these reservoirs were initiated with these specific objectives: (1) to determine the existing trophic conditions, (2) to estimate the rate of eutrophication, if it was possible, by measuring changes in several parameters [*Fruh et al.*, 1966], (3) to identify sources of nutrient inputs, and (4) to evaluate preventive and remedial measures. The preliminary results reported herein are extracted from work still in progress; more detailed information will be provided in subsequent publications.

METHODS

During June, July, and August, each of the study reservoirs (Holmes, Wagon Train, Pawnee, Stagecoach, and Branched Oak) is sampled at weekly intervals. Weekly sampling continues on Pawnee throughout the year except during ice cover, when the reservoir is sampled at less frequent intervals. Vertical profiles of dissolved oxygen and temperature are determined with a dissolved oxygen–temperature monitor at each of three permanent stations on each reservoir except Stagecoach, which has only two permanent stations. Underwater light intensity is measured with a submersible photometer, and transparency is determined by using a Secchi disk. Water samples are collected at each meter of depth with a Van Dorn bottle, and a sample representing each station is composited. Oblique tows from bottom to surface are made with a Clarke-Bumpus sampler, and bottom samples are obtained with an Ekman dredge along transects crossing the reservoirs at each station. The water samples are analyzed in the laboratory for alkalinity, *p*H, hardness, total dissolved and suspended solids, iron, chemical oxygen demand, orthophosphate and total phosphate, ammonia, nitrate and organic nitrogen, chloride, sulfate, and turbidity. All analyses are performed by the standard methods published by the *American Public Health Association* [1965] except those for sulfate, iron, and turbidity, which are measured with a Hach Drel (direct reading engineer's laboratory) kit. Orthophosphate and total phosphate are determined on the filtrate of filtered samples, but all nitrogen analyses are performed on unfiltered water. Chlorophyll is determined according to the method outlined in *Golterman and Clymo* [1969]. The genera of algae present are identified in fresh whole mounts; numbers are determined according to the method of *McNabb* [1960] and converted to volume by appropriate formulas.

Carbon^{14} primary production is studied at frequent intervals in situ at the deepest station of each reservoir. A 4-hour incubation period with solar noon as the midpoint has proved to be adequate. Aerial flights over the reservoirs are made during the summer to record on Aero-Infrared and Ektachrome films the relative development of algae and rooted aquatics. Although striking pictures are obtained, they provide only a relative index of the spread and development of aquatic plants.

RESULTS

Of the several parameters being studied, temperature, nutrient content, Secchi transparency chlorophyll, and primary production will be emphasized here to illustrate the eutrophication trends in these reservoirs. Pertinent physical features of the study reservoirs are given in Table 1. All the reservoirs are relatively shallow and are exposed to the constant winds characteristic of the Great Plains region. Consequently, permanent thermal stratification does not develop during the summer. Weak stratification may develop following several days of calm, but it is easily destroyed with the return of windy weather. The reservoirs warm rapidly in the spring and cool quickly in the fall. The rapid warming can promote the predominance of blue green algae in early summer in some of the reservoirs. The vertical variation of temperature seldom exceeds 2°C, but the mean temperature of the entire water column fluctuates widely with changes in air temperature. It is not uncommon for the water mass to change by 7°–9°C in the course of 1 week in the spring and fall. Figure 1 shows the annual temperature cycles for Pawnee Reservoir commencing June 1968 and continuing through September 1970. This magnitude of temperature variation is also typical of the other four reservoirs. The duration of ice cover depends on the ambient air temperatures.

The reservoirs can be conveniently divided into two groups based on the nature of their water turbidities. Pawnee, Stagecoach, and Branched Oak are relatively clear water reservoirs whose turbidities result mainly in the summer from algal populations. Wagon Train and Holmes are exceedingly turbid from colloidal dispersions of clay and silt maintained in suspension by prevailing winds. Soil turbidity is the most important parameter regulating production in these two reservoirs. Because they are light limited, troublesome blooms of blue green algae do not occur, even though substantial quantities of nutrients are present (Table 2). Rooted aquatic

TABLE 1. Physical Features of the Study Reservoirs

Name	Date of Completion	Surface Area, hectares	Maximum Depth, meters	Mean Depth, meters	Watershed Area, hectares
Holmes	1962	45.3	4 to 5	1.9	1,386.2
Stagecoach	1964	78.9	5	3.0	2,513.4
Wagon Train	1962	127.5	7	2.6	4,042.1
Pawnee	1965	299.6	8	3.7	9,224.3
Branched Oak	1967	728.7	8	4.4	22,983.0

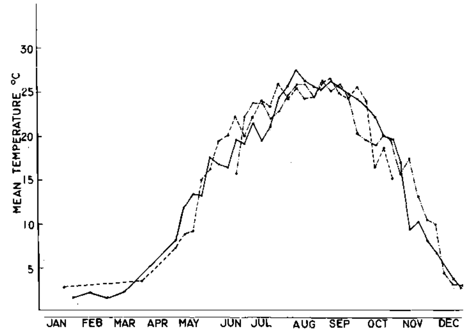


Fig. 1. Annual temperature cycles for Pawnee Reservoir commencing June 1968 and continuing through September 1970. The magnitude of variation shown is characteristic of the other four study reservoirs. The dash dot line represents 1968, the solid line represents 1969, and the dashed line represents 1970.

plants, principally *Polygonum* and *Sagittaria*, are confined to the shoreline. The average Secchi disk transparency for Holmes is usually <0.3 meter, and that for Wagon Train is <0.6 meter (Table 2). These turbid waters have occasionally begun to clear after a few days of calm, and algae, responding quickly to the improved lighting, have rapidly established substantial populations. Inevitably, wind-induced mixing resuspends the soil particles, and population growth declines. In Wagon Train Reservoir, normally less turbid than Holmes, carbon fixation rates per unit of chlorophyll with improved light conditions approximate the values obtained in the clear reservoirs (Table 3). However, under usual conditions, carbon fixation appears to be limited by insufficient light.

The dominant phytoplankton in the turbid reservoirs (Holmes and Wagon Train) are completely different from those in the clear reservoirs. Diatoms, mainly *Cyclotella*, *Melosira*, and *Stephanodiscus*, and flagellates, mostly *Trachelomonas* and *Euglena*, are the dominant forms. Various species of green algae are present but usually in small numbers. Blue greens also occur but never become very abundant. The chlorophyll content of these reservoirs is less than that of the clear water reservoirs; furthermore, there has been no consistent trend observed in the average content of chlorophyll during the three summers (Table 4). Neither have there been progressive changes in quantities of macronutrients except for a consistent decrease in the total phosphorus. In 1969, nitrate levels reached very high values, probably a reflection of the higher than average spring runoff (Table 2).

The situation in the clear water reservoirs (Pawnee, Branched Oak, and Stagecoach) is quite different from the conditions found in the turbid impoundments. During the summer these reservoirs contain extensive beds of rooted aquatics, primarily *Potamogeton pectinatus*, *P. americanus*, and *Polygonum* with some *Najas*. Weed growths hamper swimming, water skiing, boating, and fishing. Obnoxious blooms of blue green algae

TABLE 2. Summer Means (June to August) of Selected Physical and Chemical Parameters in the Study Reservoirs

Date	Secchi Depth, inches	Alkalinity, mg/l $CaCO_3$	Orthophosphate, mg/l PO_4	Total Phosphate, mg/l PO_4	NH_3 Nitrogen, mg/l N	NO_3 Nitrogen, mg/l N	Total Dissolved Solids, mg/l	pH
				Holmes				
1968	9 (23)	99	0.22	0.49	0.36	0.44	185	8.0
1969	10 (25)	102	0.27	0.35	0.44	0.99	181	8.1
				Wagon Train				
1968	23 (58)	174	0.18	0.56	0.32	0.22	244	8.1
1969	11 (28)	129	0.14	0.25	0.33	1.49	221	7.9
1970	20 (51)	178	0.04	0.13	0.28	0.10	269	8.2
				Pawnee				
1968	80 (203)	164	0.16	0.47	0.35	0.21	210	8.3
1969	72 (183)	139	0.05	0.29	0.45	0.30	198	8.4
1970	24 (61)	156	0.04	0.12	0.35	0.09	220	8.2
				Branched Oak				
1968	93 (236)	235	0.20	0.51	0.37	0.28	325	8.2
1969	68 (173)	200	0.22	0.36	0.40	0.48	335	8.2
1970	44 (112)	186	0.05	0.13	0.47	0.11	280	8.4
				Stagecoach				
1969	41 (104)	130	0.06	0.22	0.69	0.25	231	8.3
1970	27 (69)	135	0.04	0.12	0.49	0.08	243	8.7

Values in parentheses are given in centimeters.

TABLE 3. Representative ^{14}C-Chlorophyll Relationships in the Study Reservoirs

Date	Secchi Depth, inches	Carbon Assimilation, mg C/m^2/hr	Chlorophyll Content, mg/m^3	mg C/m^2 / mg chlorophyll/m^3
		Holmes		
7/11/69	10 (25)	16.85	15.98	1.05
9/8/69	8 (20)	26.61	15.70	1.69
		Wagon Train		
8/6/68	24 (61)	119.35	14.89	8.02
7/23/69	6 (15)	13.44	41.85	0.32
9/3/69	13 (33)	30.12	26.15	1.15
8/24/70	20 (51)	209.05	20.95	9.98
		Pawnee		
8/7/68	74 (188)	247.53	12.04	20.56
9/24/68	68 (173)	313.43	27.52	11.40
7/25/69	78 (198)	159.06	20.34	7.82
6/16/70	22 (56)	296.22	63.20	4.69
7/3/70	24 (61)	241.52	30.06	8.03
7/21/70	21 (53)	188.15	66.85	2.81
		Stagecoach		
7/1/69	53 (135)	117.98	30.90	3.82
8/27/69	33 (84)	164.78	56.85	2.90
7/9/70	20 (51)	190.06	157.86	1.20
7/31/70	16 (41)	633.26	225.28	2.81
8/27/70	56 (142)	298.31	20.67	14.43
		Branched Oak		
8/22/68	73 (185)	64.34	25.63	2.51
6/19/69	27 (69)	906.09	67.83	13.36
8/28/69	36 (91)	273.78	25.12	10.90
7/8/70	32 (81)	774.09	58.05	13.33
7/17/70	22 (56)	254.71	87.64	2.91

Values in parentheses are given in centimeters.

from three genera, *Aphanizomenon, Anabaena,* and *Microcystis* are common. Moreover, the frequency of bloom formation and the intensity of individual blooms have been increasing as the reservoirs age. Other algae are present and sometimes can become abundant. In the summer, however, blue green algae dominate.

Problems are associated with the use of chlorophyll as an index of standing crop; however, as long as these limitations are kept in mind, chlorophyll can be used as a parameter to measure eutrophication [*Vollenweider*, 1968]. Figure 2 shows the trend of increasing concentrations of chlorophyll in Pawnee Reservoir during the past 3 years. The monthly means of chlorophyll given in Table 4 show similar trends in Branched Oak and Stagecoach. As the reservoirs age, higher standing crops are produced earlier in the season, and tremendous increases have occurred in successive years in each of the three reservoirs, the oldest reservoir having the largest standing crop. Pawnee had 1.7 times more chlorophyll in 1969 than in 1968 and 2.0 times more in 1970 than in 1969. Branched Oak had 4.0 times more chlorophyll in 1969 than in 1968 and 1.9 times more in 1970 than in 1969. A significant fish kill occurred in Branched Oak in August 1970 at the height of an *Aphanizomenon* bloom. There was 2.6 times more chlorophyll in Stagecoach Reservoir in 1970 than there was in 1969. (No data are available for 1968.) It suffices to say that during much of the recreational season these three reservoirs have a pea soup appearance. In Pawnee, high chlorophyll concentrations can persist until late October. The highest concentration recorded in 1969 was 107 mg/m^3 and occurred on October 15 during an *Aphanizomenon* bloom.

Nutrient concentrations in the waters of both clear water and turbid impoundments are similar (Table 2). The only consistent change during the 3 years has been an apparent decline in total

TABLE 4. Monthly and Summer Means of Chlorophyll per Milligram per Cubic Meter in the Study Reservoirs

Date	June	July	August	Summer
		Holmes		
1968	8.64	19.78	11.84	13.42
1969	10.50	20.06	22.97	17.85
		Wagon Train		
1968	18.75	27.99	27.27	24.67
1969	16.51	22.07	19.10	19.23
1970	24.05	31.10	23.46	26.20
		Pawnee		
1968	4.23	9.92	30.00	14.72
1969	19.92	18.95	36.43	25.10
1970	38.25	52.86	62.86	51.32
		Branched Oak		
1968	6.03	4.32	10.10	6.82
1969	26.53	16.84	38.05	27.14
1970	14.87	79.64	64.23	52.91
		Stagecoach		
1969	22.53	50.46	59.27	44.09
1970	99.02	144.98	95.19	89.74

phosphorus. High nitrate values in 1969 are attributed to heavy spring runoff. No nutrient appears to be in short supply, although nitrate N and orthophosphate values sometimes decline to barely detectable amounts coincident with intense algal blooms. Ammonia concentrations during these times remain at fairly high levels, a not unusual situation [*Vollenweider*, 1968].

A decreasing Secchi depth has been cited by *Fruh et al.* [1966] and others as indicating the progressive eutrophy of a lake. In Figure 3 the average Secchi depth for Branched Oak Reservoir for each of the three summers is shown. Clearly, the average Secchi depth has declined as the numbers of algae in the water increased. The same trend was observed in Pawnee and Stagecoach reservoirs.

The ^{14}C production rates, as would be expected, are higher in the clear water reservoirs. The highest production rates were associated with low standing crops, as others have noted [*Wright*, 1959; *Findenegg*, 1965], and, as crops increased, production per unit of plant material decreased (Table 3). *Fruh et al.* [1966] have suggested that changes in primary production over a period of time can be used as a measure of eutrophication. Although the average rate of carbon fixed per square meter per hour appears to be increasing as the clear reservoirs age, our data are not complete enough to allow us to make a definitive statement.

NUTRIENT SOURCES

The runoff waters entering the Salt Valley reservoirs are principally from cultivated farmland. The watersheds contain very few or no point waste sources, such as domestic sewage effluents or drainage from large feedlots. All the reservoir watersheds contain agricultural lands in current production. Fertilizers plus nutrients in the naturally fertile soils are carried into the reservoirs mainly during spring runoff periods. Because the reservoirs discharge very infrequently, most of the nutrients that enter are retained. For example, Pawnee Reservoir has had only one major discharge since it was filled in 1965; this occurred with a greater than normal runoff in the spring of 1969. Consequently, the total concentration of nutrients in the reservoirs is increasing, although it is not known to what extent nutrients are lost to the bottom sediments and become unavailable for plant growth.

DISCUSSION

If the observed trend between reservoir age and chlorophyll increase continues for reservoirs with low soil turbidity, it can be predicted that in a few years Branched Oak Reservoir (the newest,

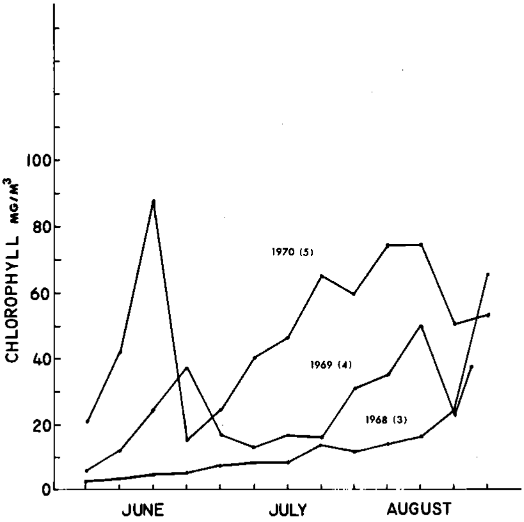


Fig. 2. Trend of chlorophyll concentration in Pawnee Reservoir in 1968, 1969, and 1970. Similar trends were observed in Branched Oak and Stagecoach reservoirs. The numbers in parentheses are the reservoir ages.

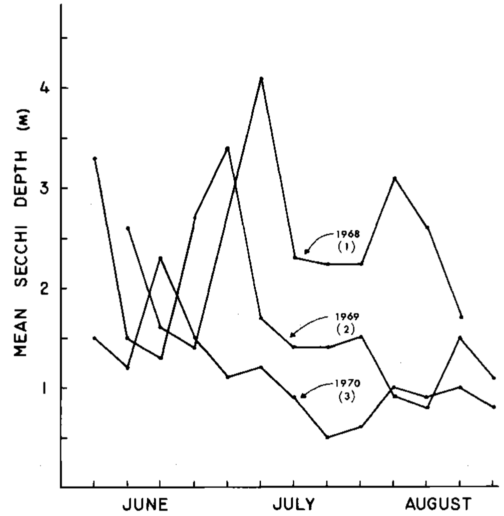


Fig. 3. Average Secchi depth for Branched Oak Reservoir for each summer of the study. Similar trends were observed in Pawnee and Stagecoach reservoirs and are a result of increasing numbers of algae. The numbers in parentheses are the reservoir ages.

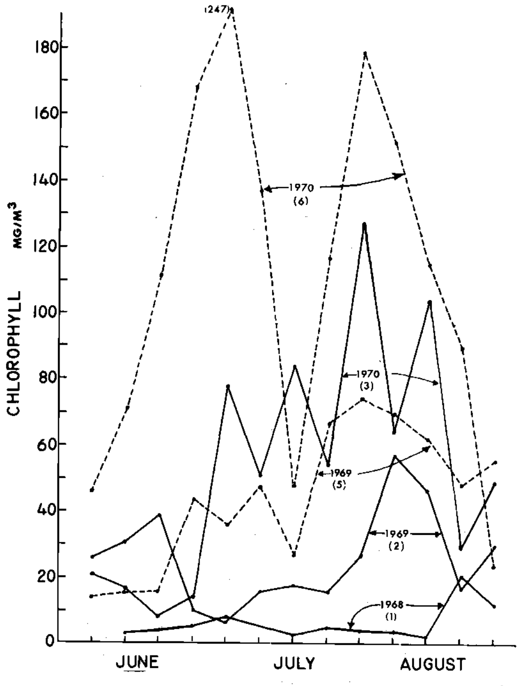


Fig. 4. Relationship between reservoir age (in parentheses) and chlorophyll content exemplified by Stagecoach (solid line) and Branched Oak (dashed line) reservoirs.

largest, and most desirable for recreation because of its size) will be in the advanced stage of hypereutrophication currently exhibited by Stagecoach Reservoir. The relationship between age and chlorophyll for these two reservoirs is shown in Figure 4. When Branched Oak reaches that state of eutrophy now present in Stagecoach, most forms of water recreation will suffer seriously, except perhaps fishing.

Considerable funds have gone into the development of recreational facilities at these reservoirs. If eutrophication cannot be effectively controlled, the wisdom of spending funds to construct paved access roads, beaches, bathhouses, boat docks, picnic areas, and other facilities is open to question. Of more profound importance is the problem of how future recreational reservoirs can be justified in the Great Plains if their fates are to be similar to those of the Salt Valley reservoirs. That the potential for eutrophication problems exists in Great Plains reservoirs must be recognized by those planning future construction. This potential may dictate changes in reservoir design, siting, watershed management, and water level regulation.

Since the source of water for reservoir impoundment is surface runoff, nutrient reduction or removal is impractical. Rather, it would be appropriate to approach the eutrophication problem from another aspect, that is, the control of photosynthesis by the regulation of light penetration into reservoirs. Examples of natural light-limited systems are Holmes and Wagon Train reservoirs. Unfortunately, water contact sports are no more popular in muddy waters than in pea soup green ones. The efficacy of adding substances that do not offend the esthetic senses either to the water or to the water surface to prevent sunlight penetration would appear to be a fruitful avenue of research. Although such a solution may only be applicable to the small shallow reservoirs in the Great Plains, it could vastly affect the future development of surface waters in the region.

CONCLUSIONS

1. Runoff waters impounded in the Salt Valley reservoirs contain sufficient nutrient salts to support abundant growths of aquatic plants.
2. Reservoirs that are light limited by soil turbidity support neither abundant growths of aquatic plants nor dense blue green algal blooms.
3. Clear water reservoirs are very eutrophic.

Shorelines choked with rooted aquatics, dense blooms of blue green algae, odorous emissions, and occasional fish kills are typical characteristics of these impoundments.

4. In clear water reservoirs the rate of eutrophication is very rapid and appears to be directly related to age. Projections based on existing data indicate that the useful life of these reservoirs for body contact recreation is only a few years.

5. Because there is no ready solution for the removal of nutrients from land runoff, methods of controlling reservoir eutrophication in the presence of abundant nutrients must be evaluated. One concept that should be investigated is the control of photosynthesis through the inhibition of sunlight penetration by the addition of various substances to the reservoir directly or to the water surface.

Acknowledgments. The work reported herein was supported by grants from the Salt Valley watershed district, the Engineering Research Center of the University of Nebraska, and the Nebraska Water Resources Research Institute, Office of Water Resources Research, Department of the Interior under the Public Law 88-379 program. The participation and cooperation of our graduate students, Richard Gorton, Robert Behrens, John Andersen, Dennis Lessig, Eugene Buglewicz, Raymond Hartung, Glen Helzer, and Sampson Ukpaka, in this research is gratefully acknowledged.

REFERENCES

American Public Health Association, *Standard Methods for the Examination of Water and Wastewater,* 12th ed., New York, N. Y., 1965.

Findenegg, I., Relationship between standing crop and primary productivity, in *Primary Productivity in Aquatic Environments, Mem. Ist. Ital. Idrobiol.,* suppl. 18, edited by C. R. Goldman, pp. 271–289, University of California Press, Berkeley, 1965.

Fruh, E. G., K. M. Stewart, G. F. Lee, and G. A. Rohlich, Measurement of eutrophication and trends, *J. Water Pollut. Contr. Fed., 38*(8), 1237–1258, 1966.

Golterman, H. L., and R. S. Clymo, Methods for chemical analysis of fresh waters, *IBP Handbook,* vol. 8, pp. 114–119, Blackwell Scientific Publications, Oxford, 1969.

McNabb, C. D., Enumeration of freshwater phytoplankton concentrated on the membrane filter, *Limnol. Oceanogr., 5*(1), 57–61, 1960.

Vollenweider, R. A., Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication, *Rep. DAS/CSI/68.27,* 159 pp., Organ. for Econ. Coop. and Develop., Paris, 1968.

Wright, J. C., Limnology of Canyon Ferry Reservoir, 2, Phytoplankton standing crop and primary production, *Limnol. Oceanogr., 4*(3), 235–245, 1959.

Nitrogen Budgets of Great Plains Impoundments

DALE W. TOETZ

Department of Zoology, Oklahoma State University, Stillwater, Oklahoma 74074

Impoundments constructed on the Great Plains of the United States vary in size from ponds of <1 ha to lakes as large as 1.3×10^6 ha. Generalizations about N budgets for these waters are premature, since each impoundment is affected differently by local geology, climate, and the perturbations of man. This paper discusses nitrogen budgets of impounded waters on the Great Plains of the United States and the internal cycling of nitrogen in reservoir ecosystems.

The nitrogen budget of a reservoir is illustrated by Figure 1. The quantification of the rates of gain and loss has never been completely accomplished for a reservoir, although observations on sources and losses have been made.

SOURCES

Nitrogen in a biologically usable form can enter a lake in the influents, as precipitation or as a gas on the surface, in groundwater, and by the process of biological nitrogen fixation. Flooded soil and litter may be an important source, especially in the first few years after impoundment.

Influents can be an important source of nitrogen for impoundments. Rivers entering impoundments carry nitrogen compounds not only from stable forest or grassland ecosystems but also from unstable ecosystems and sources such as domestic sewage, feedlot wastes, and fertilizers. J. Dawes et al. (unpublished manuscript, 1970) stated that since 1945 the use of N fertilizers in Illinois has increased by a factor of 129 and the amount of NO_3 in surface waters has doubled. Undoubtedly, an increase in the use of fertilizers was not solely responsible for the increase in NO_3 in surface waters. *Likens et al.* [1970] documented a fiftyfold increase in the NO_3 load of a stream from a forest ecosystem after deforestation. Presently, we cannot assess the magnitude of stream eutrophication on the Great Plains because we lack base line data from controlled experiments to indicate the magnitude of the loss from climax ecosystems.

More is known about NO_3 than about any other form of N in streams and rivers on the Great Plains. Data on mean discharge and NO_3 in 109 streams in the United States indicate that a close relationship exists between stream runoff and NO_3 load on an areal basis [*Feth,* 1966]. Feth points out exceptions to this rule; e.g., streams in Arkansas and Oklahoma carry more NO_3 than the runoff on an areal basis would lead one to expect. Streams in the northern Great Plains tend to have a lower runoff and nitrate load on an areal basis than those of streams in the southern Great Plains.

Seasonal variation in NO_3 load can be expected, especially where snowmelt contributes heavily to runoff. The Red River at Fargo, North Dakota, delivers 85% of its annual NO_3 load in just 30 days [*Feth,* 1966]. *Likens et al.* [1970] documented the highest concentrations of NO_3 in stream water from a forest ecosystem during the winter and the lowest concentrations from a forest ecosystem during the summer. During the growing season, low concentrations were caused by the demand for NO_3 by vegetation, whereas, during the winter, physical processes tended to dominate, and precipitation accounted for the losses.

Details on other forms of N in influents are not as well documented, although the contribution of N in plankton in discharges from upstream reservoirs could be large considering the data of *Cowell* [1970].

Groundwater may be an important source of N for certain reservoirs. *Brezonik and Lee* [1968] estimated that, of the total combined nitrogen entering the lake per annum, 45% entered in the groundwater and only 22% entered in influents. *Keller and Smith* [1967] noted the increase in NO_3 in groundwaters in Missouri from livestock wastes. Geologic sources other than the soil

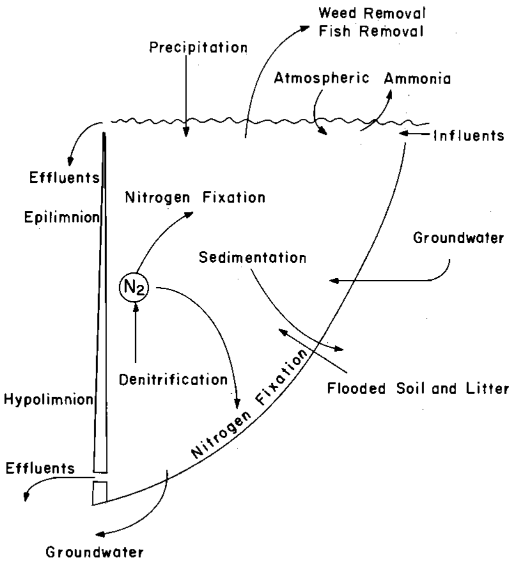


Fig. 1. Sources and losses of nitrogen for a reservoir ecosystem.

could also provide N for both influents and groundwater, but this subject has received little attention [*Feth,* 1966].

Ammonia can be volatilized from feedlot operations and enter lakes from the atmosphere. *Hutchinson and Viets* [1969] estimated that the weekly input of atmospheric NH_4-N 0.4 km from a 90,000 unit feedlot was 2.8 kg ha^{-1}. They presented evidence that the amount of NH_4 in precipitation in the vicinity of feedlots is insignificant in comparison to the NH_4 absorbed from the atmosphere.

Nitrogen also enters a lake in precipitation on the surface. Estimates of the concentration of NO_3 and NH_4 in precipitation vary with geographic location; e.g., the estimate in the northern Great Plains is higher than that in the southern Great Plains, and the lowest estimate is near the Texas coast [*Junge,* 1958]. The concentration of these ions in rainfall at Stillwater, Oklahoma, in 1968–1970 is compared to data collected during the 1930's in Table 1. The concentrations reported during the 1930's and those for the United States tend to be higher than the recent data. The data of *Heller* [1938] were used to estimate the annual contribution of NO_3, NO_2, and NH_4 at Stillwater, Oklahoma, during 1935–1936 as 2.3 kg N ha^{-1} yr^{-1}. This is below the worldwide range of 4.4 to 11 kg N ha^{-1} yr^{-1} reported by *Stewart* [1968].

Biological nitrogen fixation by certain algae, bacteria, and fungi may account for increases of N in a lake. *Dugdale et al.* [1959] first demonstrated the direct uptake of N_2 by plankton, probably heterocystis blue green algae, by using $^{15}N_2$ as a tracer. *Stewart et al.* [1967] used an indirect but rapid method that involved the quantitative measurement of the reduction of acetylene to ethylene by a sample of water to assay for N_2 fixation. The reduction apparently involves the same enzyme system responsible for the reduction of N_2 to NH_4, and the actual quantity of N_2 fixed can be estimated by using an appropriate conversion factor.

Hall [1971] used the acetylene reduction technique to assay for nitrogenase activity of particulate matter (>0.45 μ) in the surface waters of Keystone Lake, Oklahoma, at 2- to 3-week intervals during 1969–1970. No acetylene reduction was detected, and no heterocystis blue green algae were observed. On the other hand, strong nitrogenase activity was observed recently in lake water during an *Anabaena* bloom in Lake Carl Blackwell, Oklahoma (Toetz, unpublished data, 1970).

The strong nitrogenase activity in the surface waters of Lake Carl Blackwell is undoubtedly related to the presence of heterocystis blue green algae, and the absence of such activity in Keystone Lake may be due to the absence of these algae. The reason that heterocystis blue green algae develop blooms only in certain lakes is discussed by *Lund* [1969].

Further documentation of blooms of heterocystis blue green algae may suggest the importance of nitrogen fixation in impoundments. Heterocystis blue green algae are known to occur

TABLE 1. Concentrations of NO_3-N and NH_4-N in Rainfall

Location	Concentration, mg m^{-3}	
	NO_3-N	NH_4-N
United States	700 to 4700	50 to 2200
Stillwater, Okla.		
1935 to 1937	17 to 630	99 to 596
Mean of September 1935 to 1936	163	357
Stillwater, Okla.		
1968 to 1970	88 to 285	39 to 333
Mean of September 1969	94	82

The data for the United States are from *Carroll* [1962], who is cited by *Stewart* [1968]; the data for Stillwater, Oklahoma, in 1935 to 1937 are from *Heller* [1938]; and the data for Stillwater, Oklahoma, in 1968 to 1970 are from Toetz (unpublished data, 1970).

in Beaver and Bull Shoals lakes, Arkansas [*Applegate and Mullan,* 1968]. Nitrogenase activity was detected in the surface waters of Bull Shoals during the autumn of 1969 (Toetz, unpublished data, 1969). Algae capable of N_2 fixation are usually scarce in mainstream reservoirs. Diatoms are the major group of phytoplankton in the reservoirs on the Missouri River [*Benson and Cowell,* 1968] and in Keystone Lake [*Hall,* 1971]. However, in smaller impoundments not on major rivers, *Anabaena* blooms have been observed frequently [*Tiemeier,* 1951; *Cooper,* 1965; *Peterka,* 1970], and N_2 fixation may occur in these waters. The N_2-fixing potential of one heterocystis form, *Aphanizomenon,* which is often observed in reservoirs, has not been clearly established, although it is capable of reducing acetylene and is probably an N_2 fixer [*Stewart et al.,* 1968]. Feeble nitrogenase activity, which was probably microbial in origin, was observed by the author in an Oklahoma lake of 5.4 ha during the winter. In view of recent work on microbial N_2 fixation by *Brezonik and Harper* [1969] and *Howard et al.* [1970], biological fixation should not be eliminated as an N source merely because of an absence of heterocystis blue green algae.

The soil and vegetation on the bottom of a reservoir are an important source of N soon after the impoundment of a stream and are probably important in the high initial productivity of reservoirs. Reservoir sediments exposed periodically to the air may also contribute to the N supply. *Kadlec* [1960] postulated that exposing marsh sediments to air accelerates the decomposition of that colloidal complex to which nutrients were bound in the sediments. After reflooding this soil these nutrients would be released.

LOSSES

Nitrogen losses from the outlets of impoundments are probably more important in reservoirs than in natural lakes because of the higher rate of water exchange in reservoirs. In Lake Mendota, Wisconsin, outlet losses and sedimentation account for 16.4 and 66.7% of the total losses [*Brezonik and Lee,* 1968]. Biomass losses from Missouri River reservoirs as plankton are significant [*Benson and Cowell,* 1968]. These observations plus the knowledge that waters of impoundments have a high turnover rate should give a high priority to the estimation of losses through the outlet.

Less is known of the significance of other losses: the sediments as a sink, fish catch, aquatic macrophyte removal, and groundwater recharge. *Stratton* [1969] observed significant losses of NH_4 due to volatilization from an alkaline impoundment in California.

Denitrification represents an important nitrogen sink in some lakes. However, this phenomenon is restricted to anoxic water masses. Many impoundments on the windswept plains are shallow and mix well even in summer, e.g., the large impoundments on the Missouri River (N. Benson, unpublished report, 1968). Denitrification would not be expected in these lakes.

During the summer of 1968, Norton (personal communication, 1968) observed high concentrations of NO_3 near the bottom of Eufaula Lake, Oklahoma, during a destratification effort of the Federal Water Quality Administration. Oxygen was apparently absent at 22 meters when concentrations were measured with an O_2 probe and meter. Determinations of O_2 by the Winkler method, however, revealed concentrations of 0.2 g m^{-3} [*Toetz,* 1970]. Small concentrations of O_2 were apparently inhibiting denitrification in the bottom waters of the lake. *Goering and Dugdale* [1966] demonstrated that denitrification can occur rapidly even at low temperatures. Therefore thermal conditions may be less important than the concentration of the organic substrate.

Nitrate in density currents in the anoxic hypolimnion of some reservoirs can be converted rapidly to N_2. In contrast to natural lakes, outlet losses can occur from both the epilimnion and the hypolimnion of many reservoirs. If the volume of hypolimnetic withdrawal is high during stagnation, significant losses of N could occur. These would have a major impact on the productivity of the reservoir, since the hypolimnetic N would not be recycled at turnover.

INTERNAL CYCLING

Much attention has been directed to estimating seasonal changes in the standing quantities of NO_3, NO_2, NH_4, and Kjeldahl N in reservoirs. It has been shown that NO_3 concentration is positively correlated to discharge in Keystone Lake, Oklahoma [*Hall,* 1971], in rivers in Illinois (J. Dawes et al., unpublished manuscript, 1970), and in Lake Ashtabula, North Dakota [*Peterka,* 1970]. *Hall* [1971] found a reduction of NO_3 and NH_4 in the surface waters during the warm months, perhaps due to assimilation by phytoplankton. Nitrate increases during the winter in reservoirs [*Peterka,* 1970; *Hall,* 1971], presumably because the rate of nitrification exceeds the rate of NO_3 assimilation.

The fate of NO_3 in reservoirs is important because of its toxic nature and its potential for eutrophication. *Procházková* [1966] concluded that the concentration of nitrate was due more to external factors such as inflow than to uptake and cycling by the algae in the Slapy and Klicava reservoirs. She also showed that substantial decreases in NO_3 may not occur, since many algae preferentially assimilate NH_4. Moreover, the rate of recycling of NH_4 can be high enough to satisfy the demands of the algae for a source of inorganic nitrogen. *Dugdale* [1969] reported a turnover time of 50 hours for NH_4 in the sea.

It is likely that the turbidity of the water and not the paucity of inorganic nitrogen limits primary production in reservoirs. In any event, microorganisms may be an important part of the base of the food chain of fishes in reservoirs. Reservoir workers should therefore question preoccupation with primary production. Use of detritus and assimilation of dissolved organic matter by microbes may have more significance than algal production as a production process. *Sorokin* [1966] and *Kuznetsov* [1968] have clearly underlined the importance of heterotrophic biosynthesis in Russian reservoirs.

More information is needed before the fate of nitrogen compounds in a reservoir can be predicted. The construction of a nitrogen budget has an important place in such an effort. However, only a complete ecosystem analysis will permit one to see the role of nitrogen in reservoirs.

Acknowledgments. Support for my research came from the Office of Water Resources Research, U.S. Department of the Interior, project Oklahoma A-023, and the U.S. Atomic Energy Commission, project AT (11-1)—2070.

REFERENCES

Applegate, R., and J. Mullan, Standing crops of dissolved organic matter, plankton and seston in a new and an old Ozark reservoir, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, Jr., pp. 517–530, American Fisheries Society, Washington, D. C., 1968.

Benson, N., and B. Cowell, The environment and plankton density in Missouri River reservoirs, in *Reservoir Fishery Resources Symposium,* edited by C. E. Lane, Jr., pp. 358–373, American Fisheries Society, Washington, D. C., 1968.

Brezonik, P., and C. Harper, Nitrogen fixation in some anoxic lacustrine environments, *Science, 164*(3885), 1277–1279, 1969.

Brezonik, P., and G. F. Lee, Denitrification as a nitrogen sink in Lake Mendota, Wis., *Environ. Sci. Technol., 2*(2), 120–125, 1968.

Carroll, D., Rainwater as a chemical agent of geologic processes, A review, *U.S. Geol. Surv. Water Supply Pap., 1535G,* 1–18, 1962.

Cooper, M., Some algae from Lake Carl Blackwell, Oklahoma, *Proc. Okla. Acad. Sci., 5,* 17–19, 1965.

Cowell, B., The influence of plankton discharges from an upstream reservoir on standing crops in a Missouri River reservoir, *Limnol. Oceanogr., 15*(15), 427–441, 1970

Dugdale, R., The nitrogen cycle in the sea, in *Biology and Ecology of Nitrogen, Proceedings of a Conference,* pp. 16–18, National Academy of Sciences, Washington, D. C., 1969.

Dugdale, R., V. Dugdale, J. Neess, and J. Goering, Nitrogen fixation in lakes, *Science, 130*(3379), 859–860, 1959.

Feth, J., Nitrogen compounds in natural water—A review, *Water Resour. Res., 2*(1), 41–58, 1966.

Goering, J., and V. Dugdale, Estimates of the rates of denitrification in a subarctic lake, *Limnol. Oceanogr., 11*(1), 113–117, 1966.

Hall, R., Jr., Observations on nitrogenase activity in the surface waters of Lake Keystone, Oklahoma, M.S. thesis, 25 pp., Okla. State Univ., Stillwater, 1971.

Heller, V., Chemical content of Oklahoma rainfall, *Okla. Agr. Exp. Sta. Tech. Bull., 1,* 1–23, 1938.

Howard, D., J. Frea, R. Pfister, and P. Dugan, Biological nitrogen fixation in Lake Erie, *Science, 169*(3940), 61–62, 1970.

Hutchinson, G., and F. Viets, Jr., Nitrogen enrichments of surface water by absorption of ammonia volatilized from cattle feedlots, *Science, 166*(3904), 514–515, 1969.

Junge, C. E., The distribution of ammonia and nitrate in rain water over the United States, *Eos Trans. AGU, 39*(2), 241–248, 1958.

Kadlec, J., The effect of a drawdown on the ecology of a waterfowl impoundment, *Rep. 2276,* 181 pp., Game Dep., Mich. Dep. Conserv., Lansing, 1960.

Keller, W., and G. Smith, Groundwater contamination by dissolved nitrate, *Geol. Soc. Amer. Spec. Pap., 90,* 48–59. 1967.

Kuznetsov, S., Recent studies on the role of microorganisms in the cycling of substances in lakes, *Limnol. Oceanogr.. 13*(2), 211–214, 1968.

Likens, G., et al., Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem, *Ecol. Monogr., 40*(1), 23–47, 1970.

Lund, J. W., Detection and measurement of eutrophication: Phytoplankton, in *Eutrophication: Causes, Consequences, and Correctives,* pp. 306–330, National Academy of Sciences, Washington, D. C., 1969.

Peterka, J., Productivity of phytoplankton and quantities of zooplankton and bottom fauna in relation to water quality of Lake Ashtabula reservoir, North Dakota, *Res. Proj. Tech. Completion Rep. A-1101 N.*

Dak., 79 pp., Office of Water Resour. Res., Washington, D. C., 1970.

Procházková, L., Seasonal changes of nitrogen compounds in two reservoirs, *Verh. Int. Ver. Limnol.*, *16*, 693–700, 1966.

Sorokin, J., On the trophic role of chemosynthesis and bacterial biosynthesis in water bodies, in *Primary Productivity in Aquatic Environments, Mem. Ist. Ital. Idrobiol.*, suppl. 18, edited by C. R. Goldman, pp. 187–208, University of California Press, Berkeley, 1966.

Stewart, W., Nitrogen input into aquatic ecosystems, in *Algae, Man, and the Environment*, edited by E. Jackson, pp. 53–72, Syracuse University Press, Syracuse, N. Y., 1968.

Stewart, W., G. Fitzgerald, and R. Burris, In situ studies on N_2 fixation using the acetylene reduction technique, *Proc. Nat. Acad. Sci. USA*, *58*(5), 2071–2078, 1967.

Stewart, W., G. Fitzgerald, and R. Burris, Acetylene reduction by nitrogen-fixing blue-green algae, *Arch. Mikrobiol.*, *62*(4), 336–348, 1968.

Stratton, F., Nitrogen losses from alkaline water impoundments, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *95*(SA2), 223–231, 1969.

Tiemeier, O., Studies on Kanapolis Reservoir in 1950, *Trans. Kans. Acad. Sci.*, *54*(2), 175–189, 1951.

Toetz, D., Observations on mineral cycling during the 1968 destratification of Eufaula Reservoir, Oklahoma, *Completion Rep. Job 2 D. J. Proj. F-27-1*, 10 pp., Okla. Coop. Fish. Unit, Okla. State Univ., Stillwater, 1970.

Lake Destratification by Underwater Air Diffusion

HERBERT H. ROGERS, JULIAN J. RAYNES, FRANK H. POSEY, JR., AND WILLIS E. RULAND
South Atlantic Division, U.S. Army Corps of Engineers, Atlanta, Georgia 30303

Water quality problems in deep lakes and downstream releases can be caused by thermal and chemical stratification patterns that occur in lakes during summer and early fall. In the temperate climate of the southeastern United States, thermal stratification, a layering of water based on temperature-induced density differences, generally begins in early March with the warming of the surface waters of the lakes. This warmed and therefore less dense water floats on the colder denser bottom water. If the depth and shape of the lake are such that the wind action on the surface and the inflows cannot mix the lake vertically, the stable stratification pattern will continue until environmental conditions cool the surface waters and these denser surface waters sink to cause fall turnover and complete mixing.

The thermal stratification pattern in the lakes of the southeastern United States consists of an epilimnion, the warmer (25°–28°C) surface water layer of 6.1–7.6 meters; a thermocline, the water layer having the largest decline in temperature per unit of depth; and a hypolimnion, the lowest layer of cooler water of fairly uniform temperature.

WATER QUALITY PROBLEMS IN STRATIFIED LAKES

Many of the dams of deep man-made lakes are designed for hydropower production with less expensive more efficient low-level intakes to the generators. During the stratification period, water released from the hypolimnion through these intakes can be devoid of oxygen, high in iron and manganese, and low in temperature. Although this water quality is desirable for cooling purposes, it is not suitable for aquatic life and can cause water treatment problems. In a rocky-bottomed stream bed, oxygen recovery is fast at low flows, but at high flows the opportunity for surface reaeration is low, and oxygen recovery can only occur over longer stream sections. The oxidation of iron, manganese, and gases is also dependent on stream reaeration.

Numerous structural designs and operational techniques have been used to mix epilimnial and hypolimnial waters to obtain an increase in and more uniform quality of dissolved oxygen in released waters. Past work has been aimed primarily at improving downstream water quality and has not resulted in any significant disturbance of the stratification pattern of the lake. The costs have been high, and the desired degree of control has been difficult to attain. There is also the danger that epilimnial waters of a high dissolved oxygen content will be exhausted through high-level discharges, so that there will not be any control of dissolved oxygen in the early fall. Mixing or breaking up the stratification offers many advantages for water quality improvement both in the lake and downstream.

ALLATOONA LAKE DESTRATIFICATION PROJECT

In early 1968 the South Atlantic Division, with advice from Dr. James M. Symons of the U.S. Public Health Service and assistance from a number of federal and Georgia agencies, began the design and installation of an air diffuser system for Allatoona Lake to determine whether a large lake could be maintained in a destratified condition, what changes would occur in water quality, and the cost and efficiency of operating such a system. Prior to 1968 a limited amount of water quality and related data in and below the lake had been gathered over a 2½-year period from 1964 through 1966. This information was used initially as a basis for comparison with destratification results. Additional base data were obtained in 1970, when the destratification system was not operating.

Allatoona Lake, completed in 1955 and located about 48 km northwest of Atlanta, Georgia, is a multipurpose project for flood control, hydroelectric power generation, streamflow regulation, and other purposes. It receives considerable use for recreation (over 6 million people in 1969). Water is withdrawn a short distance below the dam for water supply. The 58-meter-high dam creates a lake with a surface area of 48 km^2 and a volume of 454 hm^3 at a normal summer pool level of 256 meters above mean sea level. Water depths near the dam are 46 meters, and one major arm of the lake backs water up the Etowah River for a distance of 45 km. Some municipal and poultry-processing waste effluents discharge into the upper reaches of the Etowah River and a tributary, the Little River.

The Allatoona Dam powerhouse consists of one small and two large turbine units. The large turbine unit penstocks are 6.1 meters in diameter, the center line of the intake being 27.4 meters below the normal summer pool level of 256 meters above mean sea level. The small turbine penstock is 1.7 meters in diameter, its center line being 16.8 meters below the normal summer pool level. Although the large turbines are below the small one, their discharges in the summer have dissolved oxygen levels about 2 mg/l higher than the discharge of the small turbine.

The air diffuser system for mixing the lake was chosen over mechanical pumping and other methods because of its flexibility of operation, expected ease of installation, and higher destratification efficiency and oxygenation capacity, as shown by work done by Dr. Symons. Five 60.8-hp electrically powered rotary-type compressors were located on the north abutment near the dam for delivery of air to a diffuser array system located in 42.7 meters of water. Airflow of 118 l/sec per diffuser array was through a manifold with a rate of flow controller on each of the lines leading to five diffuser arrays. The system was designed for a maximum supplied air temperature of 70°C and a pressure of 70,310 kg/m^2. The diffuser array system was located 457–610 meters upstream of the dam, an array being placed at each of the quadrant points of a 152-meter-diameter circle and a fifth unit being placed in the center. Each diffuser array was in the form of a cross with 10 diffusers located on each of the four arms (Figure 1) for a total of 200 diffusers in the five arrays. The arrays were suspended 3 meters from the bottom by a buoy, anchor, and cable system, as is shown in Figure 2. The air supply line was attached at the center of the cross.

AIR DIFFUSER SYSTEM OPERATIONS

The air diffuser system first began operation on May 9, 1968, and continued until September 30, 1968. One of the five air compressors was inoperative until August 12. During 1969 the five air compressors operated continuously from March 17 to September 30 except for minor shutdowns. Initially, eight sampling stations were established in the lake, and five were established downstream. Extensive sampling was done before the start-up of the destratification system. This sampling program continued with three intensive lake and downstream surveys during April, July, and September 1968. During the interim, temperature and dissolved oxygen profiles and other water quality determinations were made. A continuous recording monitor measured four parameters (temperature, dissolved oxygen, *p*H, and specific conductivity) 640 meters below the dam. A similar sampling program was carried out in 1969–1970. Hydrologic and meteorological data were obtained near the dam in 1968–1970. Supplemental meteorological data were obtained in 1969–1970 from a weather station established on the lake.

Equipment, design, procurement, fabrication, and installation of the system resulted in an investment of $82,500. Power and other operation costs for the calendar year 1968 were $10,300. The costs for the first year (1968) for sampling and evaluating the data were approximately $90,000. Future annual operational and depreciation costs are estimated at $35,000–40,000.

DATA ANALYSES

The degree of thermal stratification was mathematically calculated as stability of the lake. Stability is the energy necessary to lift a body of water from its center of gravity under stratified conditions to its center of gravity under isothermal conditions. In Allatoona Lake the stability increases from about mid-March when the lake begins to stratify to a peak in mid-July. A gradual decrease in stability occurs until late August, and then a rapid decline occurs until turnover in early October.

Data for 1966, before destratification, were used as a basis for comparison with data gathered during the operation of the destratification equipment in 1968–1969. More comprehensive data were gathered in 1970, when the air diffuser system was not operating, to develop a mathe-

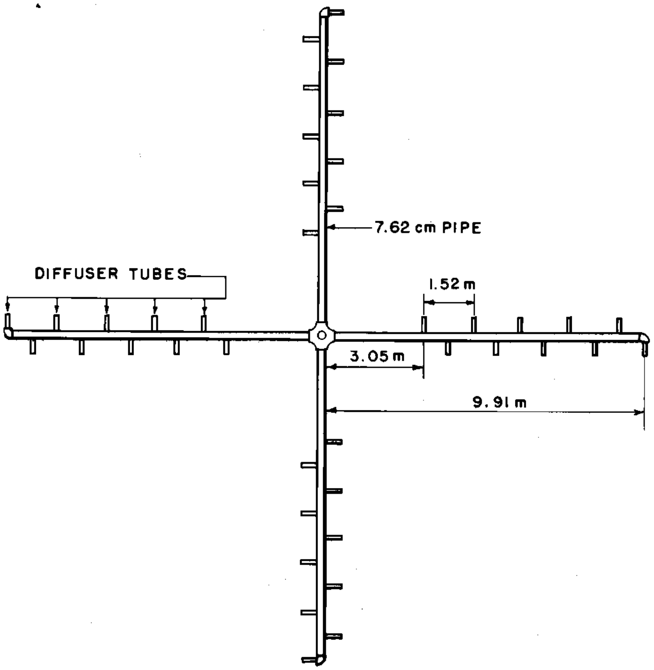


Fig. 1. Plan (not to scale) of the air diffuser unit.

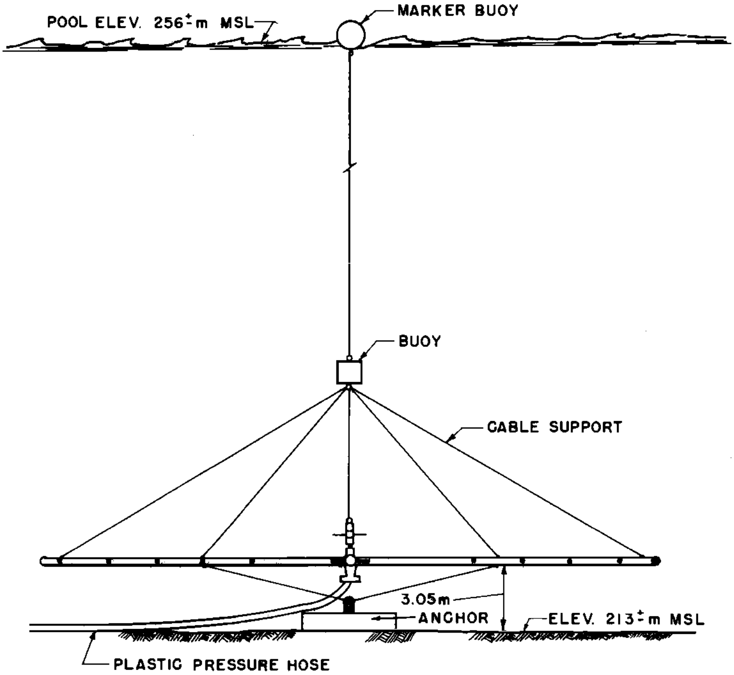


Fig. 2. Elevation (not to scale) of the air diffuser unit.

matical model that could be used to predict what the temperature and dissolved oxygen conditions of the lake would have been in 1968–1969 if the destratification equipment had not been operating. Predicted conditions were used for further evaluation of the operation.

The data for 1966 show that thermal stratification begins to develop in Allatoona Lake about mid-March and that by mid-May there is a well-defined 6.1-meter epilimnion with temperatures of 20°–23°C and dissolved oxygen of about 9 mg/l. The thermocline is 3 meters in depth and exhibits a 3°–5°C drop in temperature. The hypolimnion at that time is that part of the lake below 9.1 meters with temperatures from about 18°C at 9.1 meters to 11°C at the bottom (39.6 meters) and corresponding dissolved oxygen levels of 7 mg/l to 5 mg/l. The depth of the epilimnion reaches about 16.7 meters in early September with temperatures in the 25°–28°C range, dissolved oxygen levels of 6–7 mg/l in the top 6.1 meters decreasing to <1 mg/l at the 9.1-meter level and below. Dissolved oxygen is exhausted below 24.3 meters. In late September, thermal stratification begins to disappear, and there is some improvement in dissolved oxygen; complete turnover occurs about October 10. The temperature and dissolved oxygen profiles of the lake for 1970 generally paralleled those for 1966. In early July the thermocline was at the 6.1- to 9.1-meter level above which the dissolved oxygen was 7–8 mg/l. Below 9.1 meters the dissolved oxygen was 2 mg/l or less, and by mid-August 1970 the dissolved oxygen had been exhausted below 9.1 meters. The major difference between operations for 1966 and those for 1970 was that in 1970 the normal pool level started dropping in early July because it was necessary to generate power to overcome shortages. By early August 1970, pool levels were 0.9–1.2 meters below normal.

A comparison of the temperature and dissolved oxygen profiles for 1968 with those for 1966 shows a decrease in water temperature in the top 6.1 meters and an increase below 9.1 meters and an increase in dissolved oxygen for depths from 6.1–20.1 meters and decreases above and below this zone. During late August and early September, dissolved oxygen is normally low or absent except in the epilimnion; in 1968 it became uniformly mixed in the lake at concentrations of 4–5 mg/l (Figure 3).

Since downstream dissolved oxygen contents are different for low and high discharges, comparisons are made for each flow condition. In May–October 1966 the dissolved oxygen content of the low discharges ranged from 7.5 to 0.7 mg/l with levels <4.0 mg/l for 3 months. During the same period of 1968 the low discharges were maintained at >4.0 mg/l except for the third week in August. Water quality comparisons for high discharges indicate dissolved oxygen levels for the 2 years to be about the same except from early July to early August, when the dissolved oxygen levels for 1968 fell to 2.5 mg/l or about 1 mg/l below the high-discharge results for 1966. In late August and September, however, the dissolved oxygen levels for 1968 increased significantly over those for 1966.

Results of the analyses of iron and manganese are not too conclusive owing to differences in sample analysis techniques during 1966 and 1968.

During 1968, three intensive biological surveys were conducted in Allatoona Lake in mid-April, mid-July, and mid-September. The air diffuser operations had minor short-term effects on the benthic and planktonic communities in the lake. The most noteworthy biological change was the appearance of freshwater jellyfish surrounding the diffusers in September. They seemed to have been feeding on the midge larvae transported upward in the air column. Qualitative studies of the benthic biota below the dam indicated a more diverse community than that that had existed during a survey in 1961.

An examination of bacteriologic data failed to demonstrate any effect of artificial destratification on bacterial density or vertical distribution patterns. The distribution and density of total coliforms near the diffusers were similar to those at sampling sites several miles upstream.

As was indicated earlier in this paper, there was a late start-up of the equipment in 1968, one compressor being inoperative for 3 months. The start-up was about 2 months after stratification began. In 1969 the start-up coincided with the beginning of stratification, and all five compressors operated from March 15 to September 30. The results of the operations of 1969 compared with those of 1968 and of the base year 1966 indicate that the dissolved oxygen levels at the greater depths were higher, dissolved oxygen in both low and high discharges was higher, and the downstream dissolved oxygen did not fall below 4.0 mg/l except for a short period in early August. Thermal stratification developed in June

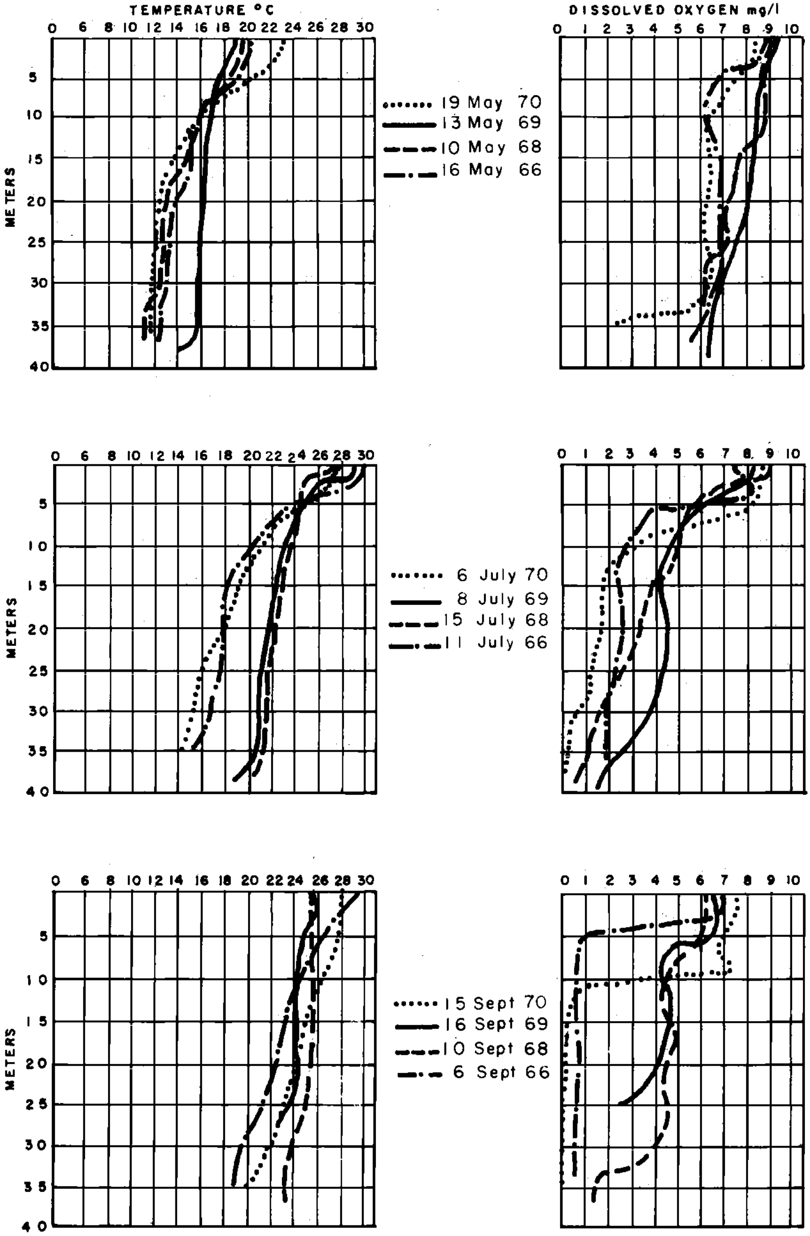


Fig. 3. Allatoona Lake destratification equipment test.

1969 in the upper 3–6 meters of the lake but was held at this level throughout the summer. Again, in late August 1969 an early turnover began, and dissolved oxygen conditions improved throughout the lake and downstream.

SUMMARY

The operation of an air diffuser system for the stratification periods of 1968–1969 in Allatoona Lake, Georgia, has provided useful information regarding operations and water quality improvement.

1. The system is sized sufficiently to maintain the lake in an adequately destratified condition if the equipment is started when stratification begins and is operated continuously during the stratification season.
2. Water quality 4–5 km upstream of the dam and 3–5 km downstream was improved when the equipment was operated at about 80% capacity and was started 2 months after stratification began. When the equipment was started when stratification began and was operated at full capacity, dissolved oxygen levels in both low and high discharges were maintained at 4.0 mg/l and better except for a few days in early August.
3. Temperatures of the discharged waters were elevated a maximum of 6°–8°C above those of discharges from a stratified lake at the same season.
4. Effects on iron, manganese, and biological life appear to be beneficial. No difference was noted in bacteriologic conditions. Further evaluation is needed.
5. Annual operation costs (including depreciation and excluding monitoring and sampling) for a 454-hm^3 lake with physical, meteorological, and hydrologic characteristics similar to those of Allatoona Lake are approximately $40,000. Initial investment costs are $85,000–100,000. Evaluations of other destratification systems on a cooperative basis are needed to determine whether such systems may be more efficient and more economic.

Effect of Induced Aeration on Stratification and Eutrophication Processes in an Oregon Farm Pond

K. W. MALUEG, J. R. TILSTRA, D. W. SCHULTS, AND C. F. POWERS

Pacific Northwest Water Laboratory, Federal Water Quality Administration
U.S. Department of the Interior, Corvallis, Oregon 97330

The rapid deterioration of water quality in many of the nation's lakes, brought about largely by accelerated eutrophication resulting from increased human use and contamination of natural waters, has received much popular and scientific attention in recent years. The National Eutrophication Research Program (NERP) of the Federal Water Quality Administration has as its ultimate objective the development of techniques and methodology to prevent and reverse accelerated eutrophication and to restore already severely eutrophied lakes to useful and esthetically satisfactory conditions.

One of the techniques currently under investigation by NERP and others is artificial aeration to induce circulation and eliminate vertical stratification. Uneven distribution of heat within a productive lake often results in a stratified condition affecting its chemical, physical, and biological properties. These conditions typically result in nuisance blue green algal blooms, a profusion of rooted aquatic plants, low oxygen levels in the hypolimnion, fish kills, and other undesirable properties associated with eutrophication.

The study described herein was conducted on a eutrophic Oregon farm pond in which dense populations of blue green algae and severe hypolimnetic oxygen depletion were the norm during summer months. Air was bubbled from perforated tubing lying on the bottom to maintain a state of continuous circulation. The objectives were to determine, first, the effect of aeration on the quantity and quality of phytoplankton and, second, its effect on the oxygen and dissolved nutrient distribution.

Cline's Pond, constructed in 1953, is located in Polk County, Oregon. Its surface area is approximately 0.4 ha, the maximum depth being 4.9 meters and the average depth being approximately 2.5 meters. The pond receives surface water by slope wash from a 1-ha drainage area south of the pond and groundwater from a small intermittent spring at the southwest corner of the pond.

METHODS

In experiments involving manipulation of lakes and ponds, one common procedure is to characterize the body of water under study by carrying out a limnological survey through at least 1 full year and by comparing conditions prior to manipulation with those obtained during and following the experimentally induced change. This method of assessing experimental results can be unsatisfactory in that one is never certain of the degree to which natural year to year variation has accounted for observed differences. Another commonly used procedure is the simultaneous comparison of the experimental lake with a control lake in the same vicinity. This is likewise often unsatisfactory owing to the uniqueness of individual lakes.

Our study was an attempt to improve these methods. A single pond was partitioned into experimental and control parts, so that the uncertainty of comparing conditions for different years or between different lakes was eliminated. The striking differences in, for example, algal crop that were observed when the two sections were compared can therefore be related with a great deal more confidence to effects of aeration than they could be if the other procedures had been applied.

Partitioning and aeration. The pond was partitioned to create two sections of equal surface area and similar bathymetry (Figure 1). The partition was formed by installing watertight vertical

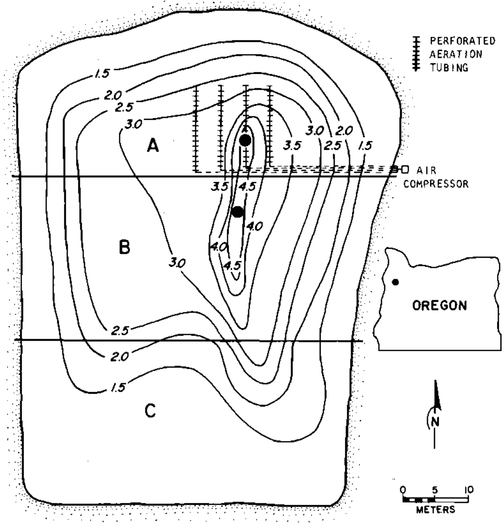


Fig. 1. Location and bathymetric map of Cline's Pond, Oregon. The two solid dots are sampling locations.

barriers of clear polyethylene sheeting from surface to bottom along two horizontal transects. Ballasts of gravel-filled polyethylene tubes 5 cm in diameter were heat sealed to the bottom edge of each barrier. Polyethylene air bladders approximately 15 cm in diameter were bonded to the upper edge of each barrier and were kept inflated to provide surface support. Guy ropes extending from the ends of the barriers to shore provided transect alignment and anchorage. The height of the inflated air bladders was sufficient to prevent waves from spilling over the top. Sections A (north) and B (middle) constituted, respectively, the experimental and control areas. The shallow southern third of the pond was not a part of the experiment.

Four 12-meter lengths of weighted perforated tubing were placed at the bottom of section A. Weighted air feeder lines connected this tubing to a 0.186-kw air compressor on shore. Individual gate valves were used to regulate and balance the air pressure and volume to each of the tubes. (The aeration equipment was designed and manufactured by the Hinde Engineering Company, Chicago.)

Monitoring. The study was conducted from May through October 1969. Reported data are from sampling stations located at the deepest points in each of the two sections (Figure 1). Water was sampled at the surface and at 1-meter-deep intervals with a Kemmerer bottle. Monitoring was at 2-week intervals except immediately after the initiation of aeration, when it was more frequent.

Physical measurements were obtained as follows: temperature, thermistor-type thermometer at 1-meter-deep intervals; transparency, 20-cm black and white Secchi disk; light penetration, submarine photometer with standard Weston cell; specific conductance, Wheatstone conductivity bridge using a glass dip cell with platinized electrodes; and pond stage, staff gage readings.

Chemical determinations were made for dissolved oxygen, *p*H, total alkalinity, total inorganic carbon, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, total Kjeldahl nitrogen, orthophosphate, and total phosphate. All analyses were according to *Federal Water Pollution Control Administration* [1969] methods. Samples for nitrogen and phosphorus were fixed with 4 ml of saturated $HgCl_2$ per liter sample immediately following collection. The samples were refrigerated and analyzed shortly thereafter.

Biological measurements consisted of the determination of chlorophyll *a* and the identification and enumeration of phytoplankton. Samples for chlorophyll analysis were filtered through a 0.45 μ membrane filter in the field immediately following collection. After filtration the filters were stabilized with $MgCO_3$ and stored in a desiccator-refrigerator during the trip to the laboratory. Chlorophyll *a* was measured according to the method of *Strickland and Parsons* [1965]. Samples for the identification and enumeration of phytoplankton were stabilized with sufficient formalin to effect a 3% final solution. These were later analyzed by using a compound microscope and a Sedgwick-Rafter plankton counting cell. Two strips the length of the cell were scanned at a magnification of 200 by using the 'clump-count' method [*Weber*, 1966]. Each one-celled alga, filament, clump, or colony was counted as one organism. All counts were converted to numbers per milliliter.

RESULTS

The pond exhibited strong thermal and chemical stratification by May 1. Aeration of section A was initiated at noon on May 19 with the resultant release of odoriferous benthic gases. Frequent sampling and measurement of physical parameters in the aerated and control sections began immediately and continued until late afternoon, at which time section A appeared to be completely destratified. On the following day it was discovered that chemical and physical changes were occurring in the control section because of leakage under the barrier. The induced circulation in section A had raised the ballast from the bottom. Aeration was discontinued, and the ballast was firmly staked down into the pond mud by a scuba diver to provide a durable effective seal.

Five weeks were allowed to permit sections A and B to become strongly stratified again, and aeration was reinitiated on June 30. (Henceforth, 'aeration' will refer to this reaeration period.) Aeration was maintained until fall overturn of the stratified control section, at which time the experiment was terminated.

Total inflows during the experiment were slightly less than total losses. Pond stage decreased gradually from May through mid-September by 0.4 meter. September rains reversed the trend, so that the pond stage increased gradually during the rest of the experiment.

Temperature data in Figure 2 show that complete thermal destratification occurred within 3 days following the reinitiation of aeration. Destratification persisted during the rest of the experiment, and temperature variations with depth were generally <0.2°C. Data in Figure 3 show that thermal stratification, averaging about 3°C, persisted in the control section throughout the summer and early fall. The temperature gradient, however, was less than had been expected and was probably due to some thermal conductivity through the barrier.

Secchi disk data distinguished the transparencies of the two sections. Prior to aeration, both sections had readings of 0.5 meter. Several days after aeration began, the readings of the two sections diverged. Those for section A went as high as 1.5 meters and were usually double those of section B. Photometric light penetration values revealed similar trends. For example, on August 20, a typical day during the experiment, the 1% level of surface illumination for section A was at 1.80 meters, and that of section B was at 0.95 meter.

Dissolved oxygen data in Figure 4 are profound evidence of destratification. Prior to aeration, dissolved oxygen ranged from 11.1 mg/l at the surface to undetectable at 4 meters. On July 3, 3 days after aeration was initiated, concentrations were a uniform 5.1 mg/l at all depths, but 1 week later they had decreased at all levels. Dissolved oxygen then increased and remained at about 7 mg/l for the rest of the study. Dissolved oxygen in the control section remained highly stratified throughout the experiment, the range being from 16.1 mg/l at the surface to undetectable at 4 meters. On September 15, following a windy period, section B exhibited near homogeneous oxygen values, but it was again stratified by the next sampling date.

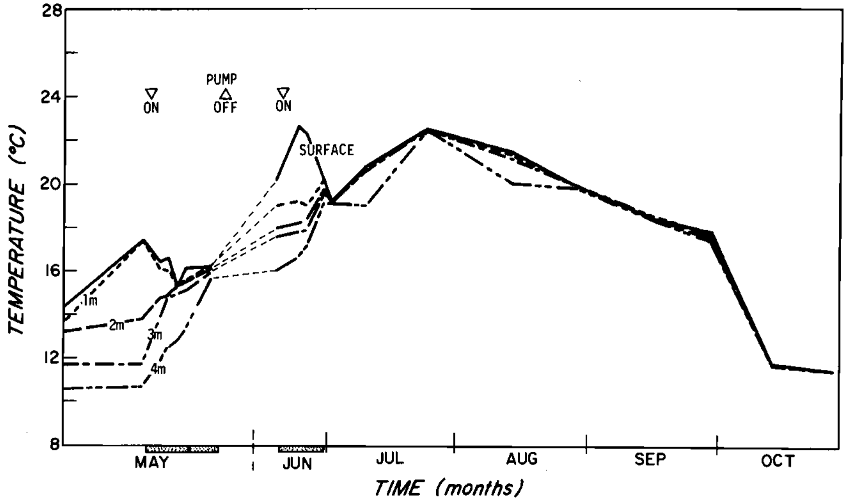


Fig. 2. Temperature distribution for section A. Shaded areas on the abscissa indicate periods of multiple daily sampling (May 19–20 and June 30; note the interrupted scale between these dates).

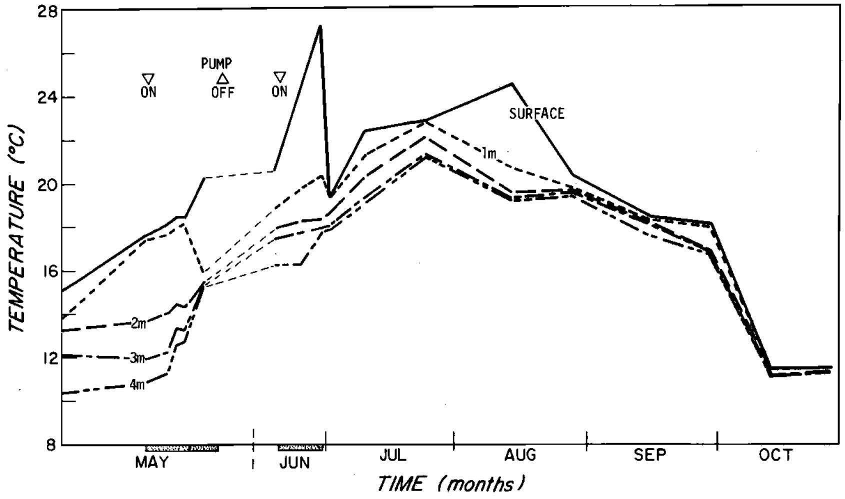


Fig. 3. Temperature distribution for section B.

Total phosphate phosphorus concentrations of the aerated and control sections did not differ significantly. Concentrations in the aerated section ranged from 0.10 to 0.43 mg/l, and those in the control section ranged from 0.10 to 0.41 mg/l. However, temporal patterns in the two sections were not the same. In section A, orthophosphate values increased during destratification from 0.02 to >0.06 mg/l. In August they decreased to <0.03 mg/l and remained constant until October. Such a rise did not occur in section B; rather there was a general tendency for orthophosphate values to decrease from the initial 0.02 mg/l. Fluctuations were most pronounced at the 4-meter level.

The effect of aeration on *p*H was especially pronounced and resulted in an almost complete homogeneity of values at all depths in section A (Figure 5). The *p*H there ranged from only 6.4 to 7.2 during aeration, whereas in the control section, which remained highly stratified, it ranged from 6.2 to 9.6 during the same period.

Specific conductance varied with time and depth from 90 to 140 $\mu\Omega^{-1}$/cm at 25°C, and values for both sections remained fairly uniform with respect to depth and date.

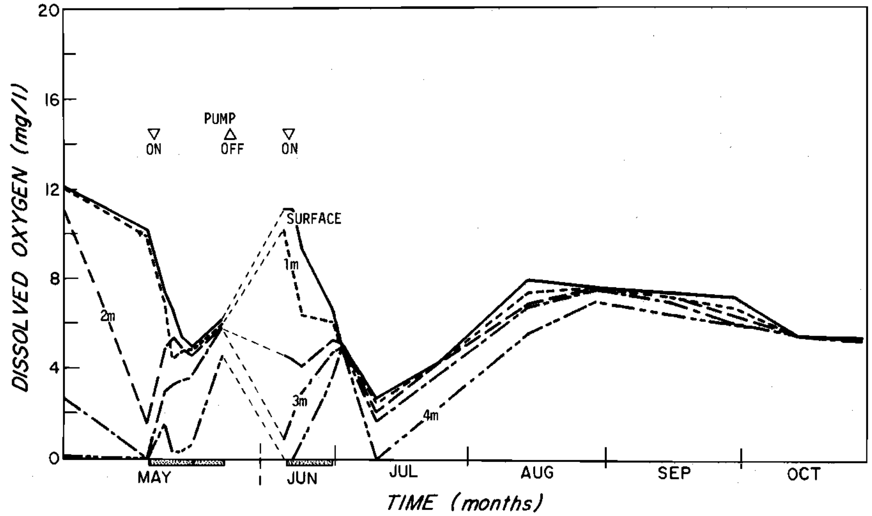


Fig. 4. Dissolved oxygen distribution for section A.

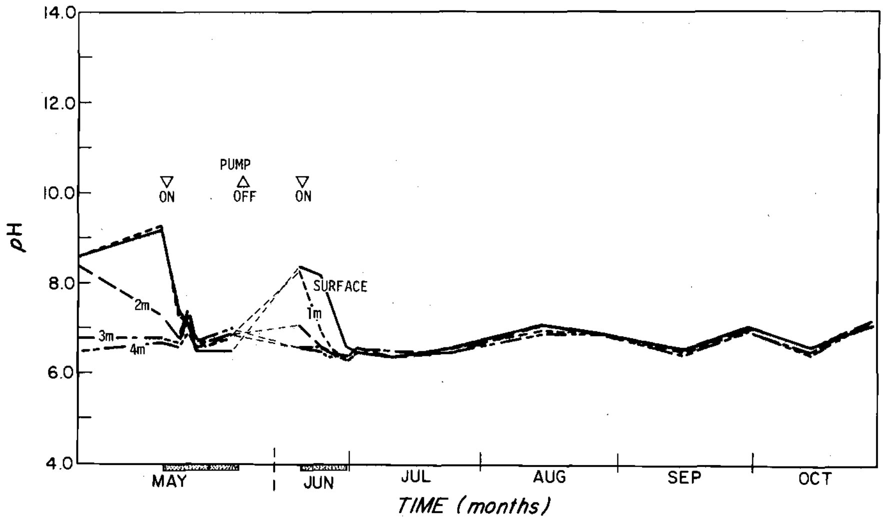


Fig. 5. Distribution of *p*H for section A.

Total alkalinity in the control section was only slightly stratified, values increasing with depth. Concentrations in both sections generally ranged from 30 to 50 mg/l.

Total inorganic carbon concentrations generally ranged between 12 and 20 mg/l in both sections. No significant change occurred in section A at the time of aeration, nor was any trend with depth apparent in either section.

Total Kjeldahl, ammonia, and nitrate nitrogen concentrations did not vary as widely with depth in the aerated section as in the control. Total Kjeldahl nitrogen in the aerated section ranged from 1.5 to 2.2 mg/l at various depths during aeration, whereas that in the control ranged from 1.4 to 3.5 mg/l during the same period. Concentrations in the control section were generally greater at the surface and at 1-meter levels than at lower depths.

Ammonia nitrogen concentrations in the aerated section ranged from 0.02 to 0.31 mg/l during aeration. In comparison, concentrations in the control section ranged from 0.03 to 0.59 mg/l. However, both sections experienced high (4.25 mg/l) concentrations at the 4-meter level immediately prior to aeration. The concentration at the 4-meter level in the control remained higher than that at other depths during the experiment.

Nitrate nitrogen concentrations for both sections remained <0.08 mg/l during aeration. Differences with depth were insignificant in section A. However, in section B during September and early October, concentrations differed by 0.04 mg/l from the surface to the 4-meter level. An increase from undetectable amounts to maximum concentrations approaching 0.08 mg/l occurred between mid-August and October in both sections. Nitrite nitrogen concentrations for both sections remained <0.01 mg/l during the entire study.

During aeration, section A was uniformly low in chlorophyll *a*, the average being about 20 mg/m^3 throughout the experiment (Figure 6). The maximum concentration in August–October was 30 mg/m^3. In contrast, section B had values as high as 110 mg/m^3 in July, August, and early September with a wide range between the various depths (Figure 7). In October, concentrations decreased to those of section A.

The entire pond was dominated by a bloom of *Aphanizomenon flos-aquae* (L.) Ralfs during May and June, the maximum concentration being 4.1×10^4 cells/ml on May 19 (Figure 8). A few weeks later, *A. flos-aquae* had decreased to $<10^3$ cells/ml in both sections, and a green coccoid, *Dictyosphaerium pulchellum* Wood, predominated, a maximum concentration of 2.8×10^4/ml being reached on June 30.

During aeration the genera and concentrations of phytoplankton in the aerated section differed widely from those in the control. In section A, there was an initial decrease in phytoplankton, and *Aphanizomenon* and *Dictyosphaerium* had

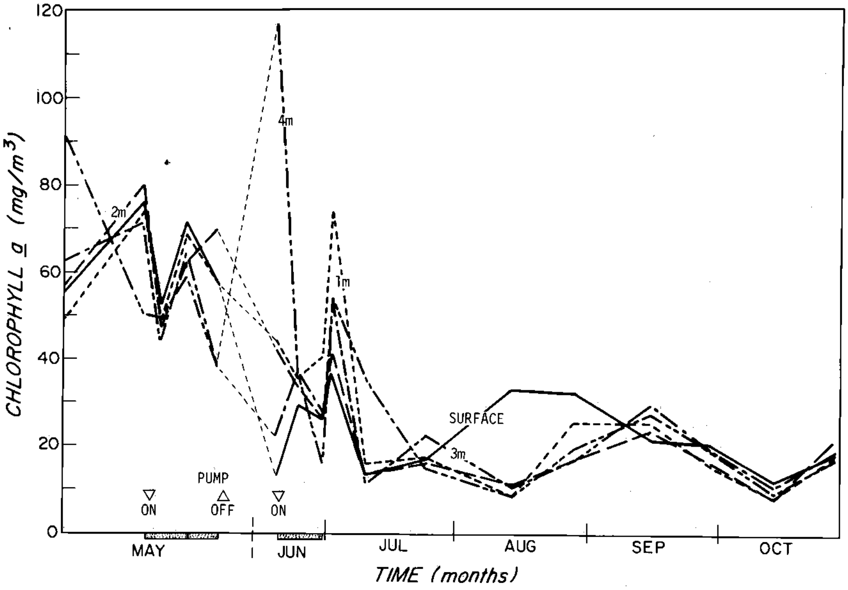


Fig. 6. Chlorophyll *a* distribution for section A.

virtually disappeared by July 11. The green flagellate, *Trachelomonas* spp., predominated at all depths during the rest of the season. It reached a peak concentration of 4.7 × 10^4 cells/ml on August 28 and then decreased. *Anabaena affinis* Lemm. and *Anabaena helicoidea* Bernard (tentative identification) developed in trace numbers in the aerated section in September and October.

By contrast, in the control section, only a slight drop in total phytoplankton occurred by July 11, although *D. pulchellum* had decreased markedly. This section experienced a series of concentration peaks of both greens and blue greens:

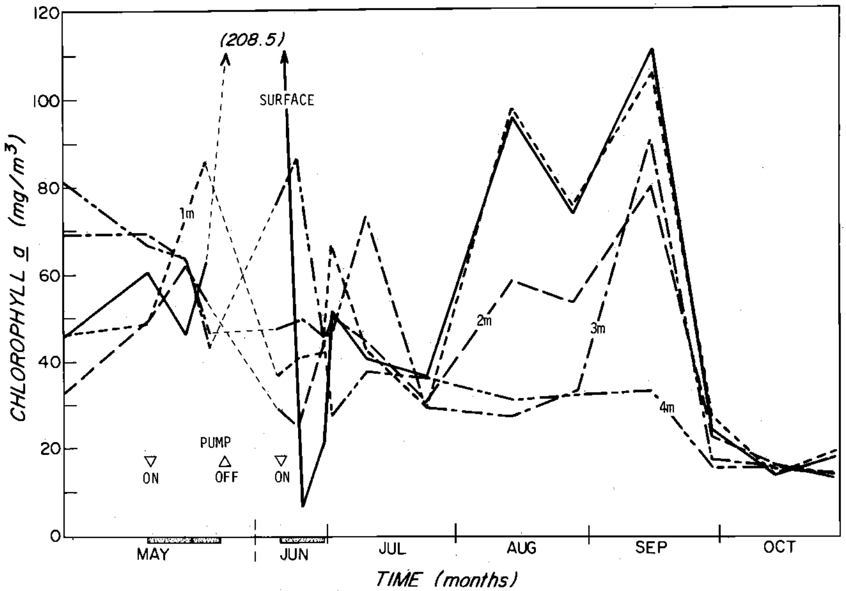


Fig. 7. Chlorophyll *a* distribution for section B.

Trachelomonas spp. at 2.0 × 10^4 cells/ml on July 25, *A. affinis* at 5 × 10^3 cells/ml on August 14, *A. helicoidea* at 6.9 × 10^3 cells/ml on September 15, and *Trachelomonas* at 2.2 × 10^4 cells/ml on October 13. The *Anabaena* pulse lasted from July to October and was ordinarily accompanied by equally high values of *Trachelomonas.*

DISCUSSION

Experiments on artificial aeration of a lentic environment date from at least the late 1940's with the manipulation of a Swiss lake [*Mercier*, 1955]. Work of this nature was continued in the United States in the early 1950's by *Hooper et al.* [1953] on a Michigan lake. Since that time, numerous experiments have taken place in several different countries. The methods of aeration generally fall into two groups: those that destratify and thus affect all depths and those that aerate and therefore affect only the hypolimnion [*Mercier*, 1955; *Bernhardt*, 1967; S. Björk, unpublished report, 1970].

Aeration with destratification has been accomplished in basically three ways. First, a compressed gas has been released through a diffuser into a body of water. Most researchers have used compressed air [*Derby*, 1956; *Riddick*, 1957; *Schmitz and Hasler*, 1958; *Ford*, 1963; *Irwin et al.*, 1968]. Other gases used or proposed include chlorine [*Derby*, 1956], ammonia [*Sager*, 1963], and oxygen [*Anthony and Fulton*, 1970]. Second, an Aero-Hydraulics gun (Aero-Hydraulics, Ltd.) has been used [*Bryan*, 1964; *Wirth and Dunst*, 1967; *Brezonik et al.*, 1969]. Third, water has been pumped mechanically from one depth to another [*Hooper et al.*, 1953; *Irwin et al.*, 1966; *Symons et al.*, 1967].

When compressed air is introduced to the water by a diffuser or by the Aero-Hydraulics gun, aeration occurs both through the diffusion process and through contact with the atmosphere at the water surface. When water has been pumped mechanically, aeration takes place only when the water is in contact with the atmosphere.

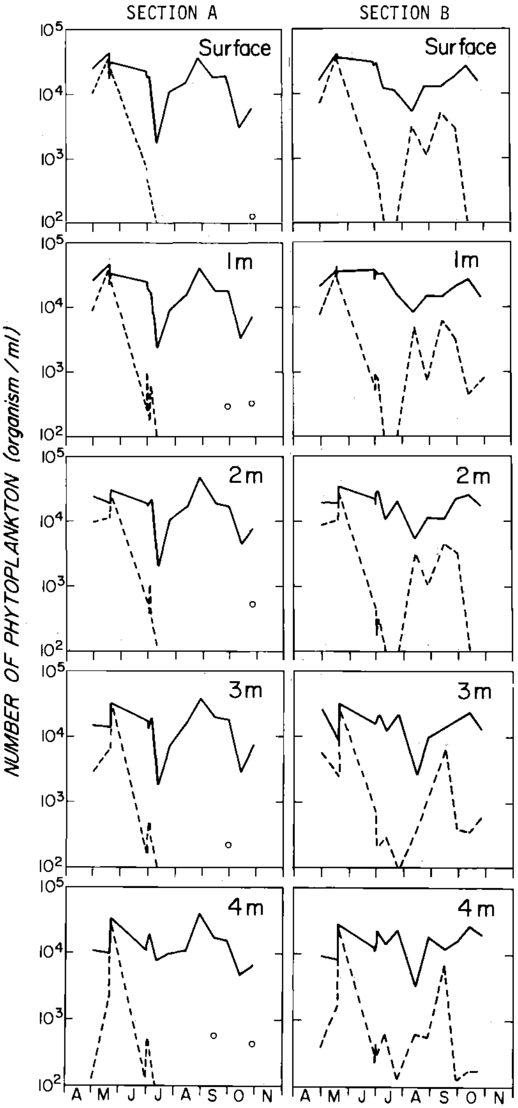
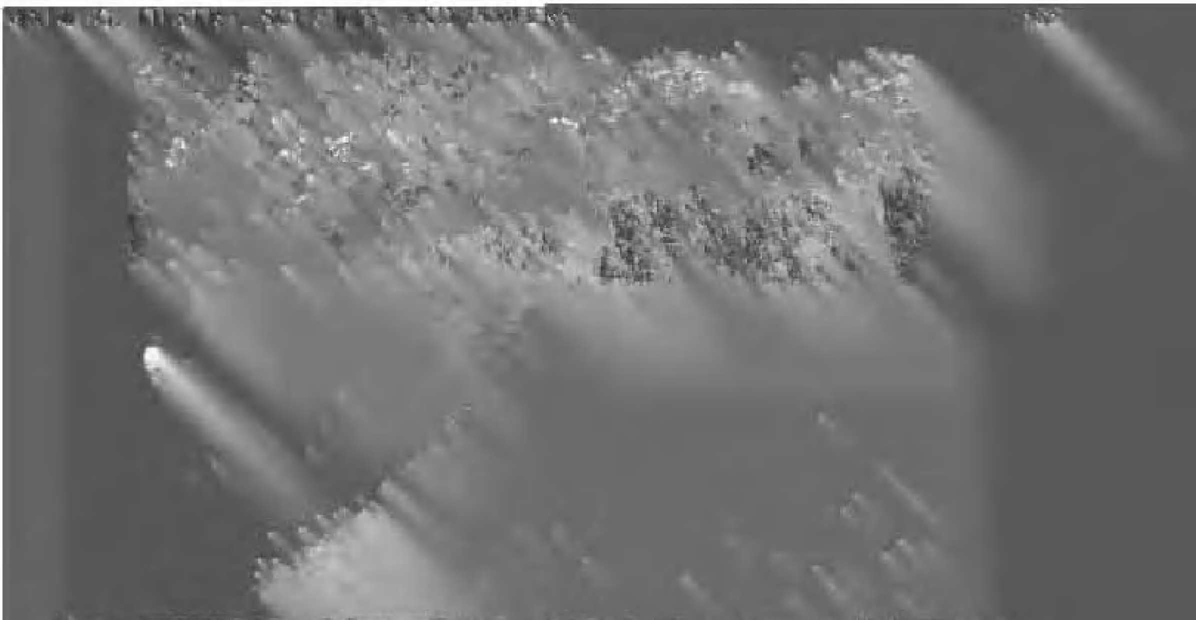


Fig. 8. Comparison of the distribution of phytoplankton in sections A and B from April through November. The dashed lines are the blue green cell counts, the solid lines are the total cell counts, and the open dots are the isolated blue green cell counts.

Most work on destratification has been directed toward physical and chemical changes, particularly those that affect the quality of drinking water. Several authors report on important algal nutrients such as nitrogen and phosphorus; only a few report effects on phytoplankton. Some of these have noted an increase in phytoplankton during or following destratification [*Hooper et al.*, 1953; *Nickerson*, 1961; *Johnson*, 1966; *Ambühl*, 1967], whereas others found a decrease [*Riddick*, 1957; *Fast*, 1966; *Hedman and Tyley*, 1967; *Wirth and Dunst*, 1967; *Irwin et al.*, 1966; *Robinson et al.*, 1969].

The most common postulate for a decrease in phytoplankton is that vertical mixing carries the algal cells out of the photic zone periodically. However, this same vertical mixing has likewise been proposed as an explanation for increased



[illegible]

[illegible]

[illegible]

to undetectable at deeper levels. Dissolved oxygen in the test section was homogeneous at 5.1 mg/l after 3 days of destratification, decreased 1 week later, and then increased to about 7 mg/l.

3. The pH ranged from 6.4 to 7.2 in the test section, whereas the values ranged from 6.2 to 9.6 in the control.

4. The total phosphate concentrations of the test and control sections did not differ significantly.

5. Orthophosphate concentrations increased in the test section following destratification but decreased after several weeks. No such increase occurred in the control.

6. Little difference in nitrogen concentrations occurred between sections.

7. Specific conductance ranged from 90 to 140 $\mu\Omega^{-1}$/cm at 25°C in both sections, total alkalinity ranged from 30 to 50 mg/l, and total inorganic carbon ranged from 12 to 20 mg/l.

8. The transparency in the test section was almost always greater than that in the control section.

9. The aerated section had generally uniform concentrations of chlorophyll *a*, averaging about 20 mg/m^3, whereas the control section had greater concentrations in the upper waters, the maximum concentration being 110 mg/m^3.

10. Total numbers of phytoplankton declined in the aerated section following destratification. Later a large population of the green flagellate, *Trachelomonas*, developed and predominated at all depths. In the control section, *Trachelomonas* and a blue green, *Anabaena*, occurred in bloom proportions.

11. Destratification vastly enhanced the esthetic appearance of the aerated section relative to that of the control.

Acknowledgments. The authors wish to acknowledge the kind cooperation of Mr. and Mrs. Lester Cline, Independence, Oregon, on whose land the study was carried out and to extend their thanks to Mr. Gerald Schuytema for performing the algal counts and to Mr. David Specht and Dr. Harry Phinney for identifying species.

REFERENCES

Ambühl, H., Discussion of 'Impoundment destratification by pumping,' *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *93*(SA4), 141–143, 1967. (Reproduced in *Water Quality Behavior in Reservoirs; A Compilation of Published Research Papers*, compiled by J. M. Symons, pp. 287–290, U.S. Government Printing Office, Washington, D. C., 1969.)

Anthony, H. V., and G. P. Fulton, Method and apparatus for purifying a natural body of water, U.S. Patent 3,505,213, April 7, 1970.

Bernhardt, H., Aeration of Wahnbach Reservoir without changing the temperature profile, *J. Amer. Water Works Ass.*, *59*(8), 943–964, 1967.

Brezonik, P. L., J. J. Delfino, and G. F. Lee, Chemistry of N and Mn in Cox Hollow Lake, Wis., following destratification, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *95*(SA5), 929–940, 1969.

Bryan, J. G., Physical control of water quality, *Brit. Waterworks Ass. J.*, *46*(383), 1–19, 1964.

Derby, R. L., Chlorination of deep reservoirs for taste and odor control, *J. Amer. Water Works Ass.*, *48*(7), 775–780, 1956.

Fast, A. W., Artificial destratification of lakes and its significance in fisheries management, *Rep. 66-16*, 16 pp., Inland Fish. Admin., Dep. of Fish and Game, Calif., 1966.

Federal Water Pollution Control Administration, *FWPCA Methods for Chemical Analysis of Water and Wastes*, 280 pp., U.S. Department of the Interior, Cincinnati, Ohio, 1969.

Ford, M. E., Jr., Air injection for control of reservoir limnology, *J. Amer. Water Works Ass.*, *55*(3), 267–274, 1963.

Hedman, E. R., and S. J. Tyley, Elimination of stratification at Lake Cachuma, California, open-file report, 40 pp., Water Resour. Div., U.S. Geol. Surv., Menlo Park, Calif., 1967.

Hooper, F. F., R. C. Ball, and H. A. Tanner, An experiment in the artificial circulation of a small Michigan lake, *Trans. Amer. Fish. Soc.*, *82*, 222–241, 1953.

Irwin, W. H., J. M. Symons, and G. G. Robeck, Impoundment destratification by mechanical pumping, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng.*, *92*(SA6), 21–40, 1966. (Reproduced in *Water Quality Behavior in Reservoirs; A Compilation of Published Research Papers*, compiled by J. M. Symons, pp. 251–274, U.S. Government Printing Office, Washington, D. C., 1969.)

Irwin, W. H., J. M. Symons, and G. G. Robeck, Water quality in impoundments and modifications from destratification, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, Jr., pp. 130–152, American Fisheries Society, Washington, D. C., 1968. (Reproduced in *Water Quality Behavior in Reservoirs; A Compilation of Published Research Papers*, compiled by J. M. Symons, pp. 363–388, U.S. Government Printing Office, Washington, D. C., 1969.)

Johnson, R. C., The effect of artificial circulation on production of a thermally stratified lake, *Fish. Res. Pap.*, *2*(4), 5–15, 1966.

Mercier, P., Evolution d'un lac eutrophe soumis à l'aération artificielle sous-lacustre, *Verh. Int. Ver. Limnol.*, *12*, 679–686, 1955.

Nickerson, H. D., Gloucester-forced circulation of Babson Reservoir, *Sanitalk*, *9*(3), 1–10, 27, 1961.

Riddick, T. M., Forced circulation of reservoir waters, *Water Sewage Works*, *104*(6), 231–237, 1957.

Robinson, E. L., W. H. Irwin, and J. M. Symons, Influence of artificial destratification on plankton populations in impoundments, *Trans. K. Acad. Sci.*, *30*(1/2), 1–18, 1969.

Sager, P. E., Some effects of aeration additions of anhydrous ammonia on a small dystrophic lake, M.S. report, 57 pp., Univ. of Wis., Madison, 1963.

Schmitz, W. R., and A. D. Hasler, Artificially induced circulation of lakes by means of compressed air, *Science, 128*(3331), 1088–1089, 1958.

Strickland, J. D. H., and T. R. Parsons, A manual of sea water analysis, *Bull. Fish. Res. Bd. Can., 125,* 1–203, 1965.

Symons, J. M., W. H. Irwin, and G. G. Robeck, Impoundment water quality changes caused by mixing, *J. Sanit. Eng. Div. Amer. Soc. Civil Eng., 93*(SA2), 1–20, 1967. (Reproduced in *Water Quality Behavior in Reservoirs; A Compilation of Published Research Papers*, compiled by J. M. Symons, pp. 299–321, U.S. Government Printing Office, Washington, D. C., 1969.)

Weber, C. I., Methods of collection and analysis of plankton and periphyton samples in the water pollution surveillance system, Water Pollution Surveillance System Applications and Development, *Rep. 19,* 19 pp., U.S. Dep. of the Interior, Fed. Water Pollut. Contr. Admin., Cincinnati, Ohio, 1966

Wirth, T. L., and R. C. Dunst, Limnological changes resulting from artificial destratification and aeration of an impoundment, *Res. Rep. 22 (Fish.),* 15 pp., Wis. Conserv. Dep., Madison, Wis., 1967.

Summary: Man-Made Lakes as Aquatic Ecosystems

NORMAN G. BENSON
North Central Reservoir Investigations
U.S. Bureau of Sport Fisheries and Wildlife, Yankton, South Dakota 57078

Man-made lakes vary so much because of geographic area, climatic conditions, water management, and plants and animals that no simple guidelines are ever going to be developed for describing or managing them on a worldwide basis. There are too many aquatic plants in tropical reservoirs and too few in north temperate reservoirs. Firm answers to understanding reservoir ecosystems are only going to develop from experience and longer term biological data than those available today. Many workers have found that concepts and principles developed from studies on natural lakes must be applied with caution to reservoirs because reservoirs are more dynamic and are usually located in areas where data from natural lakes are rare.

The papers in the following section have been placed in four groups: (1) broad descriptions of man-made lakes for prediction or evaluation, (2) aquatic weed problems, (3) phytoplankton ecology, and (4) modeling of reservoir ecosystems. They are presented in this order with three, one, two, and three papers in the respective groups.

These papers and the literature show that many specialists are describing small parts of reservoir ecosystems in great detail, whereas engineers and applied scientists are attempting to describe total ecosystems through simplified approaches. Both approaches are needed, but terminology and communication problems need to be resolved. Oversimplification often sacrifices realism and alarms some limnologists, whereas the number and variety of organisms in aquatic environments introduce an unreasonable number of variables for analysis by applied scientists. At this time I do not know of any laboratory where engineers, mathematicians, and ecologists are working together to analyze and describe reservoir ecosystems.

Few of our large man-made lakes were designed to create a specific type of aquatic ecosystem. Prediction can be precise for power, flood control, or irrigation purposes, but aquatic biologists have had to accept the resultant bodies of water and to judge how the aquatic animals and plants would react. Prediction of the reaction of organisms that evolved in natural lakes or rivers to an entirely new ecosystem has developed through experience or judgment rather than science. It is much simpler to plan the behavior of water on a volume basis than to predict its behavior as a medium for growing plants and animals. Also hydrologic data over a long period are more available than biological data. It must be recognized too that computers, laboratory data, or theory will never replace measurements in nature.

REMARKS

In all phases of planning and operations I believe that future water management programs must give greater consideration to the use of water as a medium for growing plants and animals, in addition to such primary purposes as navigation, producing power, irrigation, and domestic water. Many of the problems that have been documented here could have been averted if ecological models had been developed with the same precision as engineering or physical models.

Although man exerts some degree of control over the management of water in reservoirs, we need improved and more precise methods of prediction. It is much simpler to describe conditions than to develop equations. In prediction, enough long-term data are needed to separate natural variations from those caused by man.

A limitation in reservoir ecosystem work is that pilot studies can only be used to predict small parts of ecosystems. Likewise, elaborate theories that are developed from test tube ecosystems have limited value. The projection of classical ecological theory to large natural ecosystems must be handled with caution.

A final problem that appears in much man-made lake work concerns the broad responsibilities that aquatic biologists assume. Most ecologists are trained to work with plants and animals, but they expend much time and money collecting temperature, current, and basic chemical data that might be the responsibility of the physical scientists. The available equations for prediction of temperature and water quality have not been used enough during the planning of man-made lakes. Much more biological prediction would be possible if these data were available.

Preimpoundment Features of the Kainji Area and Their Possible Influence on the Ecology of the Newly Formed Lake

S. A. VISSER

Department of Biochemistry, University of Ibadan, Ibadan, Nigeria

Kainji Lake, a recently completed man-made lake in Nigeria, is situated in the tropics at an elevation of 155 meters. The average annual temperature of the area is about 28°C, and the average annual rainfall is 100 ± 40 cm. On the whole the heaviest rains occur between June and September (with the occasional exception of August). Between November and February it is dry, there being practically no rainfall during January.

The construction of the dam was begun in 1964 near Kainji, which is situated on the bank of Africa's third largest inland watercourse, the River Niger. The formation of the lake was completed 4½ years later in October 1968 at a total cost of $240 million.

With a length of 137 km and a width of 15–25 km, Kainji Lake has a maximum surface area of 1280 km^2 [*El-Zarka*, this volume]. At the lowest level of the lake (between May and August, when the discharge of the River Niger will fall to approximately 500 m^3/sec), this area will be reduced by 30–35%. Between September and October, when the discharge of the River Niger increases to approximately 7000 m^3/sec as a result of local rainfall, the lake will attain its highest level. This phenomenon is known as the 'white' flood because of the large concentration of silt that the water carries. From November until April the lake will be fed mainly by floodwaters originating from other west African territories, which have been retarded in the extensive swamps near Timbuktu on their way down the River Niger. Because of the clarity of these waters this phenomenon is referred to as the 'black' flood.

Because of these fluctuations in the water supply of the lake the annual drawdown will be as much as 10.4 meters; i.e., at its lowest level the lake will uncover a large area of seasonal swamps, which will have a profound effect on many ecological phenomena in the lake. The topography of the lake bottom will also, however, affect the ecology of the lake during other seasons. Three distinct ecological zones can be distinguished: (1) the northern zone, where conditions will often resemble those of the river before the construction of the dam, (2) the central zone (70% of the lake), with shallow waters and marginal swamps, and (3) the southern zone, with fairly deep waters. Before the formation of the lake, approximately 42,800 ha of land were cleared to stop the water from becoming deoxygenated during the initial formation of the lake. This phenomenon, which is due to the decomposition of submerged land vegetation, has often been observed in newly formed lakes and can result in an appreciable reduction of the fish population [*Visser,* 1970].

Before the closure of the dam the fish yield was <3000 metric tons per year in the entire reservoir area (the equivalent of approximately ½ metric ton per fisherman per year). The yield from an organized fishing industry in Kainji Lake is expected to be >10,000 metric tons per annum.

Because of the importance for present and future ecological studies of data on the Kainji area before its impoundment into a lake, the main object of this paper is to present the data of chemical, microbiological, botanical, zoological, and ecological investigations performed between 1965 and 1967, i.e., before the formation of the lake. In conjunction with future work these data will enable assessments to be made about the ultimate effects of this man-made lake on its environment.

Appendix 1 lists the average composition of the fish population of the River Niger just before the closure of the dam. These data are based on a number of reports [*Awachie,* 1965; *Banks et al.,* 1965; *Ukoli,* 1965; *Imevbore,* 1970*b*; *Motwani and Kanwai,* 1970] and comprise almost 10,000 fish

TABLE 1. Chemical Composition of Water of the River Niger in Comparison with the Composition of Water from West Africa, the Composition of Water from Tropical Africa, and the World Average Composition of Water

	River Niger Water	Median Composition West African Water*	Mean Composition Tropical African Water*	World Average Composition Water†
Conductivity, $\mu\Omega^{-1}$	70.0	76.0		
*p*H	7.1	7.3		
Sodium, ppm	4.19	9.9	11.0	6.3
Potassium, ppm	5.16			2.3
Ammonium, ppm	0.52	0.3		
Calcium, ppm	6.36	6.5	12.5	15.0
Magnesium, ppm	2.68	2.8	3.8	4.1
Total iron, ppm	0.15		1.3	0.7
Chloride, ppm	2.58	5.6	12.1	7.8
Nitrite, ppm	0.59	0.5		
Nitrate, ppm	0.30	0.4	0.8	1.0
Silicate, ppm	23.18	23.2	23.2	13.1
Sulfate, ppm	trace		13.5	11.2

*Data from *Visser* [1969].
†Data from *Livingstone* [1963].

specimens caught during different seasons and with a large variety of fishing techniques. In the various methods employed, use was made of: nets, gill nets, drift nets, cast nets, seines, and filtering nets, which included lift nets and clap nets; traps, most of them fitted with a fyke; fishing lines, long lines with a horizontal primary line and short secondary lines to which baited or unbaited hooks were attached or standing lines with a single baited hook; fences, usually 1–2 meters in height and approximately 6 meters in length; poisons, usually extracted from local plants; an electric fishing machine using direct current; and underwater explosions. Appendix 1 lists the distribution of 10,000 individuals spread over 150 species and composing 27 families.

The phytoplankton of the River Niger appeared to consist mainly of blue green algae and diatoms of the genera *Melosira* and *Nitzschia*, whereas the following species of crustaceans were found to be present in the zooplankton (adapted from *Thomas* [1965]):

Moina dubia Gurney & Richards	53.9%
Cyclops leukarti Claus	20.7%
Diaphanosoma exisum Sars	14.1%
Ceriodaphnia cornuta Sars	4.9%
Cyclops hyalinus Rehberg	4.7%
Diaptomus banforanus Kiefer	1.7%

The general poorness of both phytoplankton and zooplankton was probably due to the low concentration of nutrients in the water and to the poor light penetration prevalent in the river.

TABLE 2. Microorganisms Present in Niger Water near Kainji before Closure of the Dam

	Surface	1 Meter below Surface	2 Meters below Surface	3 Meters below Surface	Average of First 3 Meters	Mud	Average of Tropical Muds*
Total microflora	7.3 x 10^{5}	1.6 x 10^{7}	5.1 x 10^{5}	5.5 x 10^{5}	4.4 x 10^{6}	8.4 x 10^{11}	
Actinomycetes	1.1 x 10^{2}	2.1 x 10^{6}	1.2 x 10^{4}	3.5 x 10^{3}	5.3 x 10^{5}	6.6 x 10^{8}	1.6 x 10^{8}
Fungi	7.4 x 10^{4}	2.5 x 10^{4}	4.2 x 10^{3}	2.1 x 10^{3}	2.8 x 10^{4}	1.4 x 10^{3}	8.1 x 10^{4}
Algae	6.6 x 10^{4}	5.9 x 10^{4}	3.6 x 10^{4}	8.7 x 10^{3}	4.2 x 10^{4}	7.1 x 10^{6}	1.5 x 10^{8}
Aerobic nitrogen fixers	10.5	6.2	2.4	2.0	5.3	10.4	6.9
Anaerobic nitrogen fixers	2.9	2.4	4.3	5.7	3.8	7.5 x 10^{4}	1.6 x 10^{4}
Proteolytic organisms	5.8 x 10^{3}	2.9 x 10^{6}	9.7 x 10^{3}	9.9 x 10^{3}	7.3 x 10^{5}	5.9 x 10^{11}	1.3 x 10^{11}
Ammonifiers	9.1 x 10^{3}	0.4 x 10^{6}	3.2 x 10^{3}	4.5 x 10^{3}	1.0 x 10^{5}	1.2 x 10^{10}	2.8 x 10^{9}
Nitrifiers, $\rightarrow NO_2$	6.7	3.1	<1	<1	$\sim$2.5	7.4 x 10^{4}	2.7 x 10^{4}
Nitrifiers, $\rightarrow NO_3$	5.3	2.9	<1	<1	$\sim$2.1	1.9 x 10^{2}	1.9 x 10^{2}
Denitrifiers	8.8 x 10^{3}	9.7 x 10^{5}	0.9 x 10^{3}	7.7 x 10^{2}	2.4 x 10^{5}	7.1 x 10^{9}	1.9 x 10^{9}
Starch decomposers	4.6 x 10^{4}	6.9 x 10^{6}	9.5 x 10^{2}	7.7 x 10^{2}	1.7 x 10^{6}	6.0 x 10^{9}	3.2 x 10^{9}
Pectin decomposers	8.8 x 10	9.3 x 10^{2}	7.2 x 10	8.5 x 10	2.9 x 10^{2}	1.2 x 10^{4}	8.0 x 10^{4}
Hemicellulose decomposers	5.2 x 10^{5}	2.3 x 10^{6}	4.4 x 10^{5}	5.2 x 10^{5}	9.5 x 10^{5}	2.3 x 10^{11}	2.0 x 10^{11}
Aerobic cellulose decomposers	8.2	6.4 x 10	8.7	7.9	2.2 x 10	7.8 x 10	6.2 x 10
Anaerobic cellulose decomposers	9.7	6.8 x 10	3.5 x 10^{2}	4.2 x 10^{2}	2.1 x 10^{2}	1.3 x 10^{6}	7.0 x 10^{7}

**Visser and Middleton* [1969].

The chemical composition of the water of the River Niger is given in Table 1 and is compared with the median composition of water from west Africa, the mean composition of water from tropical Africa, and the world average composition of water. The River Niger is shown to have a low salt content with the possible exception of potassium.

The composition of microflora in the river before impoundment is shown in Table 2. These data also suggest the relative scarcity of nutrients in the River Niger. The microflora was investigated by methods described by *Pochon and Tardieux* [1962]. The data have been discussed in greater detail by *Imevbore and Visser* [1969]. With respect to the turbidity of the water it was found that the maximum silt load of the River Niger was 0.5 kg/m^3 [*Imevbore,* 1970*a*]. Although this is relatively low for tropical rivers, it nevertheless resulted in almost complete darkness in the river at a depth of 1 meter below the surface. By means of X ray diffraction techniques it was found that the silt was made up mainly of the following mineral matter: feldspar, hematite, illite, kaolinite, lepidocrocite, and quartz. As the silt settles in the reservoir, the trophic level increases, and conditions for the growth of phytoplankton and zooplankton improve greatly.

With respect to the higher plants, Appendix 2 (data adapted from *Cook* [1965]) lists 52 of the commoner aquatic or amphibious plant species in the area. The species have been divided into five ecological zones: (1) free-floating plants partly or wholly on the water surface, (2) rooted plants partly or wholly on the water surface, (3) completely and continuously submerged plants, (4) periodically inundated plants, such as those attached to rocks, and (5) amphibious plants of wet or partly flooded areas. It seems unlikely that any of these plants will create a problem at Kainji. *Ceropteris cornuta, Pistia stratiotes,* and *Salvinia nymphellula* have not to date been reported as causing problems elsewhere in west Africa, whereas the notorious *Eichhornia crassipes* and *Salvinia auriculata* are unknown in the Kainji area.

Health hazards that were present in or around the River Niger near Kainji before the formation of the lake consisted of river blindness, trypanosomiasis, schistosomiasis, and malaria [*Boyo,* 1962].

APPENDIX 1: AVERAGE COMPOSITION OF THE FISH POPULATION OF THE RIVER NIGER NEAR KAINJI BEFORE CLOSURE OF THE DAM PER 10,000 SPECIMENS

Alestes leuciscus	699
Citharinus citharus	648
Synodontis gobroni	622
Gnathonemus niger	414
Polypterus senegalus	395
Synodontis clarias	341
S. gambiensis	273
S. budgetti	255
S. nigrita	248
Gnathonemus tamandua	246
Synodontis courteti	226
Schilbe mystus	224
Polypterus ansorgei	216
Alestes dentex + A. baremose	206
Hyperopisus bebe occidentalis	205
Distichodus rostratus	196
Labeo coubie	194
Tilapia nilotica	191
Polypterus bichir lapradei	182
Synodontis sorex	175
Mormyrus macrophthalmus	170
Hemichromis bimaculatus	162
Eutropius niloticus	160
Gnathonemus abadii	158
Mormyrops deliciosus	152
Marcusenius psittacus	150
Synodontis ocellifer	129
Clarias lazera	123
Ctenopoma kingsleyae	120
Mormyrus rume	118
Citharinus latus	114
Alestes macrolepidotus	101
Auchenoglanis biscutatis	99
Polypterus endlicheri endlicheri	92
Labeo senegalensis	91
Synodontis membranaceous	88
S. vermiculatus	85
Distichodus brevipinnis	81
D. engycephalus	69
Synodontis resupinatus	68
Gnathonemus pictus	66
Gymnarchus niloticus	65
Clarias anguillaris	63
Clupisudis niloticus	63
Bagrus docmac niger	62

Synodontis batensoda	61
Chrysichthys nigrodigitatus	59
Gnathonemus senegalensis	59
Lates niloticus	58
Alestes nurse	57
Chrysichthys auratus longifilis	56
Clarotes laticeps	54
Synodontis violaceous	51
Petrocephalus bane ansorgei	50
Citharinus distichoides	49
Gnathonemus cyprinoides	44
Tilapia galilaea	42
T. zillii	41
Auchenoglanis occidentalis	41
Gnathonemus deboensis	38
Mormyrops oudoti	33
Heterobranchis bidorsalis	29
Labeo pseudocoubie	28
Xenomystus nigri	28
Bagrus bayad macropterus	25
Hydrocynus forskali	19
H. lineatus	19
Hepsetus odoe	19
Synodontis eupterus	18
S. robbianus	14
S. melanopterus	14
Chrysichthys furcatus	14
Heterobranchus longifilis	14
Physailia pellucida	12
Paraphiocephalus obscurus	10
Molapterurus electricus	10
Synodontis filamentosus	9
Clarotes macrocephalus	9
Marcusenius harringtoni	8
Labeo parvus	6
Mormyrus hasselquisti	5
Hemichromis fasciatus	4
Synodontis schall	4
S. amias	4
Protopterus annectens	4
Barbus occidentalis	3
Gnathonemus petersii	3
Tetraodon fahaka strigosus	2
Tilapia monodi	2
Siluranodon auritus	2
Barbus senegalensis	2
Alestes imberi	2
Marcusenius isidori	2
Mormyrops engystoma	2
Mastacembalus sp.	1
Eleotra nana chevalieri	1
Ctenopoma petherici	1
Tilapia melanopleura	1
Pelmatochromis güntheri	1
Tylochromis jentinki sudanensis	1
Gobiocichla wonderi	1
Aplocheilichthys gambiensis	1
Epiplatys bifasciatus taeniatus	1
E. senegalensis	1
Chiloglanis micropogon	1
C. niloticus waterloti	1
Synodontis xiphias	1
Mochocus niloticus	1
Bagrus filamentosus	1
Arius gigas	1
A. latiscutatus	1
A. heudeloti	1
Heterobranchus isopterus	1
Clarias submarginatus	1
Barilius senegalensis	1
B. niloticus	1
Barbus ablabes	1
B. leonensis	1
B. macinensis	1
B. atokorensis	1
B. wurtzi	1
Labeo chariensis	1
L. brachypoma	1
Chelaethiops elongatus brevianalis	1
Garra waterloti	1
Citharidium ansorgei	1
Nannocharox niloticus gracilis	1
N. lasciatus	1
N. ansorgei	1
Paradistichodus dimidiatus	1
Nannaethiops unitaeniatus	1
Ichthyoborus besse	1
Phago loricatus	1
Alestes brevis	1
A. longipinnis	1
A. chaperi	1
Hydrocynus somonorum	1
H. brevis	1
Micralestes acutidens	1
Gnathonemus gillii	1
Marcusenius petricolus	1
M. lhuysi	1
Mormyrops engystoma	1
Petrocephalus simus	1
P. bovei	1
Microthrissa miri	1
Cromeria nilotica occidentalis	1
Papyrocranus afer	1
Pantodon bucholzi	1
Calanichthys calabaricus	1

APPENDIX 2: COMMON PLANTS OF THE RESERVOIR SITE AND THEIR ECOLOGICAL ZONES BEFORE IMPOUNDMENT OF THE LAKE

Aeschynomene afraspera J. Léonard	5
A. nilotica Taub.	5
Alloteropsis ? paniculata Stapf.	5
Alternanthera nodiflora R. Br.	5
Ceratophyllum demersum Linn.	3
Ceratopteris cornuta (P. Beauv.) Lepr.	1 + 2
Commelina sp.	5
Cyperus ? denudatus Linn. f.	5
C. digitatus Roxb.	5
C. procerus Rottb.	5
Echinochloa pyrimidalis Hitchc. & Chase	5
Eclipta prostrata (Linn.) Linn.	5
Eichhornia diversifolia (Vahl) Urb.	2
Eragrostis sp.	5
Fuirena umbellata Rottb.	5
Hydrophila sp.	5
Ipomoea aquatica Forsk.	5
I. asarifolia (Desr.) Roem. & Schult.	5
Lemna perpusilla Torr.	1
Limnophila sp.	2
Jussiaea erecta (Linn.) Hara	5
J. hyssopifolia (Don.) Exell.	5
J. leptocarpa (Nutt.) Hara	5
J. suffruticosa (Linn.) subsp. *brevisepala* (Bren.) Raven	5
J. stenorraphe (Bren.) Hara	5
J. repens (Linn.) Raven	5
Marsilea diffusa Lepr. ex A. Br.	5
Mimosa pigra Linn.	5
Mitragyna inermis (Willd.) O. Ktze.	5
Naias affinis Rendle	3
Nitella furcata (Roxb. ex Bruz.) Ag. em.	3
Nymphaea lotus Linn.	2
N. maculata Schum. & Thonn.	2
N. micrantha Guill. & Perr.	2
N. rufescens Guill. & Perr.	2
Oldenlandia sp.	5
Oryza perennis Moench.	5
Ottelia ulvifolia (Planch.) Walp.	3
Pistia stratiotes Linn.	1
Polygonum salicifolium Brouss. ex Willd.	5
P. senegalense Meisn.	5
Pycreus ? odoratus Urb.	5
P. tremulus C. B. Cl.	5
Salvinia nymphellula Desv.	1
Scirpus sp.	5
Sphenoclea zeylanica Gaertn.	5
Striga bilabiata (Thunb.) O. Ktze. subsp. *rowlandii* (Engl.) Hepper	5
S. forbesii (Benth.)	5
Tristemma littorale Benth.	5
Tristicha trifara (Bory) Spreng.	4
Utricularia gibba Linn. subsp. *exoleta* (R. Br.) P. Tayl.	3
U. inflexa Forsk. var. *stellaris* (Linn. f.) P. Tayl.	3

REFERENCES

Awachie, J. B. E., Preliminary notes on the parasites of fish in the area of the Kainji Reservoir, in *The First Scientific Report of the Kainji Biological Research Team,* edited by E. White, pp. 65–69, University of Liverpool, Liverpool, Eng., 1965.

Banks, J. W., M. J. Holden, and R. H. McConnell, Fishery report, in *The First Scientific Report of the Kainji Biological Research Team,* edited by E. White, pp. 21–42, University of Liverpool, Liverpool, Eng., 1965.

Boyo, A. E., Medical problems of the Niger dams project, *Proc. Sci. Ass. Nigeria, 5*(54), 1962.

Cook, C. D. K., The aquatic and marsh plant communities of the reservoir site, in *The First Scientific Report of the Kainji Biological Research Team,* edited by E. White, pp. 78–88, University of Liverpool, Liverpool, Eng., 1965.

El-Zarka, S. E.-D., Kainji Lake, Nigeria, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Imevbore, A. M. A., Some general features of the Kainji Reservoir basin, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 17–26, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970*a*.

Imevbore, A. M. A., Some preliminary observations on the sex-ratios and fecundity of fish in the River Niger, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 87–98, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970*b*.

Imevbore, A. M. A., and S. A. Visser, A study of microbiological and chemical stratification of the Niger River within the future Kainji Lake area, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, Ghana Universities Press, Accra, 1969.

Livingstone, D. A., Chemical composition of rivers and lakes, in *Data of Geochemistry,* edited by M. Fleischer, pp. G40–G41, U.S. Government Printing Office, Washington, D. C., 1963.

Motwani, M. P., and Y. Kanwai, Fish and fisheries of the coffer-dammed right channel of the River Niger at Kainji, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 27–48, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Pochon, J., and P. Tardieux, *Techniques d'Analyse en*

Microbiologie du Sol, Editions de la Tourelle, Saint-Mandé, France, 1962.

Thomas, M. P., Zooplankton studies, in *The First Scientific Report of the Kainji Biological Research Team,* edited by E. White, pp. 17–20, University of Liverpool, Liverpool, Eng., 1965.

Ukoli, F. M. A., Preliminary report on the helminthic infection of fish in the River Niger at Shagunu, in *The First Scientific Report of the Kainji Biological Research Team,* edited by E. White, pp. 70–73, University of Liverpool, Liverpool, Eng., 1965.

Visser, S. A., Variations in the composition of waters from lakes and rivers in west and east Africa, *J. West Afr. Sci. Ass.,* 1969.

Visser, S. A., A man-made lake as an ecosystem, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 1–16, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Visser, S. A., and D. Middleton, Investigation into the influence of the moisture content of the environment on the occurrence of soil micro-organisms in the tropics, *Rev. Ecol. Biol. Sol, 6,* 99–113, 1969.

Bureau of Reclamation Reservoirs and the Environment

O. A. DOLVEN AND CURTIS O. NESS

Division of Water and Land Operations, Bureau of Reclamation
Billings, Montana 59103

The purpose of this paper is to present a brief overlook or a 'state of the art' survey, as it were, in an attempt to bring into a common focus some of the accomplishments, problems, and needs relating to the construction and management of the man-made lake as experienced by the Bureau of Reclamation over some 68 years encompassing evolutionary needs and practices. This paper does not cover the far-reaching environmental impacts outside the dam and reservoir area.

Man-made lakes created by the Bureau of Reclamation have had a tremendous impact on the environments of the 17 western states. Totaling about 230 in number, these reservoirs have a combined shoreline of some 18,700 km, a water area of >688,000 ha, and 1.5 million ha of shoreline lands available for public recreational use. Locations vary from scenic canyons and foothill areas of mountain ranges to the Great Plains east of the Continental Divide. Sizes vary from about 80,000 to <40 ha of water surface.

In 1969 these reservoirs provided different forms of outdoor recreation totaling 54.5 million visitor days. The game catch included 21.7 million fish and 289,000 ducks and geese, and the game population was protected on about 235,000 ha of state and federal game refuge areas. Often, the conversion of a live stream to a lake with fluctuating water levels is not without some loss in the preservationist's point of view. However, compensating environmental benefits are or can be significant.

Environmental benefits now being realized are in a large measure provided by reservoirs justified by and built for other purposes. Although the early proponents of reclamation were conservationists, conservation relating to environmental preservation and enhancement evolved gradually as needs were recognized and the potentials of reclamation development to meet such needs became more fully appreciated. The total environmental quality goal has often been elusive owing in large measure to the difficulty in quantifying benefits, a requirement of the bureau's conservation development objectives. Incorporating these implied goals with old legislative tools was difficult. As a result the reclamation objectives for environmental quality originated to a large extent from two sources: (1) implicitly from a changing national concept of the quality of life and (2) explicitly from water resource managers who had to cope with specific goals not directly related to previously authorized objectives. Inescapably, disservices have been created by narrowly viewed developments, and potential benefits have been forgone. However, options available for the continued implementation of such narrow views have been substantially lessened by public interest in recreation and the environment.

Chronologically, the first environmental impact of the man-made reservoirs is the displacement involved in the acquisition of right-of-way. Although many early bureau reservoirs were located in remote and scarcely populated areas, the progressively narrowing list of potential damsites almost inevitably resulted in the displacement of some owners, tenants, and workers, the relocation of some sections of highway and railroads, and occasionally the relocation of an entire town. In accordance with the principle set forth in the fifth amendment to the Constitution it was long the policy of the federal government to pay the property owner the market value of his land. However, all other expenses and losses incurred by owners, tenants, and others, such as moving and relocation costs and sentimental values, were viewed by the courts as consequential damages and were not compensable. On May 29, 1958, however, Congress passed an act that recognized that payment of market value is not always enough and so authorized the payment of expenses involved in moving the people, their families, and their possessions as a direct result of such acquisition.

The construction scars of borrow pits, construction trails, and construction campsites and the environmental compatibility of the new structure design were given only secondary consideration in the early history of the reclamation program. As more comprehensive congressional enactments permitted and as public awareness and interest in the preservation and enhancement of environmental quality advanced, the bureau has been in the vanguard of federal agency involvement. Current policy energetically supports a program that embraces planning, construction, and operation to preserve and enhance the qualitative virtues of the natural environment and the quality of life of all the people.

The multipurpose operation of its reservoirs is a practice that the bureau has lived with since the filling of its first reservoir. The public interest has demanded a vastly more efficient use of our water supply and of the physical opportunities for its regulation and enjoyment than was in many cases encompassed in the original plan. West of the 100th meridian, where most of the bureau reservoirs are located, the aridity of the country is such that streamflow fluctuates more violently and more complete control of streams and rivers is required. The total water supply is generally adequate for all consumptive uses in most of the areas that the streams and rivers serve, but storage must be provided for protection against floods, to generate power, to meet international treaty obligations, and, even on the great rivers, to assure an evenly regulated water supply for consumptive use.

FLOOD CONTROL

During the initial phases of river basin development when only a few major reservoirs are in operation, the flood control function involves different degrees of pool level fluctuations, since the flood control storage space must be evacuated to make room for the next flood. On Bureau of Reclamation reservoirs, flood control operations occasionally create such environmental problems as the flooding of nesting areas and interference with fish spawning or with recreational use at high-water and low-water stages. By timely cooperation with fish and game management agencies and the U.S. Army Corps of Engineers, which controls the flood control operation, potential fish and wildlife losses have been held to a minimum. As the number of reservoirs in a basin increases and therefore the fully regulated river approaches elimination of the flood hazard, flood control storage space becomes available for other uses as well. Although the Bureau of Reclamation has seldom reached this optimum objective in its comprehensive river basin development programs, by closely coordinated operations with other reservoir management agencies in the basin, it has approached this goal.

RECREATION

Some of the environmental and ecological significance of the recreational resources of the man-made lakes of the bureau is indicated by: a national recognition of the large permanent value of outdoor recreation for the health and well-being of the nation, the surging demand by whatever measuring rod (visitations, number of fishing license holders, number of boats in use, and so on) of an exploding population for outdoor recreation, preferably water oriented, and the average 0.57 ha of water surface provided to each person within the United States in 1850, which had decreased to 0.16 ha by 1950 and is still decreasing.

Against this background the resources of the bureau reservoirs range from resources of strictly local significance to those of such national importance as the Flaming Gorge National Recreational Area of the Colorado River storage project and the Bighorn Canyon National Recreation Area of the Missouri River basin project. In total they constitute a major factor in meeting the growing demand for water-based recreation. The National Park Service prepares a general development plan for the recreational areas, and qualified federal, state, or local agencies administer them. In a few instances the lack of funds has resulted in a lack of coordination between local administering agencies and a lack of success.

The bureau, acting as a custodian of public property, through its own program and by means of agreements with the recreational managing agencies establishes and maintains guidelines that are designed to provide unbiased recreational opportunities for public use. Such guidelines include: (1) unrestricted public access consistent with public safety and reservoir management needs to reservoir shoreline lands and water areas, (2) balanced development to facilitate comparable opportunities among the various pertinent recreational activities, (3) time and space limitations on quasi-private recreational uses, such as cabin site and trailer use, to avoid preemption of potential public use areas by special interests, and (4) avoiding commitments that would provide special benefits or privileges not compatible with the public interest to nearby private landowners. Reservoir fluctuations due to flood control and drawdown for irrigation, power generation, and municipal and industrial water supplies are carefully controlled to minimize detrimental effects to the recreational activity.

The degree of fluctuation varies widely within reservoirs as it does between reservoirs, usually in an inverse ratio to the size of the reservoir. Although this fluctuation can have some minor adverse effects on the quality of the recreation provided, it apparently has little effect on the demand as measured in terms of visitor days.

Our experience with recreational development and public use of bureau reservoirs indicates that the recreational resources involved have a significant potential for meeting the future expansion of public demand if administrative practices reflect a cognizance of the need to protect environmental values and to insure development and management practices that are consistent with the public interest.

Most public health officials agree that recreation on water supply reservoirs under appropriate regulation presents no threat if the water is properly filtered and chlorinated prior to domestic use. Public health regulations and public sentiment usually prohibit body contact sports such as swimming and water skiing in domestic water supply reservoirs, but even swimming presents no special health hazard provided the water is completely treated before it is used for domestic purposes. Probably more important from a health standpoint is the installation and maintenance of on-site sanitary facilities for recreational users.

FISH AND WILDLIFE

The biota of the new reservoir becomes established in a very different kind of environment from that from which it evolved. River impoundment can upset the long-established balance of temperature, oxygen content, seasonal distribution, and energy flows in the biotic environment. Resulting changes occur in species composition, invertebrate succession, aquatic vegetation, and the biotic base that sustained them. The changeover, however, is from stability to dynamism. The big new man-made lake is the recreational hope of the future. Reasonably protected from major deleterious changes and broad enough to encompass the competing recreational pursuits of fishing, boating, swimming, and water skiing, it is deep enough to sustain a variety of fish and rich enough to grow them big. However, the state of the art of maximizing the fishery potential of reservoir impoundments has a long way to go. Nevertheless, some encouraging results have been realized when the controlled fluctuation of some bureau reservoirs has been used to facilitate fish spawning and nesting, to destroy the hatch of undesirable species, and to improve the feeding grounds for both fish and wildlife.

Most bureau reservoirs are used frequently by migratory waterfowl as resting and feeding areas. Some are important as nesting areas. Others, such as the Klamath project reservoirs in southern Oregon and northern California, are principal supporting components of major flyways. In addition, many reservoirs, such as those in the Great Plains states, complement state game management programs by supplementing scarce water areas for nonmigratory waterfowl and other wildlife management purposes.

SEEPAGE AND FLOODING

The question of whether the presence and operation of a reservoir can contribute to a seepage or high-groundwater problem in the adjoining land area and whether the presence of the reservoir at high stage, low stage, or in between can contribute to the severity or the frequency of ice jam flooding has been an issue on some bureau reservoirs. Although the preponderance of evidence is to the contrary, there is an element of doubt due to the lack of specific historical data from which a sharp differentiation between cause and effect and coincidence can be made.

EXPOSED BEACHES AROUND RESERVOIRS

Many bureau reservoirs are evacuated or drastically drawn down during the irrigation season. The drawdown exposes beaches, particularly at the upper end of the reservoir. The exposed beaches are unsightly and vulnerable to wind erosion. If the beach material is fine-grained dust, blowing problems are common. If the beach material is sand, winds drift the sand onto the adjoining areas and oftentimes destroy the native vegetation. Although the problem is not widespread, it is difficult to correct.

Several dust suppression measures have been considered, and substantial experimental work has been performed or initiated including cultural practices oriented toward suppression of dust by either establishing a vegetative cover over the dust-contributing area or keeping the exposed soil wet or roughened. These practices have been successful at the higher reservoir elevations but have not solved the wind erosion problem in areas subject to prolonged seasonal inundations. Preliminary observations indicate that a diking program may be a more permanent means of dust suppression. However, the extent of the adverse effects of wave and ice action on such dikes is not known at this time; costs of repair or reconstruction following periods of inundation may be costly.

EVAPORATION

Reservoir evaporation ranges from <1% to about 20% of reservoir inflow. The average evaporation loss is approximately 5% of reservoir inflow. The feasibility of the large-scale application of monolayers for reservoir evaporation reduction has been investigated, but the conclusions of the study indicate that the average reduction in evaporation is only 12% because of significant film separation caused by wind action. The cost is approximately $\$0.02/m^3$ of water conserved.

SEDIMENTATION

Sedimentation rates as related to the life expectancy of the reservoir site are generally within design requirements. The maximum life is greater than a projection of observed rates of sediment accumulation, however, because the sediment storage capacity is greater than the water storage capacity and the current average specific weight of sediment is increased by compaction. Sediment storage capacity frequently changes turbulent silt-laden streams of low fishery values into streams of clear sparkling water and outstanding fisheries. Geodetic surveys show that the weight of water has caused minor subsidence of the earth crust.

WATER QUALITY

Most reservoirs bring about a dramatic change in the sediment load carried by the river. In 1930, for example, measurements indicated that 57% of the silt in the Yellowstone River came from the Bighorn River. Following completion of Yellowtail Dam and Bighorn Lake the Bighorn River below has become a clear sparkling trout stream with fishery value far in excess of original estimates.

There have, however, been increases in mineral content such as those found from the upper to the lower end of Lake Mead, the greatest increases being in the sulfates and chlorides of calcium and sodium. The location and operation of multiple outlets will affect the limnological regime of the reservoir and permit selection of the water quality to be served downstream. Related atmospheric control operations, such as cloud seeding for increased snowfall, can enhance the water quality.

NEED FOR RESEARCH

Sufficient management of water resources to meet the needs of an expanding population will require more fully developed systems of storage reservoirs to provide control of the periodic and seasonal fluctuation of streamflow. The number of potential reservoir sites in the nation is physically limited, and some are being preempted by incompatible development. A program for the reservation of storage sites on public domain has been under way, but no national program or policy exists with respect to the reservation of many other favorable sites that are privately owned. A study is needed therefore to consider (1) identification of potential sites for federal or nonfederal development, (2) restriction of future incompatible development through purchase, easements, land use contracts, or a combination of these means, and (3) reclamation through a long-term program at a limited number of key reservoir sites now encumbered or partially developed.

More research is needed in all phases of the environmental impact of the multipurpose reservoir. Since the current impetus is on the recreational, wildlife, and esthetic values of reservoir development and management, a great deal of the available literature is outdated, lacking in scope, and single-purpose oriented. The old concept of water use in terms of withdrawal needs to be replaced with a new concept of 'the duty of water' for all purposes including the appreciation of social values and the national requirements for water of certain characteristics. The duty of water may have no relationship to the volume of water involved, but it has a very specific relationship to the way in which water must be distributed both geographically and in time within the total environment.

For reasons stated previously the scope of this discussion has been limited to what is essentially the 'take-line' of the Bureau of Reclamation reservoir, procedurally, those lands above and below the maximum flowage line needed for permanent structures, public access, and such current and future requirements of fish, wildlife, and recreational uses as may be authorized.

In no sense, however, can the Bureau of Reclamation multipurpose reservoirs be separated from their direct and indirect influence on the environment of the community and the nation that they serve. They have provided the means for making many areas of the western United States suitable for settlement. They have provided a frontier in which people could find opportunity for profitable employment and a feed base for the optimum use of the adjacent rangeland. It is in this sense that the environmental significance of the flood control function lies, for example, not so much in the inviolate storage space at specific elevations in the reservoir pool as in the property damage and loss of lives prevented downstream. It is only in that context that the full environmental impact of the Bureau of Reclamation reservoirs can be assayed.

Ecosystem of the Salton Sea

JUHEE KIM

Department of Microbiology, California State University
Long Beach, California 90840

The Salton Sea is a saline lake in southeastern California. The lake occupies about 930 km², and its elevation is 70.7 meters below mean sea level, the deepest depth being about 12.8 meters. The lake was formed between 1905 and 1907 when a flood cut through irrigation headworks and the flow of the Colorado River entered the Salton sink [*MacDougal,* 1914]. The sea receded by evaporation until 1920 to its elevation of about −76.2 meters, its salinity being slightly higher than that of the ocean. Since then drainage water from irrigation has equaled or exceeded evaporation, and the sea has risen. The changing salinity of the Salton Sea water is presently about 37–38‰, and its *p*H was about 8.1–8.3 during the study period between 1967 and 1970. Although the total salinity of the Salton Sea is similar to that of ocean water, its chemical compositions are significantly different, most conspicuously in the ratio of sulfate to chloride. Sulfate accounts for 9.2% of the anions (equivalent basis) in the ocean and 28.0% of the anions in the Salton Sea [*Pomeroy and Cruse,* 1965]. The Salton Sea water has been saturated with respect to carbonates and calcium sulfate. The chloride content of the Salton Sea is primarily a result of inflow through irrigation canals, leaching of the soils of the surrounding valleys, and diffusion from the bottom, which is composed of salt crust. However, if the level of the Salton Sea falls as expected, the total loss of the water by evaporation would only slightly exceed the total gain of the water; thus the salinity would increase [*Pomeroy and Cruse,* 1965]. The Salton Sea follows the mean atmospheric temperature quite closely, probably owing to its shallow depths, and for a major part of the year the sea is quite well mixed. The region is noted for hot dry summers and warm dry winters, and the temperature of the sea ranges from 9° to 36°C. During the hot summer months the decay of organic matter from the bottom results in an intermittent anoxia [*Carpelan,* 1961*a*].

MICROBIAL LIFE

Although the salinity of the sea is only slightly above that of the oceans, the ionic composition differed from that of marine water because it resulted from evaporation of Colorado River water. The types of microorganisms found in the sea are, however, very similar in nature to marine organisms. The flood that entered the Salton basin in 1907 was practically freshwater, but many of the bacterial species isolated from the sea between 1967 and 1969 are slightly halophilic, like the typical marine bacteria. They grow best in the presence of 2.5–5.0% salt [*Kim and Nakaji,* 1969]. Species of halotolerant bacteria capable of growing in the presence of up to 15% salt were obtained, whereas obligate halophilic bacteria that require and grow in 20–30% salt were not found in our investigations. The majority of the bacteria are Gram-negative motile rods, like many of the marine bacteria. Luminous bacteria, which are known to occur in the marine habitat, are also present in the sea, but there they are free-living rather than symbiotic, pathogenic, or saprophytic. Four species were isolated from the sea and identified as species of the genus *Photobacterium*; but they differed from the known species of the genus [*Nakaji and Kim,* 1968]. One of the interesting characteristics of these bacteria is that two of the four species show a very dim luminescence, unlike the known species of this kind, which luminesce brightly. A bacteriophage active against one of the isolated species of luminous bacteria was also isolated from the sea by an enrichment technique. Sulfate-reducing bacteria are abundant in the black silky-textured sediments that are collected from the shoreline to about 183–274 meters offshore.

Sulfur-oxidizing bacteria, namely, photosynthetic bacteria, are also abundant in the mud samples. These photosynthetic bacteria are also slightly halophilic. The sulfate reducers and sulfur oxidizers must play a key role in the cycle of sulfur and are important in the ecology of the sea, the water of which is saturated with sulfates. Most of the fungi that have been isolated from the sea are typical species of marine yeasts, such as *Rhodotorula, Candida,* and *Sporobolomyces.* The marine yeasts grow at 5°C but not at all or poorly at >30°C, and they carry out oxidative rather than fermentative processes [*Fell and van Uden,* 1963].

PLANT LIFE

The principal plants of the sea, both near the shore and in the open water, consist of the individually floating cells of the phytoplankton. Most of them are microscopic single-celled algae composed of diatoms, green algae, and dinoflagellates but not seaweeds. According to *Carpelan* [1961*b*], who studied phytoplankton and zooplankton in the sea in the mid-1950's, the dinoflagellates (species of *Glendonium* and *Exuviella compressa* were the most prevalent) averaged about 1000 cells per ml during most of the year, and they seemed subject to local blooms. The maximum numbers of diatoms (*Cyclotella* sp. and *Nitzschia longissima* were the most prevalent) appeared in late winter and spring and exceeded 15,000 per ml. The blue green algae, consisting of at least nine species, grew and were restricted to the bottom in shallow quiet areas. Only small numbers of the green alga were present (possibly *Westells botryoides*) during the winter, but they exceeded the number of all other phytoplankton cells during early summer by reaching up to 40,000 colonies (160,000 individual cells occurring in groups of 4) per ml. However, Carpelan stated that because of their small size the mass of the green alga is very small. When both size and numbers are considered, the diatoms and dinoflagellates make up the great bulk of plant material produced in the sea. He also estimated that the productivity at the surface of the Salton Sea would seem to be about 4 times greater than that of fertile coastal seawater. The high plant productivity creates a potential food source for fish, but it also deposits organic matter on the bottom, which could create anoxic conditions in summer.

ANIMAL LIFE

Some of the numerically significant animals in the plankton are rotifers, annelids, barnacles, and copepods [*Carpelan,* 1961*d*]. The worm and the barnacle are not planktonic during their entire life and are most prevalent in spring and fall. The largest numbers of total plankton occur in late summer when large populations of the copepod and rotifer become predominant (1590 per liter in 1955 and 1717 per liter in 1954). In contrast, zooplankton is sparse in the winter with 1-15 per liter, and the food chain in the sea becomes weak [*Carpelan,* 1961*d*]. On the other hand, the Salton Sea provides a difficult environment for the varieties of marine animals because of the extremely wide range of annual temperature, the lack of dissolved oxygen at the bottom in summer, the absence of suitable habitats such as rocks and inundated structures, the lack of visible plants, a heavy algae bloom, a poor food chain, and the changing salinity. Furthermore, the vast amount of inflow through irrigation canals from the surrounding farming areas brings agricultural pesticides and fertilizers into the sea. The inflow was about 1.85 million km^3 in 1963 [*Pomeroy and Cruse,* 1965].

Various invertebrate animals including crab, squid, oyster, shrimp, and clams were introduced into the sea in the 1950's [*Carpelan,* 1961*c*], but there is no evidence that any of these varieties have flourished. According to *Walker et al.* [1961*a*] the introduction of longjaw mudsuckers from San Diego Bay in 1930 was evidently the start of the present population in the sea. In 1961, nine species of fish, most of which were planted early in the 1950's by the California Department of Fish and Game, were evident. Some of them, such as the corbina, the bairdiella, and the sargo, are taken by anglers. The presence of only two food chains [*Walker et al.,* 1961*b*] in the sea presents a weakness in the ecology. The most important chain to the sport fishery is: phytoplankton to zooplankton to detritus to detritus-eating worm (*Neanthes*) to worm-eating fish (bairdiella and sargo) to fish-eating fish (corbina). The level represented by *Neanthes* is a weak link, since they are the only organisms in the sea converting detritus into food for other fish and since they are also killed regularly by anoxia in the deep waters during the summer. Of secondary importance is the food chain: phytoplankton to zooplankton to threadfin shad to corbina. The threadfin shad enters the sea via irrigation laterals, and there has been no sign that this species spawns in the sea [*Walker et al.*, 1961*a*].

ORIGIN OF THE LIFE FORMS FOUND IN THE SEA

Clearly, the fish found in the sea today are some of the species that have adapted to survive, since they were introduced in the 1950's. The desert pupfish, which is considered to be the only native species in the sea, is known to tolerate extreme environmental conditions [*Walker et al.*, 1961*a*]. They are known even to survive and spawn in the isolated pools where the salinity has exceeded 2 times that of ocean water and the temperatures are often >99°F in summer and sink as low as 35°–36°F. There are no large visible plants such as seaweeds in the sea, probably because they have never been introduced. Whether they would survive and propagate if they were introduced should be investigated if the presence of the plants in the sea is desirable. The existence of large numbers of free-living luminous bacteria in the sea is of interest to microbial ecology. They were probably introduced in the early 1950's with many of the fish and other fauna (some fish and fauna were introduced as early as 1929). Such bacteria could also have been introduced by the sea gulls presently living at the sea.

A comparison of two populations of *Neanthes succins*, one found in the Salton Sea (introduced in 1930) and the other from Alamitos Bay, was made to determine the quantitative composition of free amino acids [*Mearns and Reish*, 1969]. Glutamine occurred in significantly higher concentrations in the Alamitos Bay samples, whereas L-alanine appeared in significantly higher concentrations in the Salton Sea specimens. Mearns and Reish stated that the differences observed between these two populations could be the result of genetic changes in the ensuing 37 years of isolation, environmental differences, food differences, or some other factors.

SALTON SEA AS A POLLUTED ENVIRONMENT

Lying in the bottom of the lowest elevation of the Salton sink and having no outlet for outflow, the Salton Sea is bound to receive surface inflow of about 1.85 million km^3 each year, mostly through irrigation canals from the surrounding farming areas. The principal avenues of wastes entering the sea are the New and Alamo rivers, which discharge a total annual volume of approximately 1.23 million km^3 into the south end of the sea [*California State Department of Public Health*, 1958]. The rivers are composed chiefly of irrigation or drainage waters into which the sewage, both treated and untreated, from Mexicali and the communities of Imperial Valley is disposed. The bacteriologic quality of the Salton Sea water, which is determined by coliform counts, is unfit for recreational purposes, especially around the mouths of the rivers and ditches. Despite the high salinity of the water, high densities of coliforms, generally agreeing with coliform distributions investigated by the *California State Department of Public Health* [1958, 1963], were observed during our investigation in 1967–1968. Water samples taken at the mouth of the Alamo River in October 1967 showed a most probable number in excess of 6000 per 100 ml. When the survival of coliform bacteria in the Salton Sea samples was compared with that in the Pacific Ocean samples, the measuring device being the difference in the survival of cells of *Escherichia coli*, the cells died more rapidly in the Pacific Ocean samples than in the Salton Sea samples. Of the Salton Sea samples the survival of the bacteria in the samples collected from the mouth of the Alamo River was better than the survival in the samples collected from the sea itself, probably because the water at the mouth of the river is diluted and contains less salts and more organic matter and nutrients. The area is also noted for a heavy algae bloom, which it had for much of the time during each year of our studies, probably owing largely to the high concentrations of nutrients supplied by the river. Another major pollutant that is washed into the sea and threatens its life consists of the agricultural chemicals from the surrounding farming areas, which cover 1.2 million km^2. The Salton sink is the natural repository of the drainage water and the residual salts. Agriculture is dependent for its survival on the use of the sink for disposal. The Salton Sea is in turn dependent on agriculture for its existence [*Pomeroy and Cruse*, 1965]. Almost all the pesticides and fertilizers washed and drained from the surrounding farming areas enter the sea and have probably been accumulated in the sea. Some of them are, of course, degraded or used by the organisms in the sea. It is frightening to speculate how much of the stable chlorinated hydrocarbons such as DDT could have accumulated in the tissues of the fish living in the sea.

FUTURE OF THE SALTON SEA

According to the calculated projection [*Pomeroy and Cruse*, 1965] the future chlorosities of the Salton Sea may reach the probable critical range for fishery and water contact sports by 1980, an annual inflow of 1.3 million km^3 being assumed. Because of the uncertainty concerning the inflow of the water, which depends on the farming, one cannot be sure of the critical dates. However, the calculated and projected chlorosity indicates that the Salton Sea will have a chlorosity of 22.78 g/1, which is equivalent to a salinity of about 50.00‰, by 1980. It was further projected that by 1990 the total chlorosity would reach about 27.00 g/l, which is equivalent to a salinity of about 59.00‰. The *p*H of the Salton Sea water varies from time to time. It was recorded as 8.3–8.8 in 1955 [*Carpelan*, 1961*a*], 7.6–7.9 in 1964 [*Pomeroy and Cruse*, 1965], and 8.1–8.3 in 1968 (our studies). As the farming is practiced in the surrounding areas, the sea will receive certain amounts of agricultural pesticides and fertilizers each year and add to the already existing chemicals. Wastes originating from the communities and entering the sea should increase as the communities expand. Thus the water quality of the sea will be lowered, and algae bloom will be encouraged, anoxic conditions being created when the algae decay. Close to the sea a strong unpleasant odor, probably stemming from the putrefaction of organic matter, is readily noticeable. A sudden massive die-off of millions of fish occurs every year in the sea. For instance, a solid band of dead 9- to 18-cm gulf croaker was formed along a 13-km stretch of the north shore of the sea during the first week of March 1968. Toxic algae poisoning was blamed as the principal cause of death by officials of the State Department of Fish and Game, but it is also very possible that the pesticides that wash into the sea could cause such a sudden die-off. The Salton Sea, which now attracts >1.5 million visitor days each year [*Pomeroy and Cruse*, 1965] for recreational activities, will not have too bright a future unless some changes are made to control the conditions of the sea.

CONCLUDING REMARKS

Various recommendations have been made by several groups of investigators in an effort to save the dying sea. A group of biologists, headed by *Walker et al.* [1961*b*], made management recommendations on biological grounds concerning only those actions that would directly benefit the fishery. They encouraged: (1) limiting the fish fauna to a few forms so that production of the most desirable species would be highest, (2) planting new fishes only if the present fishery proved inadequate, (3) strengthening the food chain by introducing zooplankters, mysids, and amphipods, (4) securing information on growth and catch of the existing fish and pursuing high rates of fish harvest, and (5) investigating methods to control the salinity of the sea. A cooperative study made by various agencies including the *California State Department of Public Health* [1958] recommended continuous investigation of the bacteriologic quality of the Salton Sea water and indicated the necessity for certain communities to treat their sewage. Their second report [*California State Department of Public Health*, 1963], which was made 4 years later, indicated that though some improvements had been made the sea was still receiving untreated sewage. A group of engineers headed by Pomeroy suggested some constructive plans to control the Salton Sea water in their report [*Pomeroy and Cruse*, 1965] prepared for the California State Water Quality Control Board. Their suggestions were: (1) to control plankton bloom, possibly by removing nutrients by essentially engineering techniques and by harvesting fish at a greatly increased rate, (2) to maintain a stable surface elevation by either importing supplemental water during low periods or exporting water during high periods, and (3) to control salinity by removing water from the sea at a rate that will remove chloride as fast as it flows in, by removing water to a diked-off part of the sea or to an evaporation area adjacent to the sea, and by removing salt by desalinization. They also added that any plan to control the condition of the Salton Sea would be expensive but that the values to be preserved would be well worth it.

Despite all these recommendations and efforts we are not likely to see a single fish living in the sea in the near future if all the agricultural chemicals are allowed to continue to wash in indiscriminately. Also, since the fish population of the warm turbid water is overcrowded, an epidemic disease might endanger the life of the sea. Therefore it is urgent and important to control, in addition to the increasing salinity, the sewage and agricultural chemicals entering the sea if the Salton Sea is to be saved.

Acknowledgment. This investigation was supported by the grant-in-aid from California State University, Long Beach Foundation.

REFERENCES

California State Department of Public Health, Salton Sea bacteriological study (April, 1958), 47 pp., Bur. of Sanit. Eng., Los Angeles, 1958.

California State Department of Public Health, Salton Sea bacteriological study (November-December, 1962 and April-May, 1963), 32 pp., Bur. of Sanit. Eng., Los Angeles, 1963.

Carpelan, L. H., Physical and chemical characteristics, The Ecology of the Salton Sea, California, in Relation to the Sportfishery, *Fish Bull. 113*, pp. 17–32, Calif. Dep. of Fish and Game, Sacramento, 1961*a*.

Carpelan, L. H., Phytoplankton and plant productivity, The Ecology of the Salton Sea, California, in Relation to the Sportfishery, *Fish Bull. 113*, pp. 33–42, Calif. Dep. of Fish and Game, Sacramento, 1961*b*.

Carpelan, L. H., Invertebrate fauna, The Ecology of the Salton Sea, California, in Relation to the Sportfishery, *Fish Bull. 113*, pp. 43–47, Calif. Dep. of Fish and Game, Sacramento, 1961*c*.

Carpelan, L. H., Zooplankton, The Ecology of the Salton Sea, California, in Relation to the Sportfishery, *Fish Bull. 113*, pp. 49–61, Calif. Dep. of Fish and Game, Sacramento, 1961*d*.

Fell, J. W., and N. van Uden, Yeasts in marine environments, in *Symposium on Marine Microbiology*, edited by C. H. Oppenheimer, pp. 329–340, Charles C. Thomas, Springfield, Ill., 1963.

Kim, J., and M. K. Nakaji, Microbial ecology of the Salton Sea (abstract), *Bacteriol. Proc.*, p. 35, 1969.

MacDougal, D. T., The Salton Sea, *Carnegie Inst. Wash. Publ., 193,* 1–182, 1914.

Mearns, A. J., and D. J. Reish, A comparison of the free amino acids in two populations of the polychaetous annelid *Neanthes succinea, Bull. S. Calif. Acad. Sci., 68,* 43–53, 1969.

Nakaji, M. K., and J. Kim, Luminous bacteria from the Salton Sea (abstract), *Bacteriol. Proc.*, p. 33, 1968.

Pomeroy, R. D., and H. Cruse, A reconnaissance study and preliminary report on a water quality control plan for the Salton Sea prepared for the California State Water Quality Control Board, 198 pp., Pomeroy, Johnston, and Baily, Civil and Chem. Eng., Pasadena, Calif., 1965.

Walker, B. W., R. R. Whitney, and G. W. Barlow, The fishes of the Salton Sea, The Ecology of the Salton Sea, California, in Relation to the Sportfishery, *Fish Bull. 113*, pp. 77–91, Calif. Dep. of Fish and Game, Sacramento, 1961*a*.

Walker, B. W., R. R. Whitney, and L. H. Carpelan, General considerations and recommendations, The Ecology of the Salton Sea, California, in Relation to the Sportfishery, *Fish Bull. 113*, pp. 185–192, Calif. Dep. of Fish and Game, Sacramento, 1961*b*.

Aquatic Weeds in Man-Made Lakes

DAVID S. MITCHELL

Department of Botany, Division of Biological Sciences
University of Rhodesia, Salisbury, Southern Rhodesia

Elton [1958] described the events following the disturbance caused to an ecosystem by the invasion of a plant or animal from a foreign but similar environment and discussed the ecology of these phenomena. *Salisbury* [1961] reviewed the aggressive behavior of weeds and alien plants, and *Sculthorpe* [1967] highlighted his discussion of the expanding ranges of hydrophytes in alien situations with descriptions of the spectacular spreads of plants such as *Elodea canadensis, Azolla filiculoides, Eichhornia crassipes,* and *Salvinia auriculata.* Man-made lakes provide an alien environment even for plants indigenous to the area in which they are built and are particularly liable to be colonized by floating aquatic plants, which frequently undergo explosive population growth on the newly available surface of standing water. Especially noteworthy have been the growth of *Salvinia molesta* D. S. Mitchell (*S. auriculata* auct.) [*Mitchell,* 1973] on Lake Kariba, central Africa [*Mitchell,* 1968, 1969, 1970], and that of *Eichhornia crassipes* on Jebel Aulia Dam, north Africa [*Little,* 1966; *Holm et al.*, 1969]; Lake Brokopondo, Surinam [*van Donselaar,* 1968]; Lake Apanas, Nicaragua [*Little,* 1969]; and Lake Rio Lempa, El Salvador [*Little,* 1966]. *Pistia stratiotes* is another floating plant that has occasionally caused minor problems, as it did in Volta Lake [*Ewer,* 1966; *White,* 1969].

Weed growth on man-made lakes has been discussed by *Little* [1966], *White* [1969], *Holm et al.* [1969], *Lagler* [1969], and *Mitchell* [1969, 1970]. The depth of the water and the extent of the fluctuations in lake level are important factors in determining the type of plant infestation that can occur. Emergent plant species, such as *Typha* spp., can only occur in shallow water or damp soils along the shoreline and are unlikely to survive large changes in lake level. Submerged species, such as *Lagarosiphon*, and floating attached species, such as *Nymphaea* and *Eichhornia azura*, cannot usually become established in depths >10 meters and are also adversely affected by large lake level fluctuations. Floating species, such as *Salvinia* and *Eichhornia crassipes*, are independent of depth and substratum requirements as well as largely unaffected by changes in lake level, and these species thus pose the greatest threat. One other life form that is potentially troublesome, usually in conjunction with floating species, consists of those plants that can form floating 'sudd' islands. *Scirpus cubensis, Ludwigia* spp., *Vossia cuspidata,* and *Cyperus papyrus* are examples of species reported to occur on man-made lakes or to be possible threats [*Wild*, 1961; *Boughey*, 1963; *Mitchell*, 1969, 1970; *Lawson*, 1970].

A review of the literature makes it clear that in the tropics the greatest threat is posed by *Salvinia molesta* and *Eichhornia crassipes*. *Salvinia molesta* is a problem in Lake Kariba, Zambia and Southern Rhodesia; India; Australia; Lake Naivasha, Kenya [*Mitchell*, 1970]; Ceylon [*Williams*, 1956; *Dias*, 1967]; the Congo River, Zaire [*Little*, 1965*a*]; and the Chobe River, Botswana [*Mitchell*, 1968]. It has also been reported from other parts of Zambia and Southern Rhodesia as well as from various parts of the Republic of South Africa [*Mitchell*, 1968]. *Eichhornia crassipes* is more widespread and has been reported as being troublesome in the southern United States, Japan, India, Ceylon, Malaysia and other countries of Southeast Asia, the Philippines and other Pacific Islands, Australia and New Zealand, as well as in its native environment of Central and South America [*Little*, 1965*b*; *Sculthorpe*, 1967; *Holm et al.*, 1969; *Mitchell and Thomas*, 1972].

SALVINIA ON LAKE KARIBA

Problems have occurred mainly but not exclusively in man-made water bodies, as is exemplified spectacularly by the growth of the water fern *Salvinia* on Lake Kariba [*Mitchell*, 1960, 1968, 1969, 1970; *Hattingh*, 1961, also unpublished report, 1962; *Lake Kariba Coordinating Committee*, 1961; *Schelpe*, 1961; *Boughey*, 1963]. Lake Kariba is situated in central Africa and was formed as a result of the dam built across the Zambezi River in the Kariba Gorge to provide hydroelectricity. It is approximately 280 km long, covers an area of about 5500 km², and contains 160 km³ of water. When it was built, it was the largest man-made lake in the world, and it still contains the largest volume. *Salvinia* was first reported in May 1959, 6 months after the dam was finally closed and Lake Kariba had started to fill, a process that was not completed until 1963. The plant was first observed in the central area of the lake, where it was noted as a constituent of a mat of floating vegetation 20 ha in extent, together with *Utricularia inflexa* var. *inflexa* and *Pistia stratiotes*. *Salvinia* was already known to be in the Zambezi River system, since it had been reported in 1948 from Katambora, which is 54 km above the Victoria Falls and approximately 160 km above Lake Kariba, but it seems clear that the riverine environment of continuously running water and the action of annual floods prior to the construction of the Kariba Dam were unfavorable for the development of large colonies of the plant. During the formative years of the lake, however, the plant underwent explosive growth and in May 1962 was estimated to cover an area of about 1000 km², 21.5% of the lake surface at that time. Up to this time, there were a number of factors favoring the growth of the plant. First, the change from riverine to lacustrine conditions had resulted in the development of extensive areas of calm still water on which the plant rapidly established large populations. Second, the natal waters of the lake were nutritionally rich, since they must have contained plant nutrients released from newly flooded soils and from drowned decaying plant and animal matter as well as nutrients dissolved from the ashes of vegetation burnt after the bush-clearing program. Third, because of its floating habit the plant was largely unaffected by the periodic rises in lake level. Finally, *Salvinia* was able to take advantage of the shelter and anchorage afforded by the large areas of partially submerged woodland in which, as a consequence, large 'permanent' carpets of weed were formed.

During the middle of 1962 and the first half of 1963 the lake rose to its normal full level, and the total area of the lake occupied by *Salvinia* decreased to about 800 km², approximately 15% of the lake surface. The reason for this decrease was threefold. First, the shape of the lake at full level provided fewer areas sheltered from wind and wave action and a higher proportion of steep shorelines than any previous level. Second, there was a marked decrease in the area of partially submerged woodland. Third, at full level the lake contained several long stretches of water uninterrupted by islands and partially submerged woodland. The wind blowing over these increased fetches caused the more frequent formation of large waves. These destroyed many of the large weed mats, which up to this time had been a conspicuous feature of the open water of the lake, and broke up many of the *Salvinia* carpets that had hitherto found sufficient protection in the partially submerged woodlands.

At the end of 1963 and the beginning of 1964 the lake level rapidly dropped 7.5 meters owing to extensive water spilling through the dam sluice gates. During this period, large quantities of *Salvinia* were stranded on the shoreline, and in March 1964 the weed was estimated to occupy 530 km², just over 10% of the lake surface. However, when the lake returned to its normal level, the quantity of weed increased again. In May 1965 it occupied 650 km² and in June 1967 about 820 km² of the lake surface.

At present the area of lake colonized by *Salvinia* appears to fluctuate between about 600 and 850 km². Three factors are important contributors to these fluctuations: changes in lake level, flash floods in influent rivers, and frequency of storms. The effect of a fall in lake level has already been mentioned. A rise in lake level has the opposite effect, and, as areas of sheltered water become available, they are rapidly occupied by *Salvinia*. Furthermore, *Salvinia* growth is encouraged by nutrients released into waters flooding marginal areas of the lake that have been colonized by vegetation and fertilized by grazing game animals.

Changes in lake level can also modify the effect of river floods. With the exception of two rivers, the Zambezi and the Sanyati, the rivers flowing into Lake Kariba only flow during and after the 4- to 6-month rainy season. They are particularly susceptible to the sudden onset of flash floods, which can have a devastating effect on the *Salvinia* mats growing in their 'estuaries.' The extent of the effect in any one estuary depends on its morphology and depth at that time and thus to some extent on the water level. A fall in level prior to the floods normally has the effect of condensing the mat, so that it is more resistant to being flushed out by the floods, whereas a rise in level often loosens the mat, so that it is more liable to be moved by wind or water currents. When a river comes down in flood, it tends to drive the weed mat before it until the drowned river valley becomes deep enough to contain the floodwaters. These then begin to flow beneath the surface as a density current. The 'plunge point' at which this density current begins is usually marked by the deposition on the surface of large quantities of damaged *Salvinia*, which can form a large impenetrable blockage of dead and decaying plants. Where the mat is particularly unwieldy, the floodwaters can begin to flow under the weed mat before the plunge point is reached, though this occurrence seems unlikely. This general situation is also affected by the quantity of sudd plants growing on the *Salvinia* mat, and on a number of occasions a large floating island of *Salvinia*, which has been knit together by sudd plants in a wide part of the river inlet, has plugged a narrower part lower downstream.

The main factor now limiting the extent of *Salvinia* on Lake Kariba is wave action [*Mitchell*, 1970]. *Salvinia* mats can only form in sheltered areas, and any plants that are blown or swept out into the open lake by river flood action are liable to be destroyed when they are dashed against an exposed shore by the waves. However, during periods of calm weather these individual plants can be moved from one area to another without being damaged. Under these conditions, large numbers of plants can be found on the open lake, though the quantities are very variable. Estimates of numbers have ranged from 200 to >10,000 per km^2 with a mean of 3290 per km^2. Clearly, therefore the frequency of storms on the lake is an important factor affecting the amount of *Salvinia* present at any one time.

OTHER EXPLOSIVE GROWTHS OF AQUATIC WEEDS

Eichhornia crassipes evidently responded in a similar fashion to *Salvinia* to the same factors in Lake Brokopondo, Surinam [*van Donselaar*, 1968], and within 2 years had colonized 53% of the lake, which by that time was about 78,000 ha in extent. *Ceratopteris pteridoides* was also important at this time and covered 21% of the lake surface. Subsequently, chemical control was applied to *Eichhornia*, and as a result the area occupied by this weed was greatly diminished. The amount of *Ceratopteris* has also substantially decreased but for unknown reasons.

Instances of explosive growth of other aquatic plants have also been reported. For example, during the adventive spread of *Elodea canadensis* in Europe last century and that of *Azolla filiculoides* in the same region, there were many reports of waters rapidly becoming filled or covered by these plants [*Sculthorpe*, 1967]. In tropical conditions, reports are more numerous and have already been exemplified in this paper by the spread of *Salvinia* and *Eichhornia crassipes*.

A comparison of these phenomena shows a number of common factors. Probably the most striking of these is the ability of many of the plants to regenerate from relatively small pieces of plant tissue. Also the explosive growth of the population is apparently invariably brought about by vegetative propagation, and sexual reproduction often seems to be relatively less important in the initial spread of the plant. For example, *Salvinia auriculata* in Lake Kariba and India is sexually sterile [*Loyal and Grewal*, 1966; *Mitchell*, 1970], *Elodea canadensis* apparently spread in the absence of male plants [*Sculthorpe*, 1967], and it is unlikely that seed and spore production have been important in the first colonization of a habitat by *Eichhornia crassipes* or *Azolla* [*Sculthorpe*, 1967; *Bock*, 1969; *Mitchell and Thomas*, 1972].

Another characteristic of many of these plants is that growth is manifested mainly as an increment in the photosynthetic area of each plant. This growth continues until all the suitable water surface is occupied. *Salvinia molesta* and *Eichhornia crassipes* both display a morphologic plasticity that accentuates this characteristic. When they are initially colonizing an open water surface, they produce large numbers of small plants in which the leaf area to dry weight ratio is high, whereas in a compact mat the plants are larger with a lower leaf area to dry weight ratio.

The floating habit of these notorious species of aquatic weeds, which has the advantage of making them independent of depth, water level fluctuations, and substrate requirements, has already been mentioned and is clearly important in making a large area available for rapid colonization.

A final common feature of reports of the explosive population growth of aquatic weeds is that much of this growth occurs when the weed is invading an alien environment. The four plants cited above as examples of vegetative spread are also examples of plants that have achieved the most notoriety when they are growing outside their countries of origin. An important aspect of this phenomenon is the ecological effect of the invading species on the original ecosystem. Comparatively little research appears to have been carried out on whether the invading plant replaces other plants and whether the ecosystem is able to compensate for this replacement by slight adjustments or is drastically and perhaps permanently changed. It is reasonable to assume that the environmental resources used by the invader were previously used by other components of the system. The major difficulty is that usually the ecosystem is complex and little understood. However, in Lake Kariba a whole new system was being formed while *Salvinia* was undergoing explosive colonization, and thus *Salvinia* was incorporated as a major component from the start. Nevertheless, as the ecosystem is evolving, it is becoming more complex, and the position of *Salvinia* in it may be affected. In the early stages of this process, *Salvinia* was the only aquatic plant present in any quantity and provided an important habitat for aquatic invertebrates [*Bowmaker*, 1968; *McLachlan*, 1969], though it inhibited the development of bottom fauna beneath weed mats [*McLachlan*, 1969] and prevented the development of colonies of submerged aquatic macrophytes, which may have been a more suitable habitat for invertebrates [*Mitchell*, 1969]. Also it trapped large quantities of nutrients released into the lake during the formative years and prevented these from being lost [*Mitchell*, 1969, 1970].

GROWTH OF SALVINIA SPP. AND EICHHORNIA CRASSIPES IN SOUTH AMERICA

During February and March 1970 I was able to carry out an ecological survey of *Eichhornia crassipes* and *Salvinia* spp. in South America under the auspices of the International Biological Program and the International Hydrological Decade. Both *Salvinia* and *E. crassipes* were observed in a wide variety of habitats during the survey. They were most frequent on small water bodies characterized by calm water, such as ponds, lagoons, and roadside ditches. They were also present in rivers, where they may be purely transitory, and in man-made canals and dams.

In all these water bodies, there is usually a complex aquatic macrophyte flora. Often this is made up of a mosaic of different species of plants. Occasionally, however, a population can be dominated by one species of plant to the extent that it forms an almost pure stand. This situation was most often observed for *Eichhornia crassipes*. Nevertheless both *Salvinia* and *Eichhornia* experience considerable competition from other aquatic plants for various environmental factors. Where observations have been made over a number of years at a particular locality, it appears that a cyclic series of changes can occur. Alternatively and more frequently, the changes are unrelated to one another and probably depend on water levels and the extent of river floods. Large populations of these plants apparently develop only when certain factors are present together in the environment. Good light conditions, temperatures of about 25°C, plant nutrients in the water, and protection from the dispersal effects of winds and water currents are all probably essential [*Mitchell and Thomas*, 1972].

Hydrologic characteristics of the water body are especially important in controlling the sizes of the populations of these plants. The regular occurrence of river floods will reduce the size of the population annually to those plants that can remain attached to marginal vegetation or are in backwaters. Flooding rivers also overflow into floodplains, so that the water level and shape of permanent pools, lagoons, and oxbow lakes are changed rapidly in these areas. Thus mats of aquatic weed vegetation are loosened, so that they are dispersed by winds and sometimes currents. Where such a water body becomes part of the main river system, large quantities of plants can be swept away. Furthermore, when the water level drops again, plants that have been blown against the margins of the enlarged water body are left stranded on the shore, where they usually become dessicated and die. Thus it is clear that control of the hydrologic regime by the construction of dams across the rivers would be likely to eliminate the substantial annual population decreases that now take place. Depending on the nature of the lake that forms behind the dam it is probable that very large populations of these plants could form rapidly, as they did on Lake Brokopondo, Surinam.

The development of large plant populations of *Salvinia* and *E. crassipes* in South America may also be limited by biological aspects of the environment, such as competition from other plant species and the attack of natural enemies of the plants. The second aspect was studied during the survey by my colleague P. A. Thomas [*Mitchell and Thomas*, 1972] and also by *Bennett* [1968]. Their work shows, however, that in their native environment the attack of phytophagous insects does not appear to exercise a marked control on the size of the population of *Salvinia* spp. or *Eichhornia crassipes* except on rare occasions.

The effect of competition between plant species on the development of large populations of individual species is difficult to evaluate both in the native environment of these plants and in the foreign environments that they have invaded because of the limited nature of our present knowledge of these aquatic ecosystems.

METHODS OF HANDLING AQUATIC WEED PROBLEMS

The problems caused by aquatic weeds on man-made lakes do not always demand the application of control measures. The course of action in this respect must depend on the consequences both of the nonapplication of control and of the application of any control method envisaged. Cognizance must also be taken of the main purpose for which the reservoir was constructed, though it has to be borne in mind that man-made lakes can be valuable assets for several different uses. Generally, the expense of control measures should be covered by the economic benefit of a reduced weed problem, though often a strict evaluation on solely economic grounds can be dangerously misleading.

The presence of large populations of aquatic weeds can lead to a number of disadvantages that may necessitate their removal. Large islands of floating vegetation could interfere with the operation of a dam that was constructed for hydroelectricity or water supply. The loss of water by evapotranspiration through plants has been shown to be higher than the loss of water by evaporation from an open water surface [*Penfound and Earle*, 1948; *Little*, 1966, 1967; *Mitchell*, 1970]. River inlets and harbors provide sheltered waters in which large floating populations can develop that will interfere with, and perhaps prevent, the passage of boats. *Little* [1966] has pointed out that plants displace a certain volume of water, and in small reservoirs this displacement can be a disadvantage. Finally, the weed plants can take up nutrients and in other ways hinder the development of more desirable aquatic vegetation. Thus fisheries production from the lake could be adversely affected. The large impenetrable areas of floating weed could also inhibit the mechanical fish-harvesting procedures.

For one or more of these reasons it may be desirable to undertake control measures. There are three main methods: mechanical, chemical, and biological. Ecologically, biological methods are the most desirable, and chemical methods are the most disadvantageous. Nevertheless chemical methods are usually the most effective though often expensive. Much more research is required on the biological control of aquatic weeds, and there is every reason to believe that methods will be found that will be effective at least on plants growing out of their native distribution range. Mechanical methods of control are often expensive, and frequently their applicability can only be evaluated with reference to local conditions. However, these methods usually involve a harvesting process and raise the possibility of using the plant material obtained in this way. *Little* [1968] extensively reviewed various means of making use of aquatic weeds. Unfortunately, many of these depend on the dry matter content and, as this is usually <15% of the fresh weight [*Westlake*, 1966], the methods are seldom economically exploitable.

CONCLUSIONS

Aquatic weed problems can often be serious, and the examples of *Eichhornia* on Lake Brokopondo and *Salvinia* on Lake Kariba should lead those considering the construction of man-made lakes, especially in the tropics, to recognize the possibility of similar events. Consultations between biologists, hydrologists, and engineers in the planning stage and coordinated preimpoundment and postimpoundment surveys and research programs should make it possible to introduce modifications of a proposed scheme that would diminish possible weed problems or make them easier to handle. Preimpoundment surveys of the whole lake catchment for plants that may cause problems are clearly indicated. Accurate surveys of the eventual lake shoreline should make it possible to distinguish those areas where weed populations are likely to develop and persist. Judicious bush clearing in these areas could substantially reduce their effectiveness as 'nurseries' for floating weeds. It may even be possible to plan a lake shoreline with the least possible percent of such areas by designing the dam to impound water to a certain level. The design of the dam wall could incorporate means of handling potential weed problems, for example, by allowing large lake level fluctuations or spilling over an adjustable spillway rather than through sluice gates drawing water from below the surface. In all these matters, however, full recognition must of course be given to other uses of the lake. Thus for fisheries it may be desirable for the lake to have large areas of shallow sheltered water and a stable water level, though these can promote aquatic weed problems. Clearly, consultation and coordination of research effort between all concerned at all stages of development are essential if a man-made lake is to fulfill its full potential for multipurpose use.

REFERENCES

Bennett, F. D., Investigation on insects as controlling agents for *Salvinia auriculata* Aubl. and *Eichhornia crassipes* (Mart.) Solms, two aquatic weeds of neotrophical origin, report, Commonwealth Inst. of Biol. Contr., Curepe, Trinidad, 1968.

Bock, J. H., Productivity of the water hyacinth, *Eichhornia crassipes* (Mart.) Solms, *Ecology, 50*(3), 460–464, 1969.

Boughey, A. S., The explosive development of a floating weed vegetation on Lake Kariba, *Adansonia, 3*(1), 49–61, 1963.

Bowmaker, A. P., Preliminary observations on some aspects of the biology of the Sinamwenda Estuary, Lake Kariba, *Proc. Trans. Rhodesia Sci. Ass., 53*(1), 3–8, 1968.

Dias, G. R. W., Eradication of a water weed in Ceylon, *World Crops, 19,* 64–68, 1967.

Elton, C. S., *The Ecology of Invasions by Animals and Plants,* Methuen, London, 1958.

Ewer, D. W., Biological investigations of the Volta Lake, May 1964 to May 1965, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 21–30, Academic, London, 1966.

Hattingh, E. R., The problem of *Salvinia auriculata* Aubl. and associated aquatic weeds on Kariba Lake, *Weed Res., 1,* 303–306, 1961.

Holm, L. G., L. W. Weldon, and R. D. Blackburn, Aquatic weeds, *Science, 166*(3906), 699–709, 1969.

Lagler, K. F., *Man-Made Lakes Planning and Development,* Food and Agriculture Organization, Rome, 1969.

Lake Kariba Coordinating Committee, The problem of the water weed *Salvinia auriculata* on Kariba Lake, *Pestic. Abstr., 7*(2/3), 73–76, 1961.

Lawson, G. W., Lessons of the Volta, A new man-made lake in tropical Africa, *Biol. Conserv., 2*(2), 90–96, 1970.

Little, E. C. S., Occurrence of *Salvinia auriculata* Aublet on the Congo River, *Nature London, 208*(5015), 1111–1112, 1965*a.*

Little, E. C. S., The world wide distribution of the water hyacinth, *Hyacinth Contr. J., 4,* 1965*b.*

Little, E. C. S., The invasion of man-made lakes by plants, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 75–86, Academic, London, 1966.

Little, E. C. S., Progress report on transpiration of some tropical water weeds, *Pestic. Abstr., 13*(2), 127–132, 1967.

Little, E. C. S., *Handbook of Utilization of Aquatic Plants: A Compilation of the World's Publications,* Food and Agriculture Organization, Rome, 1968.

Loyal, D. S., and R. K. Grewal, Cytological study on sterility in *Salvinia auriculata* Aublet with a bearing on its reproductive mechanism, *Cytologia, 31*(3), 330–338, 1966.

McLachlan, A. J., The effect of aquatic macrophytes on the variety and abundance of benthic fauna in a newly created lake in the tropics (Lake Kariba), *Arch. Hydrobiol., 66*(2), 212–321, 1969.

Mitchell, D. S., Report of incidence of *Salvinia auriculata* on Lake Kariba, *Fed. Sci. Teachers J., 1*(1), 39–46, 1960.

Mitchell, D. S., Ecological studies of *Salvinia auriculata* with particular reference to Lake Kariba (Rhodesia and Zambia) and the Chobe River (Botswana), paper presented at Meeting of Experts on Ecology and Control of Aquatic Vegetation, U. N. Educ., Sci. and Cult. Organ., Paris, Dec. 16–18, 1968.

Mitchell, D. S., The ecology of vascular hydrophytes on Lake Kariba, *Hydrobiologia, 34*(3/4), 448–464, 1969.

Mitchell, D. S., Autoecological studies of *Salvinia auriculata* Aubl., Ph.D. thesis, Univ. of London, London, 1970.

Mitchell, D. S., *Salvinia molesta* sp. nov., *Brit. Fern Gaz., 10,* 251–252, 1973.

Mitchell, D. S., and P. A. Thomas, Ecological survey of the aquatic weeds *Salvinia* spp. and *Eichhornia crassipes* and their natural enemies in the neotropics, *Tech. Pap. Hydrol. 12,* U. N. Educ., Sci. and Cult. Organ., Paris, 1972.

Penfound, W. T., and T. T. Earle, The biology of the water hyacinth, *Ecol. Monogr., 18,* 447–472, 1948.

Salisbury, E. J., *Weeds and Aliens,* Collins, London, 1961.

Schelpe, E. A. C. L. E., The ecology of *Salvinia auriculata* and associated vegetation on Kariba Lake, *J. S. Afr. Bot., 27,* 181–187, 1961.

Sculthorpe, C. D., *The Biology of Aquatic Vascular Plants,* Edward Arnold, London, 1967.

van Donselaar, J., Water and marsh plants in the artificial Brokopondo Lake (Surinam, S. America) during the first three years of its existence, *Acta Bot. Neer., 17*(3), 183–196, 1968.

Westlake, D. F., Some basic data for investigations of the productivity of aquatic macrophytes, in *Primary Productivity in Aquatic Environments, Mem. Ist. Ital. Idrobiol.,* suppl. 18, edited by C. R. Goldman, pp. 229–248, University of California Press, Berkeley, 1966.

White, E., Man-made lakes in tropical Africa and their biological potentialities, *Biol. Conserv., 1*(3), 219–224, 1969.

Wild, H., Harmful aquatic plants in Africa and Madagascar, *Kirkia, 2,* 1–66, 1961.

Williams, R. H., *Salvinia auriculata* Aublet: The chemical eradication of a serious aquatic weed in Ceylon, *Trop. Agr. Trinidad, 33*(2), 145–157, 1956.

Ecological Effects of Evaporation Retardation Monolayers on Reservoirs

BOBBY G. WIXSON

Environmental Research Center, Department of Civil Engineering
University of Missouri, Rolla, Missouri 65401

WILLIAM J. CLARK

Department of Biology, Texas A&M University, College Station, Texas 77840

WILLIAM B. DAVIS

Environmental Engineering, Department of Civil Engineering
Texas A&M University, College Station, Texas 77840

The impoundment of water in man-made lakes may cause beneficial or harmful ecological effects. One of the major environmental problems created by the impoundment of water in reservoirs is increased evaporation losses.

Different methods have been applied to prevent excessive evaporation losses. These included efficient site location, windbreaks, control of plants and seepage, floating covers of reflective materials, and the application of monomolecular films on the surface of the impounded water. The chemical-filming method has been applied widely and still holds promise for use in effective evaporation control. *Parker and Barsom* [1970] have pointed out that naturally occurring surface microlayers are also formed by organic materials in runoff or caused by the introduction of man-made substances or pollutants into aquatic ecosystems. Some of the major problems encountered with using chemical monolayers have been the method of application [*Dressler*, 1964] and the resultant changes in water quality. Reports made on the use of monolayers [*Symons et al.*, 1966] have indicated a need for further study and evaluation of theoretical, laboratory, and field applications of natural or induced monolayers.

This paper describes research that was carried out to evaluate the ecological effects of a continuous antievaporation film of hexadecanol and octadecanol and to solve an applied pollution problem resulting in part from an alcohol monolayer formed from organics discharged in lead-milling and zinc-milling waste waters and causing undesirable ecological changes.

EFFECTS OF CONTINUOUS MONOLAYERS

Many different combinations of evaporation reduction chemicals have been applied to reservoirs and lakes in an attempt to suppress evaporation and conserve stored water. One of the more common chemicals used for forming antievaporation films has been a blend of hexadecanol and octadecanol. These long-chain alcohols form a monomolecular film on the water surface that is self healing at wind speeds of up to 12.9 km/hr and is seemingly capable of reducing water evaporation by 30–50% under ideal conditions [*Gilby and Heymann*, 1948]. An additional benefit in the use of a hexadecanol and octadecanol monolayer has been that it could be biodegraded by the bacteria in the water. On the basis of ease of assimilation these compounds also received clearance from the U.S. Public Health Service [*Ludzack and Ettinger*, 1957].

However, research has indicated that a continuous monolayer can change or indirectly alter some of the ecological characteristics in treated aquatic environments. Initial evaluations of the effects of continuous monolayers were carried out in experimental aquatic ecosystems in laboratories at Texas A&M University with simulated field conditions and adjustable light banks to provide light energy at the water surface. Lights were automatically controlled to give 12-hour photoperiods (8:00 A.M. to 8:00 P.M.), and the air and water temperature of the experimental ecosystem were maintained at a constant 22° ± 2°C. Water and algae from three local ponds were used to inoculate experimental ecosystems during the summer of 1966.

Half of the experimental systems were filmed with a 1:1 mixture of hexadecanol and octadecanol that was maintained as a continuous monolayer for 30-day experimental periods. A film material dose rate of 56.05 $mg/m^2/day$ of treated water surface was used following the recommendations of *Meinke and Waldrip* [1964]. Water quality and biological population measurements were evaluated during each experimental testing period.

A Gilson differential respirometer was used to evaluate the effects of oxygen diffusion through the monolayer. At 20°C the hexadecanol and octadecanol film reduced the oxygen diffusion rate by approximately 10–15%. This test indicated that efficient monolayers can affect the kinetics of reaeration and cause oxygen deficiencies in small reservoirs. Similar adverse effects have been reported by *Amad* [1968].

The data collected for 30-day replicate tests indicated that the number of bacteria increased in aquatic systems treated with the continuous monolayer of alcohol. A lag growth period was observed for about 7 days after which the bacteria in the monolayer-treated systems progressed into a log growth period compared with the plateau or stationary growth period of bacteria in the control systems. A similar bacterial increase due to the biological oxidation of hexadecanol has also been noted by other investigators [*Wixson*, 1970]. A significant bacterial growth was observed in all experimental systems treated with a continuous antievaporation film of hexadecanol and octadecanol.

Phytoplankton population studies indicated that certain algal growths were altered by the application of a continuous monolayer. The green algae *Chlorella* in the monolayer-treated systems was inhibited during the first 15 days but increased during the rest of the time in contrast to the declining algal populations in the controls. The biodegradation of the monolayer by bacteria seemed to add nutrients that could be used effectively by some species of algae for growth.

The increased algal growth in monolayer-treated systems could be beneficial in recreational areas, where increased phytoplankton growth would furnish food for the aquatic biota. However, the same features could be most undesirable in municipal and industrial water, where an uncontrolled prolific algal growth or 'bloom' might cause water quality and filter-clogging problems.

The application of a continuous film decreased water surface tension, which caused some filamentous algae and water plants to sink rather than to float at the water surface. Reduction of the surface tension can present problems by introducing increased amounts of normally floating plants into the hypolimnion. The film can also interfere with aquatic organisms that normally use the water surface during their life cycle.

EXPERIMENTAL CONCLUSIONS

The application of continuous hexadecanol and octadecanol films increased the growth of bacteria and certain algae (Figure 1). The monolayer can also alter the oxygen content and interfere with aquatic biota that are dependent on the water surface tension during some phase of their life cycle. Water quality studies should be conducted to determine whether a reservoir has acceptable bacterial and algal populations combined with good water quality and high dissolved oxygen prior to the application of antievaporation films. The addition of a floating nutrient source at the water-air interface of a reservoir can contribute to the rapid growth of bacteria and algae, which can further alter the lotic ecosystem in man-made reservoirs.

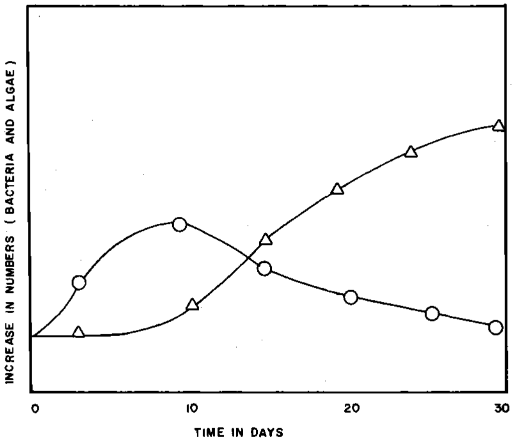


Fig. 1. Schematic comparison of bacterial and algal growth in control (open circles) and monolayer-treated (open triangles) ecosystems.

MINING POLLUTION AND MONOLAYERS

In 1955, improved mineral exploration led to the discovery of new lead deposits in the rolling forests of southeastern Missouri. By 1962 this rich belt of lead-zinc ore was found to extend for approximately 57.9 km almost due south from Viburnum, Missouri. The name given to this discovery was the Viburnum trend or 'New Lead belt.'

Geologically, the lead ore was found to be disseminated throughout the Cambrian Bonneterre formation, and, since it is a good aquifer, most mines constantly employ extensive pumping to prevent flooding. Part of the pumped mine water is used as process water for the milling procedure, chemical reagents being added during the flotation circuit to separate the lead, zinc, and copper minerals from the finely ground rock or gangue. The final discharge of mining and milling waste waters containing decomposed organic milling reagents and suspended rock material has caused undesirable water quality changes.

The pollution problem manifested itself as an unusual bacterial-algal growth that trapped large amounts of dolomite rock flour and coated the stream bottom, the result being the killing off of most of the other biota of the stream.

A research project was carried out to study the cause and effect of the mining pollution and make practical applied recommendations toward solving the existing problems and preventing future stream and reservoir pollution by the lead-zinc industry [*Wixson*, 1970].

EFFECTS OF MINING AND MILLING WASTE WATERS

Fletcher Mine, operated by the St. Joe Minerals Corporation, provided feed rates and samples of the chemical reagents used at their facility for separating and concentrating lead, zinc, and copper by the flotation process. Typical reagents employed were sodium isopropyl xanthate (collector), isopropyl ethyldithiocarbamate (collector), mixed alcohols (6–9 carbons) (frothers), zinc sulfate ($ZnSO_4$) (zinc depressant), sodium cyanide (NaCN) (zinc depressant), copper sulfate ($CuSO_4 \cdot 5H_2O$) (zinc activant), sodium dichromate ($Na_2Cr_2O_7 \cdot 2H_2O$) (lead depressant), sulfur dioxide (SO_2) (lead depressant), and starch (lead depressant). This information assisted in the development of research techniques for detecting specific decomposition products that could cause pollution problems. At the Fletcher Mine, underground water was pumped to the surface at a rate of 1.89×10^4 to 2.65×10^4 l/min. Flotation reagents were added to the part of this water (6.05×10^3 l/min) used for the milling process. The final effluent from the lead, zinc, and copper thickeners was then combined with the rest of the underground water and discharged into three sedimentation lagoons constructed in series. The water from the lagoons passed over a spillway, and the final discharge was approximately 3 times the volume of the receiving stream.

Decomposition products of the reagents used in the flotation process were found to form a surface monomolecular film in the settling lagoons. The film was not detained sufficiently for biological degradation but was drawn rapidly across the lagoon surface owing to the spillway discharge arrangement. Once this organic material reached the quiescent stream sections, it contributed to the prolific growth of bacteria and large bottom-coating mats of the blue green algae *Oscillatoria*. Decomposition products from the sodium isopropyl xanthate (collector) were found to act as nutrients for the accelerated growth of stream bacteria. Assimilation of similar alcohol monolayers by bacteria in water has been reported by other investigators [*Chang et al.*, 1962; *Silvey*, 1960]. Biochemical oxygen demand and chemical oxygen demand determinations were difficult owing to the concentration of organics in the monolayer at the water surface.

A spectrophotometric determination was used to measure the concentration and decomposition rate of sodium isopropyl xanthate. Optical absorbance was measured at 303 nm to evaluate the effects of time and frothing reagents on xanthates (Figure 2). Temperature increases were found to accelerate the decomposition rate of xanthates used in the milling process [*Wixson et al.*, 1969].

No deterioration in stream water quality was found for alkalinity, hardness, *p*H, or dissolved oxygen. However, mine water was found to contain a higher fluoride concentration (1 ppm) than the normal surface stream water (0.15 ppm). The fluoride concentration was one method used to detect mine waste water in the New Lead belt.

The responses of different biotic organisms to changes in their aquatic environments were evaluated by population studies correlated with analytical determinations of heavy metals and organic compounds. Confirmatory photomicrographs were taken for the comparison of

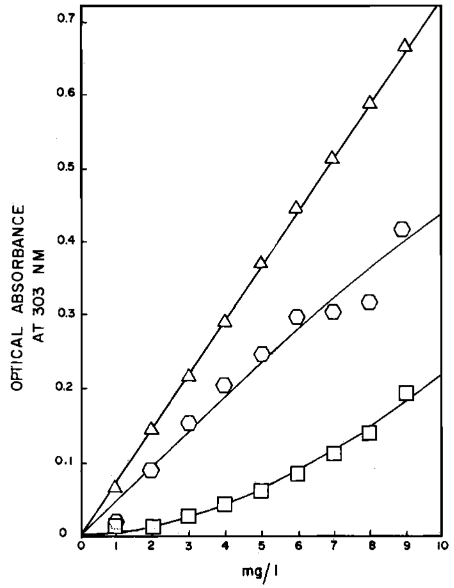


Fig. 2. Spectrophotometric determination for the concentration of sodium isopropyl xanthate. The open triangles represent the standard solution, the open hexagons represent the standard solution treated with frother 71, and the open squares represent the standard solution after 1 week of decomposition.

diatoms and filamentous and nonfilamentous algae in polluted and unpolluted streams.

A biological examination of water samples indicated that the three diatom genera *Synedra, Navicula*, and *Cymbella* could be used as biological indicators of mining pollution in the New Lead belt. A composite evaluation indicated that *Synedra* and *Navicula* were tolerant of mining pollution, *Synedra* becoming the dominant population close to the pollution source. *Cymbella* was normally found in control streams but almost disappeared in polluted streams. Immediately below the point where the mine waste water entered the stream the blue green algae *Oscillatoria* was found to cause pollution problems with large matlike growths that covered the stream bottom and destroyed the other benthic life.

APPLIED RECOMMENDATIONS

On the basis of knowledge gained through this study the following recommendations have been made and applied to assist in stream pollution abatement in the New Lead belt of southeastern Missouri: (1) that mine discharge water be separated from the milling waste water and mill effluent be recycled through the flotation process and (2) that all settling lagoons be modified for the biological treatment of monolayers or other remaining nutrients prior to the discharge of treated water into receiving streams. Streams in the New Lead belt must be protected, since most of them drain into Clearwater Lake in southeastern Missouri.

The determination of which organic or inorganic compounds, individually or mixed, form monolayers that can alter water quality and ecological systems has contributed valuable applied information toward protecting other streams, rivers, and reservoirs from lead-mining and zinc-mining pollution. This knowledge has now been applied to the development of waste treatment methods to control the monolayer problem and prevent future pollution problems.

The practical use of evaporation retardation monolayers on reservoirs has yet to be determined. More efficient antievaporation films may be used effectively on reservoirs if specific water quality and impoundment ecosystems are known. Induced or artificial monolayers that cause pollution problems can also be evaluated by their effects on water quality and aquatic ecosytems. Effective treatment can then be instigated by using all possible analytical methods. All aspects being considered, further applied studies are needed to use the promising aspects of monolayer evaporation control to conserve needed water resources in reservoirs.

Acknowledgments. This study was funded in part by grants from the U.S. Department of the Interior, Office of Water Resources (A-003-TEX and A-021-MO). Special thanks are due the St. Joe Minerals Corporation, the Missouri Lead Operating Company, the Missouri Clean Water Commission, and the Clark National Forest for their assistance.

REFERENCES

Amad, M. T., Predicting dissolved oxygen concentrations in a lake covered with evaporation suppressant, *J. Water Pollut. Contr. Fed.*, *40*, 423, 1968.

Chang, S. L., M. A. McClanahan, and P. W. Kabler, Effect of bacterial decomposition of hexadecanol and octadecanol in monolayer films on the suppression of evaporation loss of water, in *Retardation of Evaporation of Monolayers: Transport Processes*. edited by V. K. LaMer, 119 pp., Academic, New York, 1962.

Dressler, R. G., The suspension process for reservoir evaporation control, *Ind. Chem. Eng.*, *56*, 36, 1964.

Gilby, A. R., and E. Heymann, The rate of evaporation of water through duplex films, *Aust. J. Sci. Res.*, *1*, 197, 1948.

Ludzack, F. J., and M. B. Ettinger, Biological oxidation of hexadecanol under laboratory conditions, *J. Amer. Water Works Ass., 49,* 849, 1957.

Meinke, W. W., and W. J. Waldrip, Research on evaporation retardation in small reservoirs, 1958–63, *Tex. Water Comm. Bull., 6401,* 1964.

Parker, B., and G. Barsom, Biological and chemical significance of surface microlayers in aquatic ecosystems, *BioScience, 20,* 87, 1970.

Silvey, J. K. G., Physical, chemical and biological effects of hexadecanol on Lake Hefner, 1958, *J. Amer. Water Works Ass., 52,* 791, 1960.

Symons, J. M., S. R. Weible, and G. G. Robeck, Influence of impoundments on water quality, U.S. Dep. of Health, Ed., and Welfare, Cincinnati, Ohio, 1966.

Wixson, B. G., Water quality protection in streams in mining districts, in *Developments in Water Quality Research,* edited by H. I. Shuval, pp. 199–209, Ann Arbor–Humphrey Science Publishers, Ann Arbor, Mich., 1970.

Wixson, B. G., E. A. Bolter, N. H. Tibbs, and A. R. Handler, Pollution from mines in the New Lead belt of southeastern Missouri, *Proceedings of the 24th Purdue Industrial Waste Conference,* pp. 632–643, Purdue University, Lafayette, Ind., 1969.

Preliminary Investigation into the Composition and Seasonal Variation of the Plankton in Kainji Lake, Nigeria

H. A. ADENIJI

UNDP/FAO Kainji Lake Research Project, New Bussa, Nigeria

The aim of this study is to investigate the abundance of food for the fishes of Kainji Lake. The quantitative work on the composition and seasonal variation of the plankton in Kainji Lake commenced in March 1970, and this paper reports the results of the first 7 months of study.

Kainji Lake is a man-made lake formed in July 1968 by impounding the River Niger. Information on the general history, character, hydrology, and physical limnology of this lake is available in the papers by *El-Zarka* [this volume] and *Henderson* [this volume].

SAMPLING METHOD

Plankton samples were collected from the lake about every 5 weeks. The phytoplankton samples were obtained at each station from 0.5-meter depth by using a Van Dorn sampler and were immediately fixed with formalin. On arrival at the laboratory, 100 ml of each sample was poured into a measuring cylinder, and 1.0 ml of Lugol's solution was added. The treated sample was then allowed to stand for at least 24 hours. Then the top 91 ml was carefully decanted, and 0.2 ml of the remaining 10 ml was transferred into a counting chamber. All the algae present in this subsample were counted.

Zooplankton samples were collected at each station by taking vertical hauls from 5 meters to the surface with plankton nets. Four plankton nets hung on a single frame were used for collection. These were arranged in two pairs about 1 meter apart, the two nets of each pair being about 20 cm apart. Each net was made of no. 10 bolting silk, which has 4.3 meshes/mm with apertures of 0.158 mm; the opening of each net was 20 cm in diameter. After the vertical haul, each net was carefully washed into a glass container, and the zooplankton was immediately fixed with formalin. At the laboratory, each of the original net samples was diluted to 100 ml except for those in which the concentration was high, those being diluted to 300 ml.

The full set of four zooplankton samples per station with two 5-ml aliquots from each sample was counted for the September cruise. The results were analyzed for each zooplankton group by using a hierarchical or nested analysis of variance design to test variability in subsampling, between adjacent nets, between pairs 1 meter apart, and among the sampling stations. From these analyses it was concluded that most of the variability was associated with differences between adjacent nets and among stations. Subsequently, to reduce the labor of counting, the samples from one pair of adjacent nets from each station were counted by using a single 10-ml aliquot for each sample. The two estimates for each station were then averaged.

RESULTS

At the end of 1970, only four main groups of plankton algae had been recognized in the lake: blue green (Myxophyceae), green (Chlorophyceae), diatoms (Bacillariophyceae), and dinoflagellates (Dinophyceae).

The total number of phytoplankters started to rise just before the beginning of the rainy season (Figure 1) and reached a peak in July. In September, there was a drop in the total number of algae, possibly owing to the considerable turbidity of the lake water caused by the high inflow of white flood water into the lake at that time, and the average Secchi disk reading for the lake dropped to 18 cm. In October, while the white flood water was dropping and the lake was clearing, phytoplankton numbers started to increase. This increase was sufficient to create typical and evident bloom conditions.

The true zooplankton in this lake consisted of three main groups: Cladocera, Copepoda, and Rotifera. The zooplankton number was low just

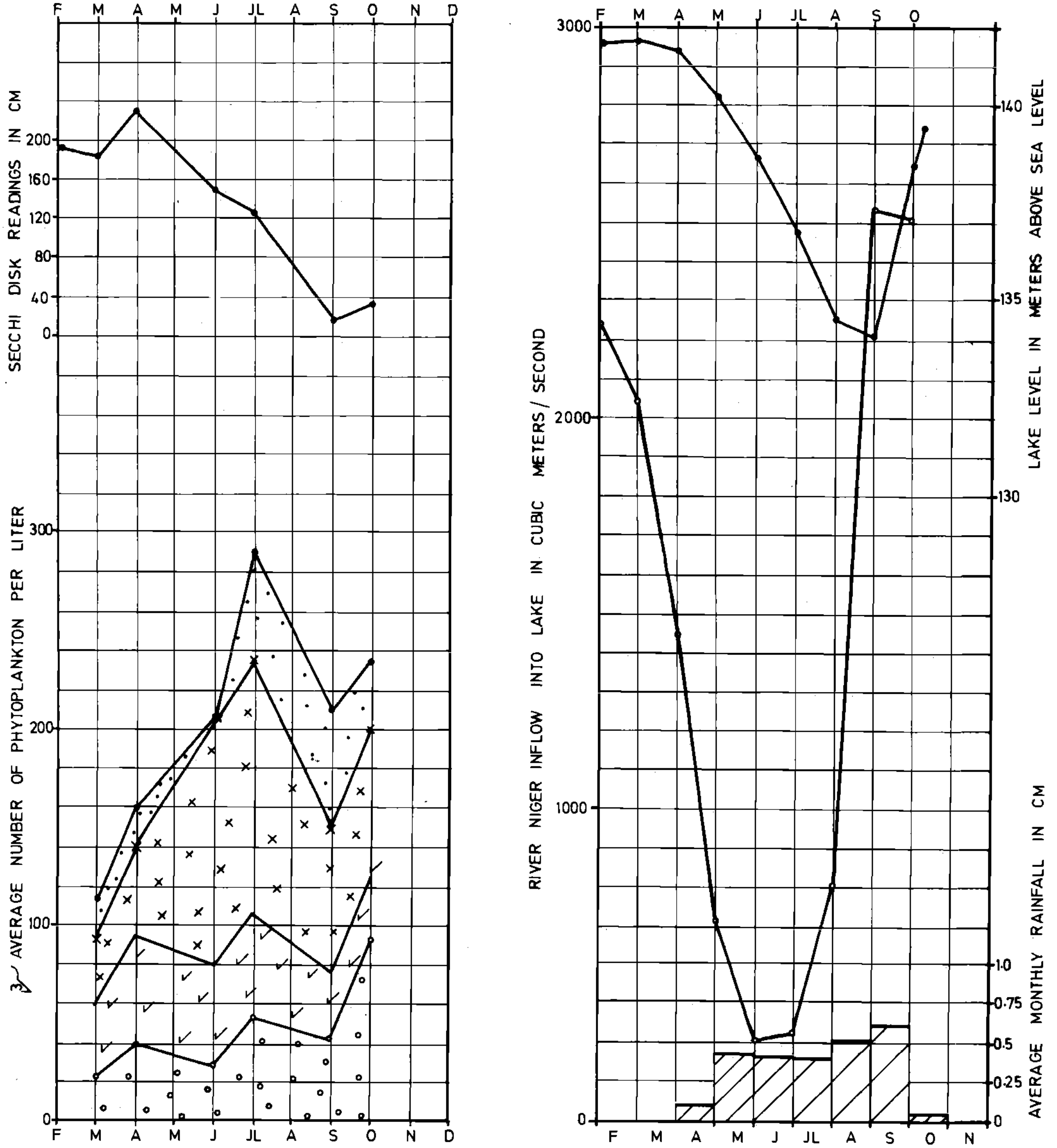


Fig. 1. Average number of phytoplankton and Secchi disk transparency (left) and lake levels, inflow, and rainfall (right) for the study period. The blue green algae are represented by open circles, the green algae are represented by checks, the diatoms are represented by crosses, and the dinoflagellates are represented by dots.

before the rainy season, but it rose steeply during the first month of rain to reach a peak of >4000 organisms per net haul or 13.3 organisms per liter (Figure 2). The zooplankton number then started to drop from May until July as the lake level fell. When the lake level started to rise in August, the zooplankton population began to increase. During the peak of the white flood from July to September, adventitious zooplankton was present and included fish larvae, ostracods, conchostracans, chaoborid larvae and pupae, *Hydra* sp., and medusoids.

Seasonal differences were discernible in the composition of the phytoplankton and zooplank-

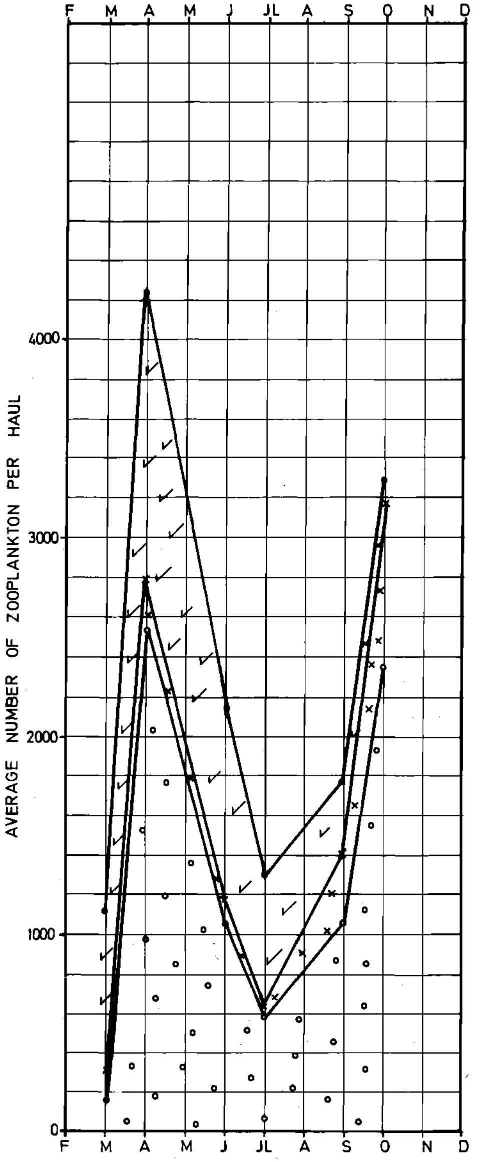


Fig. 2. Average number of zooplankton per net haul for the study period. Cladocera are represented by open circles, Copepoda are represented by crosses, and Rotifera are represented by checks.

ton communities. Green algae, mostly *Volvox* sp., dominated the phytoplankton community just before the rainy season and continued to be dominant until May, when the rains were in full swing and the diatoms, mostly *Melosira* sp., became dominant. The diatoms continued this dominance until October, toward the end of the rainy season, when the blue greens, mostly *Microcystis* sp. and *Anabaena* sp., became dominant. In October the increase in the number of the blue greens produced a layer of bloom on the lake surface.

Within the zooplankton the dominant group before the rainy season set in was the Rotifera, but as soon as the rains started in April the Cladocera became dominant. This cladoceran domination consisted mostly of *Moina* sp. and *Bosminopsis* sp. and continued until the end of the rainy season except for a brief rotiferan surge of dominance in July.

CONCLUSION

A substantial standing crop of plankton is maintained in Kainji Lake, bloom conditions developing among the blue green algae along with the rise of the white flood. The average number of phytoplankters for the 7-month study period was about 1203 per milliliter and the average number of zooplankters was 7.38 per liter or 2319 per vertical haul of the plankton net.

REFERENCES

El-Zarka, S. E.-D., Kainji Lake, Nigeria, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Henderson, F., Stratification and circulation in Kainji Lake, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Zambia's Kafue Hydroelectric Scheme and Its Biological Problems

E. WHITE

Department of Zoology, University of Liverpool, Liverpool, England

The Republic of Zambia is one of the most highly industrialized countries in Africa, copper being at the center of her industrial strength and wealth. This industry has an enormous demand for electrical power, which has stimulated the rapid development of her hydroelectric resources.

While Zambia was still Northern Rhodesia, a component part of the ill-fated Federation of Rhodesia and Nyasaland, Lake Kariba was created in the Zambezi Valley, and, up to the present time, most of Zambia's electricity has come from the power station situated on the Rhodesian side of Kariba Dam. However, Zambia is fortunate in having two alternative sites that could be developed to produce hydroelectricity. Lake Kariba itself has the capacity to service a second power station at the north bank at Kariba, and the Kafue River can be harnessed as it plunges through its gorge from the Kafue flats to the Zambezi River. The Kafue Gorge was originally considered along with Kariba as the site for the first hydroelectric development within the federation. The Kafue River carries much less water than the Zambezi River at Kariba does, but it has a potential head of water of 594 meters (1950 feet) as it descends through its gorge.

The Kafue Gorge was selected for development in preference to the north bank at Kariba. The initial phase involved a small dam at the head of the gorge and tunnels to carry the water through a head of 396 meters (1300 feet) to a 500-Mw power plant situated underground. To make full use of this power station, storage in addition to that at the Kafue Gorge Dam would be required, and a second dam would have to be built upstream. The nearest possible site was at the western end of the Kafue flats at Meshi Teshi (also referred to as Itezhitezhi), 193 km (120 miles) from the original dam. The regulated flow for that dam would be 184 m^3/sec (6500 ft^3/sec).

A third phase of development, which would need no extra water, could be achieved by using the remaining head of water in the gorge to supply another 375-Mw power plant.

The Kafue River drains the central part of Zambia into the Zambezi River (a detailed account of the ecology of the setting is given by *Lagler et al.* [1971]). It rises from the watershed between the Zambezi and the Congo river basins in the north, flows southward through the copper belt of Zambia, and skirts the western edge of the Lukanga Swamps before turning west and then south toward Meshi Teshi. Its major tributary is the Lunga River, which drains the Solwezi area and joins the Kafue River near Lubungu.

At Meshi Teshi the Kafue River breaks through a range of low hills and turns eastward across the Kafue flats (Figure 1). Here it meanders for a distance of 402 km (250 miles) at an average gradient of only 2.7 cm/km (0.145 ft/mi). At the eastern end of the flats, another range of hills is penetrated, and the gradient increases as the river plunges through the Kafue Gorge to the Zambezi River plain.

The catchment of the Kafue basin is about 155,400 km^2 (60,000 mi^2), and the tributaries that drain directly to the Kafue flats have a catchment of 42,700 km^2 (16,500 mi^2). The Kafue flats themselves have an area of 5400 km^2 (2100 mi^2) and slope gently from west to east with a loss of only 6 meters (20 feet) in elevation over 193 km (120 miles).

In general, the soils consist of heavy impervious clays, which support a rather uniform coarse grass cover. Into this plateau the river has cut a channel that meanders over the flats and divides occasionally into two or more branches. Along the river channel, there are many depressions and traces of old river channels, which form ponds when they are flooded. Little water is released from these ponds except by evaporation; some are perennial. The main river

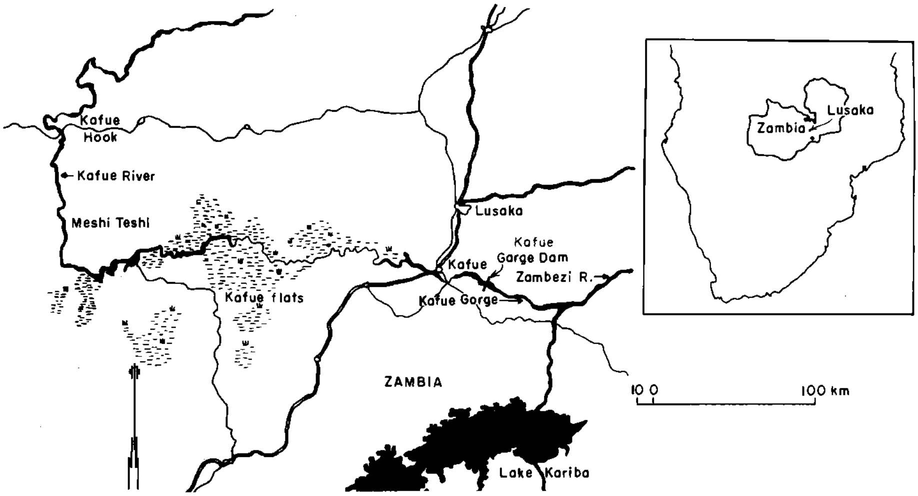


Fig. 1. The Kafue River and its flats.

is bordered over much of its length by natural levees, so that, when the river is running full, it may be a meter higher than the surrounding land. These levees effectively delay the mixing of the floodwaters of the main river and those of the Kafue flats subcatchment until the floods are quite high. The levees also restrict drainage of the flats as the floodwaters recede.

Currently, the Kafue flats support a number of economic interests. The perennial ponds and the river carry large populations of fish, which breed and feed extensively on the floodplains during inundation [*Carey et al.*, 1968; *Lagler et al.*, 1971]. They are readily harvested as the floods recede and when the river is low. The annual yield is quite variable, but it averaged 5079.2 metric tons (5600 short tons) fresh weight between 1954 and 1964.

Some 200,000–250,000 cattle eat the vegetation on the flats. In general, they are moved from the surrounding land to the flats in July and August after the floods recede to take advantage of terrestrial plant growth in the damp soils. Although the cattle remain on the flats until the rains start in October, November, or December, there is little food for them there in the latter months of the year.

Two substantial reserves provide sanctuary for the remnants of the enormous herds of game that existed 30 years ago. The antelope known as lechwe now numbers <25,000. Indiscriminate hunting and poaching have reduced the population from about 250,000. Several other species of large herbivores, such as the kudo, roan, sable, wildebeest, zebra, and eland, inhabited the flats in large herds, but these can be numbered only in hundreds now. The herds could recover if they were given adequate protection and if competition from cattle could be reduced. Government plans to build a hotel in the area to provide an overnight stopping place along the tourist routes to Livingstone could make the development of the game reserves an attractive proposition.

The management of the water for hydroelectric purposes will inevitably affect the flood regime of the Kafue flats, which in turn will influence the suitability of the area for cattle, game, and fish. As early as 1967, concern was felt in those government departments that were overseeing the interests likely to be affected, but communication problems among disciplines as various as engineering, hydrology, agriculture, and game and fishery management prevented effective discussion of the problems and requirements of all the parties, and no integrated management plan could be devised.

For this reason an attempt was made to construct a simple mathematical model that would describe the natural flood patterns for those years in which satisfactory hydrologic data had been collected (the hydrologic data used were taken from a compilation by *Juszkiewiez* [1966]). A second model using the same hydrologic information as a base but with management at the Kafue Gorge Dam superimposed was constructed to examine the effect on the flood regime of the flats. A third model added the management of a reservoir at Meshi Teshi as a further complicating factor. Variables were introduced into this model to see to what extent the requirements of game, fish, and cattle could be accommodated without jeopardizing power production.

Great accuracy could not be claimed for these models, but it was hoped that the interesting features that emerged would be used as foci for argument and discussion among the diverse disciplines concerned.

The consulting engineers, Sweco, kindly explained details of their dam proposals and consequent reservoir statistics, the timing of the several stages of development, the power plant and its water consumption, and Zambia's projected power requirements from the Kafue scheme.

The following timetable describing the implementation and operation of the Kafue hydroelectric scheme was set up for the models. Analysis would be started in October 1969 (month 1) before the Kafue Gorge Dam closed. Natural conditions were assumed to exist at that time. The Kafue Gorge Dam would be closed on January 1, 1970 (month 4). The Meshi Teshi Dam would be closed on January 1, 1974 (month 52). From then on (months 52–219) the scheme would operate for 14 years with only the first power station in operation. (The construction of a second power station lower in the Kafue Gorge would not increase water consumption.)

Model 1 estimated on a monthly basis the volume of water and areas of inundation that occurred naturally between October 1950 and September 1964. Model 2 predicted the hydrologic regime prevailing from the completion of the Kafue Gorge Dam to the closure of the Meshi Teshi Dam. Model 3 predicted the hydrologic regimes of both the Meshi Teshi Reservoir and the Kafue flats during the first 14 years of operation after the completion of the Meshi Teshi Dam.

For models 2 and 3 the hydrologic data collected between October 1950 and September 1964 were taken as being representative of conditions that are likely to occur in the future. All three models are basically of the same form; only those factors that are associated with the regulation of the hydrologic system for power production separate models 2 and 3 from the model of the natural flood regime.

In the absence of more accurate information a number of assumptions had to be made about natural conditions, civil engineering works, and methods of water management. The most important of these are mentioned below in the specific descriptions of the working of the models.

The areas of the Kafue flats that were inundated naturally were calculated from water level data and contoured maps. For the eastern part of the flats, adequately contoured maps were available (1 : 20,000 maps contoured at 0.3-meter (1-foot) intervals and drawn by Collings and Partners of Johannesburg and Lusaka between 1952 and 1956). For the western part of the flats, only 1 : 50,000 maps were available. These maps were contoured at only 15.2-meter (50-foot) intervals but also showed the level of maximum flood. To estimate the relationship between the volume of water and the area inundated, the western part of the flats was assumed to have the same sort of cross section as the eastern part. The basis of this assumption was that the flats were formed as a salt lake and the forces determining the shape of the lake basin were likely to be similar over the whole area of the lake.

The input of water to the flats at Meshi Teshi and the output of water at Kasaka between October 1952 and September 1964, as detailed by *Juszkiewiez* [1966], have been used in the calculations.

Runoff from the land adjacent to the Kafue flats is difficult to estimate with any accuracy, but, as water from this source is of great importance to cattle, game, and fishery interests in the area, it could not be ignored. A value for each month of each year was computed as follows.

1. The average monthly rainfall for the Kafue flats subcatchment was calculated for October 1950 to September 1964 by using a maximum of 13 sampling stations.
2. The area of the flats inundated in each month was estimated from water levels and map contours. These areas were used to estimate water losses by evaporation by using the method described later.
3. The annual runoff from the Kafue subcatchment equals the annual runoff at Kasaka minus the annual runoff at Meshi Teshi plus the annual evaporation loss from inundated areas.
4. The estimate of the annual runoff from the Kafue subcatchment was plotted against the annual rainfall in the subcatchment. This plot resulted in the poor relationship that is shown in Figure 2.

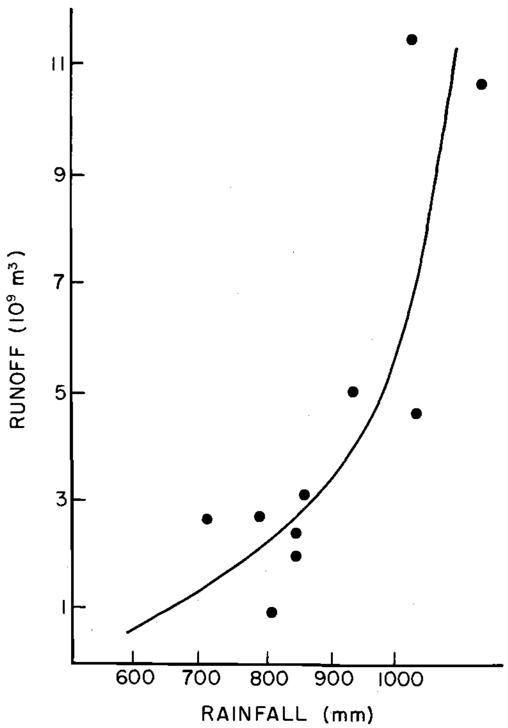


Fig. 2. Relationship between annual runoff and rainfall for the Kafue flats, Zambia.

5. Estimates of the annual runoff from the subcatchment were obtained for all years by reading the appropriate value associated with specific estimates of annual rainfall.

6. The relationship of monthly runoff–monthly rainfall in the Kafue subcatchment was established by combining all data for 1952–1964. Data from all rainfall stations were used, whereas runoff data were obtained from stations KW1, KW5, and KW6, listed in *Juszkiewiez* [1966]. Average monthly runoff-rainfall factors for the 12-year period rainfall were as follows:

January	0.79	July	1.00
February	1.49	August	1.00
March	1.51	September	1.00
April	1.04	October	1.00
May	1.68	November	0.49
June	1.00	December	0.79

7. The monthly runoff from the Kafue flats subcatchment between October 1950 and September 1964 was calculated as follows. The runoff in each month was equal to the proportion of annual rainfall occurring in that month times the appropriate runoff-rainfall factor times the estimated annual runoff from the subcatchment.

Serious overestimation or underestimation of the annual runoff is likely to occur. Limiting factors were built into each of the models to prevent the carrying over of excessive errors from one year to the next.

Hydrologists of the Department of Water Affairs, Zambia, consider that the average annual water loss from an open water surface on the flats is about 1.8 meters (6 feet). This figure has been taken as the basis for estimating evaporation losses in the models.

It has also been assumed that the monthly variation in the evaporation rate will follow the same general pattern shown by evaporimeter records in the subcatchment area. The monthly evaporation rates have been further elaborated by plotting rainfall against evaporation for each month from 1954 to 1964. From October to May a convincing inverse relationship existed between rainfall and evaporation.

On the advice of the consulting engineers the carrying capacity of the Kafue River on the flats has been taken as 170 m^3/sec (6000 ft^3/sec), which is equivalent to 444 × 10^6 m^3 (0.360 million ac ft) per month. Evaporation while the river is confined between its banks is regarded as negligible.

In model 2 the assumption was made that between the closing of the Kafue Gorge Dam and the flood season following the closure of the Meshi Teshi Dam the water level in the Kafue Gorge Reservoir would be maintained at an altitude of 979 meters (3212 feet) above national datum for as long as possible. Thus the maximum holding capacity for the reservoir would be about 5670 × 10^6 m^3 (4.600 million ac ft).

In model 3 the dead storage of the Meshi Teshi Reservoir is expected to be 740 × 10^6 m^3 (0.600 million ac ft), and the full storage capacity has been assumed to be 4810 × 10^6 m^3 (3.900 million ac ft).

There seems to be general agreement among the cattle, game, and fishery interests that, initially at any rate, as much as possible of the natural flood pattern should be retained as long as the water needed for power production is guaranteed. Model 3 includes a number of procedures directed at satisfying these needs.

1. From January to April inclusive a controlled release of 740 × 10^6 m^3 (0.600 million ac ft) per month is made at Meshi Teshi. This guarantees some flooding, even in dry years. In

most years this release will be lost in the natural overflow of the Meshi Teshi Reservoir.

2. During May and June the flow from Meshi Teshi is reduced to a compensation flow of only 15 × 10^6 m^3 (0.012 million ac ft) per month to promote drainage of the flats into the river. During March and April the Meshi Teshi Reservoir is not permitted to reach maximum capacity, and, if it is necessary, water is spilled to prevent the total volume becoming >4190 × 10^6 m^3 (3.400 million ac ft). This provision is included to prevent spillage in May and June when the flats are draining.

3. The Kafue Gorge Reservoir is drained annually during September. The reservoir is drained to combat weed growth that might otherwise choke the reservoir. Drainage being effected during September, the reservoir will remain low until natural flooding starts with the onset of the rains. The reservoir could be lowered to an altitude of about 974 meters (3194 feet) above national datum without prejudicing power production provided the river carries at least 444 × 10^6 m^3 (0.360 million ac ft) from Meshi Teshi per month from July to December.

RESULTS

Model 1. Figure 3 shows the estimated areas inundated from 1950 to 1964 under the natural flood regime. The conspicuous alternation of wet and dry regimes is obvious. The areas involved were always >121,410 ha (300,000 acres) and were usually >323,760 ha (800,000 acres).

Model 2. Model 2 was run by using different starting dates. Figure 4 shows four examples of the areas of the flats inundated under conditions of this kind. If the Kafue Gorge Reservoir is given a storage capacity of 5670 × 10^6 m^3 (4.600 million ac ft), no power failures will occur during this phase of development unless the water available becomes less than that available at any time from 1950 to 1964.

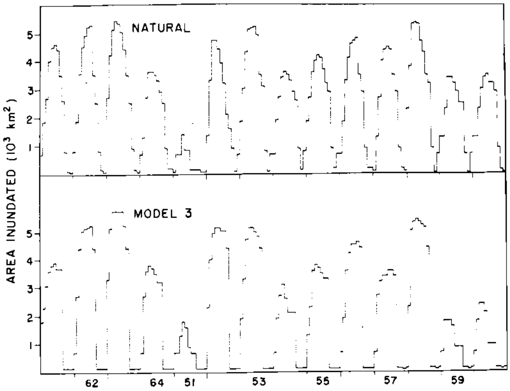


Fig. 3. Estimated areas of the Kafue flats that were inundated under natural conditions and under predicted conditions (model 3).

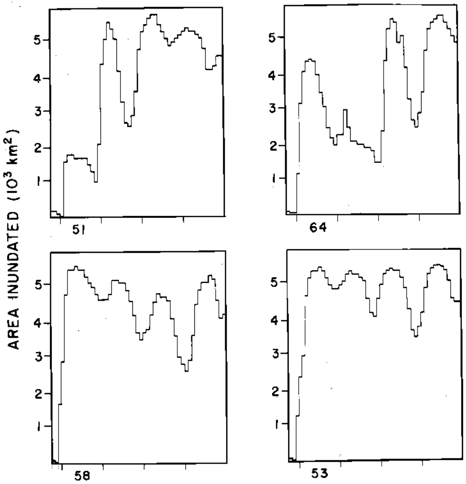


Fig. 4. Predicted areas of inundation of the Kafue flats (model 2).

Dry years, such as 1951, or a succession of dry years, such as 1958, 1959, and early 1960, have a conspicuous effect on the area of the reservoir. It is only necessary to attempt to maintain the reservoir level at 979 meters (3212 feet) to safeguard against the occurrence of several dry years in succession, and therefore the reservoir level could be lowered as the completion date of the Meshi Teshi Dam gets nearer.

It is not possible to predict with any certainty the biological consequences of inundating a large part of the flats for the 4 years between the commissioning of the first and second dams. The possibilities for catastrophe are legion. The major physical consequence of continuous inundation will be that the alternate wet and dry regimes will be lost over a very large area, at least 202,000 ha (500,000 acres), and will be replaced by continuously wet conditions. The associated chemical, microbiological, and vegetational changes will be considerable.

Very few meaningful chemical analyses exist for the water of the Kafue flats, but some data are available for October 1965 to September 1966 [*Sweco,* 1967]. It is of interest that water samples collected at Iolanda (below the flats) contained significant quantities of dissolved sulfate (20–70 ppm) from September to February but that sulfate was absent from the water from March to August. One explanation might be an intense demand for sulfate by the vegetation on the flats. Under natural conditions, burning and grazing during the dry season will dispose of much of this sulfate. Under continuously wet conditions it will be returned to the water by decomposition, and under certain circumstances it might be converted to hydrogen sulfide. *Carey et al.* [1968] suggested that the deoxygenation of water on the flats might act as a signal to fish to return to the river at the end of the flood. If deoxygenation should become serious during continuous inundation, the formation of hydrogen sulfide will be promoted, a major contribution being made toward the upset of the whole environmental regime.

Very large expanses of vegetation consisting largely of wild rice (*Oryza barthii*) grow in the area that will be continuously inundated. The normal pattern of growth for this plant is for new vegetation to keep pace with the rising flood, the tips of the leaves and the flower heads being maintained above water level. As the flood recedes, the plant dies back, dries up, and is usually burned. Under continuously wet conditions it will probably die back at the end of the natural flood season but will decompose in the reservoir. The speed of decomposition cannot be judged, but certainly a new microbiological regime will have to be established to deal with this new environment. Persistent dead vegetation in the water could be a serious menace choking the reservoir.

Perhaps more significantly the *Echinochloa* spp. and *Vossia cuspidata* that now line the riverbanks might be able to colonize large areas of the flooded flats. A prime requisite for the existence of these plants seems to be their ability to maintain their roots in wet conditions. On steep riverbanks they can survive the dry season up to 3 meters (10 feet) above water level, and during the flood they will grow actively; they will still be rooted, even though they will float in 3–5 meters (10–15 feet) of water. Even though the volume of water in the Kafue Gorge Reservoir can vary from 1230 × 10^6 to 5670 × 10^6 m^3 (1.000–4.600 million ac ft) during continuous inundation, this variation will involve changes of only a few meters in water level. A broad band of vegetation composed of *Echinochloa* and *Vossia* could develop at a considerable distance from the shore of the reservoir. If sudd-forming plants of this type become established over large areas, the proper functioning of the reservoir could be jeopardized.

In the upper parts of the Kafue Gorge, *Cyperus, Typha,* and *Phragmites* occur. These are well-known sudd-forming species, and with the formation of the reservoir they seem well placed to join *Echinochloa* and *Vossia* on the flats.

Eichhornia crassipes deserves special mention. This plant is known to have been in the upper part of the gorge since 1966 [*Bell-Cross,* 1968], and it is now well established both as a floating and as a terrestrial plant. When the Kafue Gorge Dam is closed, this plant will spread rapidly on the surface of the reservoir. The active growing season will correspond with the first few months of the life of the reservoir. It is imperative that this plant be attacked with herbicides as the reservoir fills. Every attempt should be made to prevent its establishment in the shallow water, and at all costs it must not be allowed to set seed there. It is unlikely that the eradication of *Eichhornia* can be effected unless it can be achieved in these early months.

Models 2 and 3 take no account of possible increased water loss by evapotranspiration if large areas of the reservoir become covered by vegetation. Some biologists estimate that water losses can increase 4 times over natural evaporation when weed cover is present [*Penfound and Earle,* 1948]. The hydroelectric scheme could be jeopardized under these circumstances.

It has been supposed that a general burst of biological productivity, like that at Lake Kariba, will accompany the filling of the reservoir. This is not necessarily true for the land to be inundated is flooded and drained annually. No new and vast source of nutrient materials is available as it was at Lake Kariba. No increase in productivity will occur until the end of the natural flood season, for the changes in hydrologic regime will first be effective at that time.

Model 2 shows that considerable fluctuations in the area of inundation are likely to occur within the 4-year period, even though attempts will be made to hold the reservoir at a capacity of 5670 × 10^6 m^3 (4.600 million ac ft). Where flooding and draining occur alternately, the environment may not change significantly. To this extent it is possible that grazing for game and cattle may continue to be available in quantity.

On the other hand, fish catches will drop, for the fishermen will be unable to make large catches while the fish are dispersed in the reservoir. At the present time, much of the fish crop is caught when the river is confined within its banks. At least 202,000 ha (500,000 acres) will be inundated more or less continuously. The environment in this area will certainly be modified extensively, and the fish populations are likely to be adversely affected.

From the biological point of view this period of continuous inundation is fraught with hazard. The environment may be so changed that the prospects of a return to a floodplain regime after 1974 may be negligible.

Model 3. Figure 5 shows the flow of water from Meshi Teshi under natural conditions and under those predicted by model 3. Clearly, the hydrologic regimes have several important differences, the most important of which is the monthly release of 444 × 10^6 m^3 (0.360 million ac ft) from July to December to guarantee water for power production. This is much more water than ever flows past Meshi Teshi under natural conditions at this time of year. The practical operation of the reservoir system will provide experience that will allow a closer return to natural conditions. It should be possible to relate the flow from Meshi Teshi directly to the availability of water in the Kafue Gorge Reservoir. July could probably be added to May and June as a third month of very low flow from Meshi Teshi. Thus the size of the flood on the flats would also be increased for the Meshi Teshi Reservoir would have to be maintained at a lower capacity in March and April to prevent spilling during May–July. Model 3 prevented spilling in only 7 of the 14 years of operation during May and June. A lower maximum capacity in March would help improve the draining.

Another important feature of Figure 5 is that it shows that model 3 provides a small flood in years when the Meshi Teshi Reservoir would not ordinarily overflow. Water release in excess of 444 × 10^6 m^3 (0.360 million ac ft) per month is required if any flooding is to occur. Model 3 provides for a release of 740 × 10^6 m^3 (0.600 million ac ft) per month from January to April. More extensive flooding might be achieved by varying the release in each of the 4 months, but differences in the areas flooded are unlikely to be

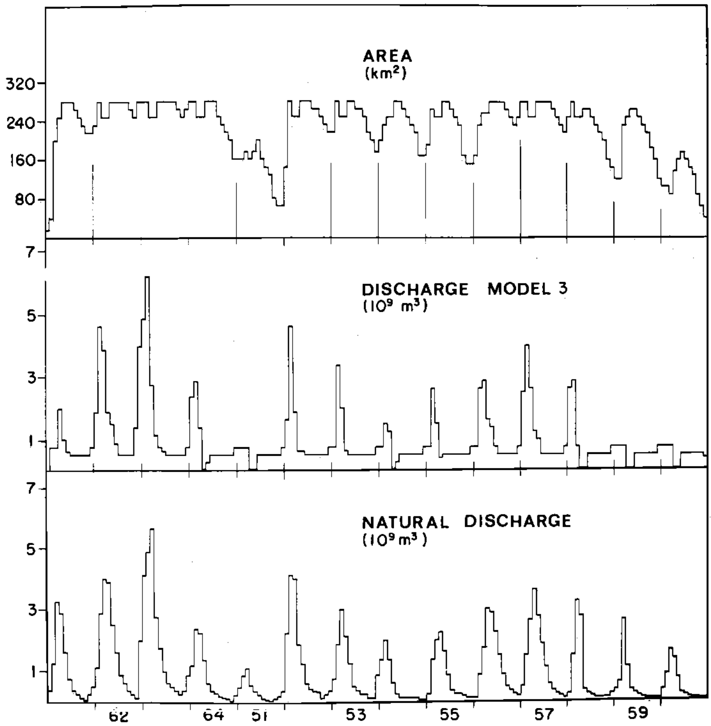


Fig. 5. Likely variation in the area of the Meshi Teshi Reservoir (model 3) together with estimates of both regulated and natural discharge at Meshi Teshi.

very significant. Figure 3 compares the flooding under natural conditions with that under the management conditions of model 3. In dry years, such as 1959 and 1960, the natural flood was considerably more extensive than that in model 3. However, in the single, very dry year of 1951 the flood produced by model 3 was better than the natural flood. Without the release of 740 × 10^6 m^3 (0.600 million ac ft) per month from January to April, there would be negligible flooding of the flats, which would be catastrophic to cattle, game, and fishery interests as they exist at present.

In other than dry years the presence of a dam at Meshi Teshi has a negligible effect on the flooding of the flats.

In the present state of knowledge the most useful and easily available measure of the flood for cattle, game, and fishery interests is obtained by considering both the area of the flood and the time that it lasts. Table 1 compares the floods under natural conditions with those under the conditions of model 3 by using the area inundated in each month. In the dry years of 1958 and 1959 the flood was halved, whereas, in the very dry year of 1951, some improvement over natural conditions was achieved. In the wet years, there was little difference between managed and natural conditions.

Visual scanning of Figure 3 shows that the distribution of the flood with time varies between natural and managed conditions. The discrepancies are not great, and, as the variation in timing under natural conditions is considerable, it is unlikely to be detrimental to the cattle, game, and fisheries. Under managed conditions, some control of the time of flooding is possible.

Model 3 provides for draining the Kafue Gorge Reservoir in September of each year. In years of considerable flooding it is unlikely that drainage could be effected in 1 month. To this extent the flooding is likely to persist longer than is indicated in Figure 3, and the end of each flood season will more nearly resemble that of natural conditions.

TABLE 1. Effective Size of the Flood under Natural and Managed Conditions

October to September	Natural Conditions, Area x Months	Model 3, Area x Months	Managed-Natural Ratio
1961 to 1962	8211	8,199	1.00
1962 to 1963	9786	10,208	1.04
1963 to 1964	6272	6,217	0.99
1950 to 1951	1469	2,207	1.50
1951 to 1952	7413	9,022	1.22
1952 to 1953	9428	8,656	0.92
1953 to 1954	6506	4,408	0.68
1954 to 1955	7985	6,275	0.79
1955 to 1956	8070	7,174	0.89
1956 to 1957	7208	7,633	1.06
1957 to 1958	9665	9,582	0.99
1958 to 1959	6126	2,709	0.44
1959 to 1960	6458	3,063	0.47

In model 3 the Meshi Teshi Reservoir was below maximum capacity at the end of June in 6 of 14 years. This situation is undesirable, but it could be ameliorated in most years. In every year, water was spilled from the Kafue Gorge Reservoir in September. In most years when Meshi Teshi was less than full at the end of June the water level in the Kafue Gorge Reservoir could be maintained at a higher level than that in model 3, and the flow from Meshi Teshi could be reduced below 444 × 10^6 m^3 (0.360 million ac ft) per month.

The Meshi Teshi Reservoir is more typical in form than the Kafue Gorge Reservoir, for it has a much greater capacity relative to its area. Water level fluctuations will be considerable, a feature that will detract from tourist attraction to the area. Minimal annual changes in water level will amount to about 1.5 meters (5 feet) and will result in the reservoir contracting about 3240 ha, (8000 acres). Under dry conditions, which may occur about twice in 14 years, the reservoir will be drawn down to close to its dead storage capacity. Under these circumstances the water level will be about 26 meters (85 feet) below maximum, and the reservoir will contract to about 4100 ha (10,000 acres).

Most of the time the Meshi Teshi Reservoir will extend for 25,000–30,000 ha (60,000–70,000 acres). Because of the frequent change of water within the reservoir the productivity should be quite high, and an appreciable fishery could be developed if the bush were cleared from the reservoir basin.

It is difficult to predict the vegetational changes associated with the formation of this reservoir. Annual fluctuations in the level and form of the basin should prevent serious invasion of the reservoir by rooted vegetation.

CONCLUSIONS AND RECOMMENDATIONS

The potential exists to operate the Kafue hydroelectric scheme as a multipurpose project serving the needs of cattle, game, and fishery interests as well as power production. If the reservoir at Meshi Teshi has a capacity of at least 4810

$\times$ 10^6 m^3 (3.900 million ac ft), careful management should make multipurpose use possible. The feasibility may be questioned by the consulting engineers, but it is hoped that differences of opinion center about the fact that runoff from the Kafue subcatchment does not enter into the engineers' computations.

For biological reasons the decision to maintain the Kafue Gorge Reservoir at a high level is potentially dangerous. The cattle, game, and fishery interests will certainly suffer, and the proper functioning of the reservoir may be jeopardized. The possibility of purchasing power from alternative sources during the dry season months of this 4-year period should be reconsidered.

The danger lies in continuous flooding rather than in the extent of flooding. Annual draining of the Kafue Gorge Reservoir is believed to be of the utmost importance if the reservoir is to function properly. Except in dry years, power from alternative sources will not be required. On the basis of runoff at Kasaka between 1950 and 1964 the average shortfall in water available for power production would be 247 $\times$ 10^6 m^3 (0.200 million ac ft) per annum. In years when the Kafue Gorge Reservoir could be held at 740 $\times$ 10^6 m^3 (0.600 million ac ft) in September, there would be no shortage. The year 1959 presents the worst prospect for the 14-year period. In this year a shortfall in natural flow over requirements would be 790 $\times$ 10^6 m^3 (0.640 million ac ft). The Kafue Gorge Reservoir storage would be unable to accommodate this amount, and some power would have to be purchased.

ADDENDUM

The information given up to this point was presented to the interested parties in mid-1968. Since that time, major changes have been made in the timetable for implementation of the scheme.

The Kafue Gorge Reservoir gates should have been closed in November 1970, and it was expected that the reservoir would be full by February 1971. The first unit (125 Mw) of the power station was to be operating by June 1971, and the next three units were to follow at intervals of 2 months so that the first stage would be completed by early 1972.

The construction of the dam at Meshi Teshi has been postponed, perhaps until 1980, and the installation of a power station at the north bank at Kariba has been brought forward to second priority.

From 1972 to 1976 the natural flood regime on the flats will be maintained, and the maximum reservoir level will not exceed that of large natural floods.

This change of plan is very satisfactory from the point of view of the biological interests. With the cooperation of the engineers it should be possible for the interested parties to formulate an integrated plan that would allow the experimental examination of the effects of persistent flooding and related problems before the Meshi Teshi Reservoir comes into operation.

Acknowledgments. I would like to record my appreciation for the welcome and cooperation that I received from the directors and staffs of the many departments that I visited during my stay in Zambia. Those that particularly spring to mind are the Department of Game, Fisheries, and Parks, the Department of Water Affairs, the Department of Agriculture, the Natural Resources Board, the University of Zambia, the Kafue Basin Multipurpose Project, the Central Fisheries Research Institute, and Sweco and their associates in Zambia. Many individuals too numerous to mention helped to make my stay both useful and enjoyable. In addition the assistance and advice that I received during a visit to Sweco in Sweden was much appreciated.

REFERENCES

Bell-Cross, B., The distribution of water hyacinth (*Eichhornia crassipes*) in the Kafue Gorge, *Fish. Res. Bull. Ndola, 4,* 103–104, 1968.

Carey, T. G., B. Bell-Cross, and C. C. Tait, Kafue River and flood-plain research, *Fish. Res. Bull. Lusaka, 3,* 9–32, 1968.

Juszkiewiez, Z. (Ed.), *Kafue Basin Multipurpose Survey,* vol. 4, *Hydrological Data Book,* Food and Agriculture Organization, Lusaka, Zambia, 1966.

Lagler, K. F., J. M. Kapetsky, and D. J. Stewart, The fisheries of the Kafue River flats, Zambia, in relation to the Kafue Gorge Dam, *Tech. Rep. 1 (FI:SF/ZAM11),* 161 pp., Cent. Fish. Res. Inst., Chilanga, Zambia, 1971.

Penfound, W. T., and T. T. Earle, The biology of the water hyacinth, *Ecol. Monogr., 18,* 447–472, 1948.

Sweco, The Kafue Gorge hydroelectric power project, project report, 101 pp., Stockholm, 1967.

A Kinetic Model of Phytoplankton Growth and Its Use in Algal Control by Reservoir Mixing[1]

GIJSBERT OSKAM

Biesbosch Water Supply Company, Werkendam, The Netherlands

Accelerated eutrophication (nutrient enrichment) caused by human activities has become a common feature of many natural and man-made lakes. The accompanying side effects, mostly due to increased primary production, are highly undesirable. Although reduction of the nutrient load (especially phosphorus) is generally considered most effective in opposing eutrophication, it will not always be an economic or practical solution.

Nutrient reduction is not feasible if most of the nutrient burden comes from diffuse sources (soil leaching) or if the reservoir has a very irregular flow regime, a condition that develops for lowland water supply reservoirs with pumped storage, such as those under construction in different European countries. A reliable in-reservoir method of algal control is of primary importance, since many of these reservoirs will draw on nutrient-rich river water.

It is thought that under certain circumstances turbulent mixing in a layer of sufficient depth might provide such a method of control. Although the relationship between natural turbulent mixing and algal growth is not very prominent in limnological studies, it is long since known in oceanography, the quantitative formulation being in Sverdrup's 'critical depth' theory. The effect of mixing on phytoplankton populations was confirmed in many destratification experiments in freshwater impoundments, most of which resulted in a decrease of the standing crop.

The object of this paper is to explain this effect by relating the algal growth rate to the mixing depth and the optical characteristics of the water.

MATHEMATICAL TREATMENT

Throughout this treatment the basic assumptions are that the algal distribution stays homogeneous, even while the growth rate is increasing, and that the nutrients are not acting as limiting factors. The generally used equation for gross photosynthesis per unit of time beneath a unit of surface is modified by introducing a self-shading factor $n\epsilon_p$:

$$P_{\text{gross}} = n \cdot \frac{p_{\max}}{n\epsilon_p + \epsilon_w} \cdot F(i) \qquad (1)$$

in grams of carbon per square meter per hour, where

n, number of algal cells per cubic meter;
$p_{\max}$, maximum photosynthesis per cell per hour, grams of carbon;
ϵ_p, specific extinction coefficient of one algal cell per cubic meter;
$n\epsilon_p$, total extinction per meter caused by photosynthesizing algae, which is the self-shading factor;
ϵ_w, average extinction coefficient per meter of water including turbidity and color;
$F(i)$, dimensionless function of the light intensity

If one assumes that respiration per cell is independent of depth, the total respiration R per unit of time in a water column of unit surface can be calculated and can be expressed as a fraction of $p_{\max}$:

$$R = n \cdot rp_{\max} \cdot z_m \qquad (2)$$

in grams of carbon per square meter per hour, where r is the respiration coefficient and z_m is the depth of the water column in meters.

The net rate of photosynthesis in a water column with a depth z_m is then given by:

$$P_{\text{net}} = P_{\text{gross}} - R$$

$$= np_{\max}\left(\frac{F(i)}{n\epsilon_p + \epsilon_w} - rz_m\right) \qquad (3)$$

If production is considered on a 24-hour basis, P_{gross} must be corrected for the 'photosynthetic day-length,' and the respiration coefficient can be adapted accordingly.

---

[1] This paper is presented in abstracted form.

From the boundary condition $P_{\text{net}} = 0, n = A$, and

$$z_m = F(i)/(A\epsilon_p + \epsilon_w)r \tag{4}$$

i.e., a maximum algal concentration exists for every given mixing depth, other factors being constant.

If the optimal generation time T ($=m/p_{\max}$, m being the carbon content of the algal cell) is introduced and both sides are divided by z_m, (3) can be rearranged to an equation of growth:

$$dn/dt = kn(A - n)/(B + n) \tag{5}$$

in which

$$k = r/T = rp_{\max}/m$$

$$A = [F(i)/z_m r\epsilon_p] - B$$

$$B = \epsilon_w/\epsilon_p$$

The solution of this equation is

$$B \ln \frac{n_t}{n_0} - (A + B) \ln \frac{A - n_t}{A - n_0} = Akt \tag{6}$$

A small computer program has been written to calculate growth curves with the mixing depth z_m and the extinction coefficient ϵ_w as parameters. The other factors were assumed to be constant. The values chosen were $k = 0.1$/day, $r = 0.1$, $T = 1$ day, $F(i) = 2.75$, and $\epsilon_p = 2 \times 10^{-11}$ m^2. Figures 1 and 2 show some of the results for $\epsilon_w = 0.2$/m and $\epsilon_w = 0.4$/m (log 10 base), respectively.

DISCUSSION

A number of factors that play a role in algal production (e.g., grazing by zooplankton, adaptation to low light intensities, nutrient limitations, and the temperature dependency of photosynthesis and respiration) are neglected or are assumed to be constant, whereas they are not (light intensity $F(i)$, optimal generation time T, and specific algal extinction ϵ_p). The resulting smooth curves resemble very much the experimental growth curves found in algal cultures under standardized conditions. It must be understood that prediction or description of a natural planktonic cycle is not the intention of the model in its present form. Still some useful conclusions that are confirmed by practical observations can be drawn.

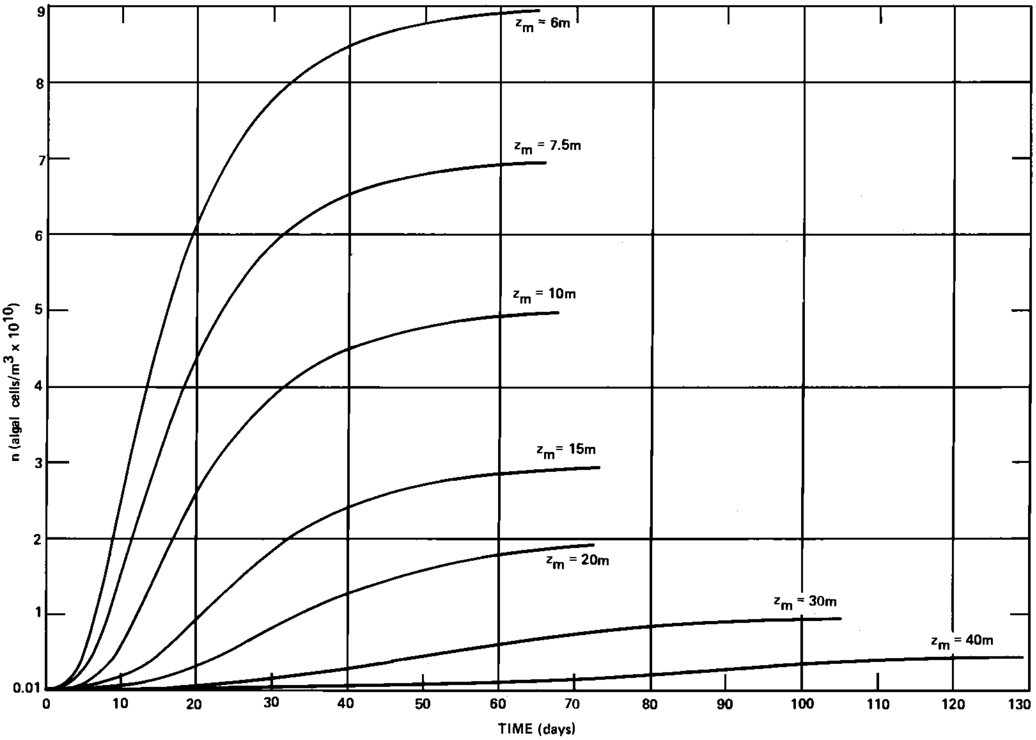


Fig. 1. Effect of mixing depth on growth for $\epsilon_w = 0.2$/m, $n_0 = 10^8$/m^3, $k = 0.1$/day, $F(i) = 2.75$, and $\epsilon_p = 2 \times 10^{-11}$ m^2.

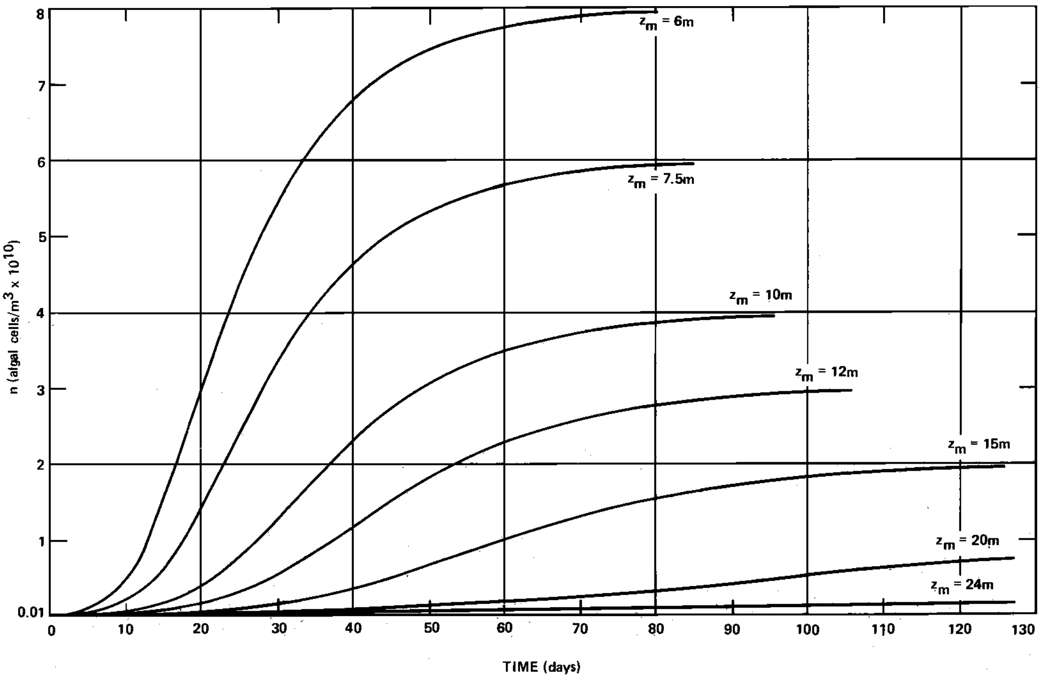


Fig. 2. Effect of mixing depth on growth for $\epsilon_w = 0.4/\mathrm{m}$, $n_0 = 10^8/\mathrm{m}^3$, $k = 0.1/\mathrm{day}$, $F(i) = 2.75$, and $\epsilon_p = 2 \times 10^{-11}\ \mathrm{m}^2$.

The model predicts that relative productivity decreases as standing crop increases, a fact borne out in many studies of primary productivity. The highest assimilation rates per unit of biomass are often found in clear nutrient-poor oligotrophic lakes.

Water with a high natural turbidity and color will be less productive. Both the saturation level and the growth rate are lower than they are in clear water under comparable conditions.

The decrease in standing crop in many destratification experiments can be ascribed to a deepening of the mixed layer. Upward transport of an otherwise limiting nutrient from nutrient-rich lower layers can explain the increase recorded in some cases.

The conclusion that mixing depth can play a decisive role in algal production in cases in which only light is limiting seems justified. Whether this principle has a practical application for reservoir management will depend on the optical characteristics of the water itself. As an example the lowland reservoirs of the Biesbosch Water Supply Company, filled with water from the Rhine or Meuse, will serve.

At storage this water has an extinction coefficient ϵ_w (log 10 base) $>0.4/\mathrm{m}$, which means that the photic zone will have a depth of <5 meters.

From present knowledge (Figure 2) the conclusion that a depth of 20–25 meters of mixed water would restrict algal growth to an acceptable level seems attractive. Maintaining a homogeneous distribution of algae over such a depth requires a continuous level of turbulence, which must be introduced artificially.

CONCLUSION

Many reservoirs subject to accelerated eutrophication will develop blooms of algae with associated undesirable side effects. Certain conditions being fulfilled, an increase in mixing depth might have a favorable influence on algal development. The use of reservoir mixing as a possible method of algal control merits attention.

Acknowledgments. The notion of applying artificial turbulence as an algal control measure in reservoir management originates from the Biology Section of the Metropolitan Water Board, London. I am greatly indebted to Drs. J. E. Ridley and J. A. P. Steel, who not only communicated this idea to me but also gave me introductory information on the basic concepts of photosynthesis and respiration.

Evaluation of the Effect of Impoundment on Water Quality in Cheney Reservoir

J. C. WARD AND S. KARAKI

Department of Civil Engineering, Sanitary Engineering Program
Colorado State University, Fort Collins, Colorado 80521

A study was conducted to determine the effect of impoundment on water quality in Cheney Reservoir, approximately 40 km west of Wichita, Kansas. Physical, chemical, and biological data were collected outside the framework of this study. This study concerned only the analysis of the data and the conclusions drawn from the analysis.

Table 1 is the water budget for the 2-year study period. After completion of construction the reservoir outlet gates were closed on November 8, 1964, and water was pumped from the reservoir for the first time on May 25, 1965.

Table 2 is the heat balance for the 1966 calendar year. The evaporation heat loss in Table 2 was used to calculate the quantity of water evaporated, which is given in Table 3, which compares evaporation quantities determined by three different methods. The percent figure for the evaporation pan (75.9%) was determined by interpolation. Therefore the annual evaporation pan evaporation is 112/0.759 (147) cm. All evaporation pan data were adjusted by a factor of 0.7.

On an annual basis the quantities of evaporation calculated are within ±12% of each other. However, if one uses the evaporation figures from the volume balance for July 1965 through June 1967, the average annual evaporation is 146 cm/yr, which is within ±2.3% of the figure calculated from the heat balance and ±1.2% of the observed evaporation pan data.

WATER TEMPERATURE IN THE ABSENCE OF EVAPORATION

As will be shown later, the excess of evaporation over precipitation is the most important single quantity that affects water quality in impoundments. For this reason and because of the desire to conserve water, various methods of evaporation reduction have been attempted in the past. Attempting to calculate the resulting water temperature either in the absence of evaporation or for a partial reduction in evaporation is believed to be worthwhile.

In the event of evaporation reduction or elimination, water temperature T will be increased. This increase will in turn increase the quantities of heat lost by convection, radiation, and conduction. Because the value of q depends on the rate of change of temperature, it would probably not be affected significantly even with a very slight increase in effective depth D. Of course, q_s would be exactly the same.

As is observable in Table 4, water temperatures would be increased from 7° to 11°C (the average being 8°C) if evaporation were completely eliminated. During some parts of the year the increased water temperatures would not matter much. However, a predicted July temperature of 36°C would be intolerable. Therefore water temperature is a limiting factor when evaporation reduction is considered. Water temperatures would be excessive at the same time that evaporation reduction would be most effective. In addition, increased water temperatures would mean reduced dissolved oxygen (DO) concentrations.

Cheney Reservoir did not stratify during the period of data collection. This fact is substantiated by the lack of vertical gradients of temperature, turbidity, and conductivity. There is a longitudinal gradient, but it is a natural result of the differences in concentration between the water in the North Fork of the Ninnescah River and the water in the reservoir. As a consequence of the vertical homogeneity of this relatively shallow reservoir the multiple-level outlet was not particularly useful during the study period.

TABLE 1. Water Budget: Monthly Totals in Centimeters Based on Average Surface Area during the Month

Date	Change in Reservoir Storage	River Inflow	Local Rainfall	Outflow Reservoir	Outflow Pumped	Evaporation and Seepage	Wichita, Kansas, Precipitation
July 1965	11.0	21.6	13.9	0.1	6.8	17.7	9.2
Aug. 1965	-7.5	7.5	19.8	0.1	6.3	28.5	12.5
Sept. 1965	51.7	49.3	32.5	0.1	5.2	24.8	21.4
Oct. 1965	13.0	22.4	1.2	0.1	5.4	5.1	0.8
Nov. 1965	5.4	17.1	0.4	0.1	4.5	7.6	0.3
Dec. 1965	26.8	28.4	7.7	0.1	5.1	4.2	5.7
Jan. 1966	14.0	21.2	0.8	0.1	4.4	3.6	0.6
Feb. 1966	27.4	30.7	4.6	0.1	3.5	4.3	3.7
March 1966	11.5	21.4	0.8	0.1	1.0	9.7	0.7
April 1966	5.3	15.2	7.1	0.1	3.5	13.4	5.6
May 1966	-10.0	9.4	2.4	1.4	4.6	15.7	1.9
June 1966	-17.7	4.1	8.5	0.0	6.5	24.0	6.8
July 1966	-11.5	9.0	6.0	0.0	7.2	19.3	4.5
Aug. 1966	-17.2	8.1	3.7	0.1	6.1	23.1	2.8
Sept. 1966	-14.2	4.1	2.5	0.1	2.9	16.3	1.8
Oct. 1966	-12.2	5.0	1.7	0.1	3.5	15.3	1.2
Nov. 1966	-0.5	9.8	0.3	0.1	0.7	9.8	0.2
Dec. 1966	1.0	11.1	1.5	0.1	4.2	7.3	1.1
Jan. 1967	10.7	20.2	1.0	0.1	4.1	6.4	0.7
Feb. 1967	2.8	13.9	0.3	0.1	2.6	8.7	0.2
March 1967	3.1	12.6	2.0	0.1	4.0	7.5	1.4
April 1967	10.0	19.8	4.3	0.6	3.8	9.9	3.3
May 1967	-10.6	9.1	5.0	5.4	4.2	15.1	3.6
June 1967	57.7	30.5	18.8	5.5	4.0	-6.0	14.3
Total	149.8	401.4	146.6	13.9	105.8	291.1	104.3

INCREASE IN DISSOLVED SOLIDS CONCENTRATION DUE TO EVAPORATION

The best way to demonstrate that the increase in dissolved solids concentration is due to evaporation is by means of a salt balance, but a salt balance for Cheney Reservoir was impossible because of inadequate and inaccurate data. However, this relationship can still be demonstrated by using the data presented in Table 1. For the 2-year period beginning July 1, 1965, and ending June 30, 1967, the total evaporation was 291 cm. During this same period the precipitation was 104 cm, so that the net evaporation was 187 cm. The stream inflow was 401 cm, and the runoff from the drainage area around the reservoir was 42 cm, so that the total inflow was 444 cm. Minus the net evaporation the difference (inflow) was 257 cm. In other words, 42% of the total inflow evaporated. Clearly, this would cause a substantial increase in dissolved solids concentration.

TABLE 2. Heat Balance: Heat Outflow Equals Heat Inflow

Month in 1966	Heat Outflow, cal/cm² day: Convection q_c	Radiation q_r	Evaporation q_e	Heat Inflow, cal/cm² day: Solar Radiation q_s	Heat Storage Change q	Heat Imbalance Δq
Jan.	119	206	142	239	16	212
Feb.	29	139	71	301	-33	-29
March	-74	114	149	398	-74	-135
April	38	161	235	497	-95	31
May	-35	116	233	519	-90	-115
June	-45	133	338	606	-61	-119
July	-56	123	307	599	-16	-209
Aug.	17	191	360	537	32	0
Sept.	26	167	258	454	59	-62
Oct.	21	163	312	350	89	57
Nov.	21	157	178	258	85	13
Dec.	96	175	151	213	59	150
Total	157	1845	2734	4971	-29	-206

The total annual net heat outflow and the total annual net heat inflow were both 4736 cal/cm² day. The value of the solar constant is 2880 cal/cm² day ± 2%.

TABLE 3. Evaporation

Month in 1966	Calculated from Heat Balance	Calculated from Volume Balance	Evaporation Pan (Observed)
Jan.	7.4	3.6	
Feb.	3.3	4.3	
March	7.8	9.7	
April	12.0	13.4	12.4
May	12.3	15.7	16.6
June	17.3	23.9	19.9
July	16.3	19.3	21.1
Aug.	19.1	23.1	16.4
Sept.	13.2	16.3	13.1
Oct.	16.4	15.3	12.1
Nov.	9.0	9.8	
Dec.	7.8	7.3	
Total	142.2	161.7	147.3
April to Oct.	106.7	126.9	111.7

All evaporation values are given in centimeters per month except the total values, which are given in centimeters per year. The percent of annual evaporation for April to October is 75.0% calculated from the heat balance, 75.9% interpolated for the evaporation pan, and 78.5% calculated from the volume balance.

This increase can easily be calculated by realizing that all the dissolved solids originally present in the 444 cm of total inflow are now present in only 257 cm, so that the increase in dissolved solids concentration can be obtained by multiplying the volume-weighted average dissolved solids concentration in the stream serving Cheney Reservoir by 1.723 (444/257).

Table 5 shows the predicted and actual concentrations of dissolved solids in Cheney Reservoir. The concentration factors show clearly that the predicted increase in concentration (172.3%) because of evaporation is very close to the actual average value (170%). The unusually high increase in sodium concentration (214%) is apparently due to possible analytical errors.

The analysis of data for calcium indicated that a limit in concentration had been reached and that precipitation in the form of $CaCO_3$ must be taking place. The slight decrease in the concentration of calcium with time is related to the *p*H of the reservoir water.

REDUCING THE INCREASE IN DISSOLVED SOLIDS CONCENTRATION

One method is to reduce evaporation, but, as was shown, this leads to intolerable water temperature increases. However, one can reduce

TABLE 4. Cheney Reservoir Water Temperatures T' in the Event of Evaporation Elimination

Month in 1966	Water Temperature T with No Evaporation Reduction, °C	Air Temperature T_a, °C	$q_s + q$,* cal/(cm^2 day)	Heat Transfer Coefficient h_q, cal/(cm^2 day °C)	Water Temperature T' with No Evaporation, °C	Water Temperature Increase $\Delta T = T' - T$, °C
Jan.	2.6	-2.1	255	20.4	10.2	7.6
Feb.	3.2	0.8	268	19.0	12.4	9.2
March	6.7	9.5	324	26.6	17.4	10.7
April	12.1	11.9	402	23.3	21.0	8.9
May	18.2	18.7	429	21.8	25.9	7.7
June	23.0	24.5	545	23.0	31.7	8.7
July	25.5	29.4	583	19.7	35.9	10.4
Aug.	25.0	24.5	569	18.3	32.8	7.8
Sept.	21.5	20.3	513	17.0	29.4	7.9
Oct.	16.0	14.4	439	22.1	23.4	7.4
Nov.	10.0	9.0	343	20.5	18.5	8.5
Dec.	5.1	0.3	272	20.0	11.9	6.8
Total			4942			
Average	14.1	13.4	412	21.0	22.5	8.4

*From Table 2.

TABLE 5. Concentration of Dissolved Solids before and after Evaporation

	Stream Serving Cheney Reservoir					Cheney Reservoir					
Chemical Parameter	Range Observed prior to 1965, mg/l	Volume-Weighted Average, mg/l	Predicted Maximum Concentration,[a] mg/l	Cation,[b] me/l	Anion,[b] me/l	July 1, 1965, mg/l	June 30, 1967, mg/l	Concentration Factor[c]	Maximum Observed Concentration, mg/l	Minimum Observed Concentration, mg/l	Decrease in Concentration,[d] mg/l
SiO_2	4 to 18	11.5	19.8			4.2	7	1.67	23	0.02	
Dissolved solids[e]	165 to 967	358	616			404	665	1.64	822	352	
Conductivity	260 to 1770	633	1090			605	1000	1.66	1075	425	
*p*H[f]	7.2 to 8.3	7.8	8			8.2	8.3		8.58	7.3	
HCO_3^-	98 to 228	163	280		2.67	188	204	1.70	256	151	
Cl^-	23 to 402	96.1	166		2.71	145	235	1.62	250	65	
Na^+	16 to 265	66.1	114	2.87		87	186	2.14	259	10	
Mg^{++}	4.6 to 22	10.7	18.4	0.88		10.9	18.3	1.68	26.7	3.1	
Ca^{++}	26 to 85	40.2	69.4	2.01		62.2	49.6		84.6	35.6	12.6
F^-	0.3 to 0.5	0.40	0.69			0.1	0		0.3	0	0.1
$SO_4^=$	11 to 85	32.9	56.7		0.68		53		89	30	
$PO_4^{\equiv}$	0.1 to 0.8	0.6	1.0			0.8	0.5		2.1	0	0.3
NO_3^-	0.4 to 10	3.3	5.7		0.05	2.1	2.0		4.7	0.3	0.1
Σ		430	742	5.76	6.12	500	756	1.51			13.1
Average								1.70			

[a] The volume-weighted average x 1.723.

[b] Volume-weighted average cations and anions computed from the volume-weighted averages.

[c] To obtain the concentration factor due to evaporation, data for June 30, 1967, are divided by those for July 1, 1965, except for HCO_3^-, which is the maximum observed concentration divided by the minimum observed concentration.

[d] The data for June 30, 1967, minus the data for July 1, 1965. Fish may be responsible for the temporary depletion of some ionic species.

[e] Data for July 1, 1965, and June 30, 1967, were computed.

[f] The volume-weighted average *p*H is simply the arithmetic mean *p*H.

the dissolved solids concentration by bypassing the stream flows containing the most dissolved solids around the reservoir. Because the lowest stream flows usually have the greatest dissolved solids concentrations, bypassing a relatively small quantity of water will effect a large reduction in dissolved solids concentration.

At this point a set of example calculations [*Ward and Karaki,* 1969] should help clarify the preceding. For example, if 10% of the stream flow containing the largest concentration could be bypassed around Cheney Reservoir, the dissolved solids could be reduced by 30%. In other words the dissolved solids concentration in Cheney Reservoir would be 431 mg/l instead of 616 mg/l, a reduction of 185 mg/l.

The effect of Cheney Reservoir on the stream below Cheney Dam is to reduce greatly the variation in dissolved solids concentration.

Bypassing 10% of the flow around Cheney Reservoir does not seriously affect the water quality below Cheney Reservoir. In other words the volume-weighted average dissolved solids concentration in the stream below Cheney Reservoir would be 616 mg/l with no bypassing. With 10% bypassing the concentration would be about 710 mg/l in the stream below Cheney Reservoir, an increase of only 11.5%. In fact, if 20% of the total stream flow was bypassed around Cheney Reservoir, the downstream concentration of dissolved solids would only be about 610 mg/l or somewhat less than it would be with no bypassing, and the dissolved solids concentration in Cheney Reservoir would be 48% less, a decrease of 300 mg/l.

ALGAE

The simplest definition of algae is that it includes all microscopic plants carrying out true photosynthesis. Photosynthesis is greatest at the water surface and decreases with depth (the lower limit of photosynthesis occurs at a depth of about 5 meters). Algae, however, may distribute themselves throughout the reservoir.

The demand by algae for oxygen in the absence of sunlight is of great importance in depleting DO. Therefore, unless algae are prevented from multiplying promiscuously, they could become a problem by depleting DO.

Algae are particularly troublesome from two viewpoints. Many species give rise to taste and odor problems, whereas others interfere seriously with filtration practices. Nitrogen and phosphorus are major mineral nutrients required by all algae. The requirement of blue green algae (Cyanophyta) for these elements is somewhat higher than that of green algae (Chlorophyta and Euglenophyta) because of the higher protein content of blue green algae.

By placing a given lake or reservoir under survey for 1 calendar year and employing modern methods of analysis for all conceivable critical nutrients, one should be able to ascertain which nutrients are actually critical in the body of water under consideration. However, there are two qualifications that must be recognized for successful application of this method of determining critical nutrients. One is that all forms of inorganic nitrogen (ammonia, nitrate, and nitrite) must be considered, not just nitrate. Only nitrate was determined in Cheney Reservoir, but probably very small quantities of either ammonia or nitrite were present. The second qualification is related to phosphorus. In many lakes or reservoirs receiving domestic waste water the phosphorus available may be so great with regard to the phosphorus requirement that a decrease in concentration may not be observable during the growing season. This condition is known to exist when phosphorus concentrations are in the range of 0.5 mg/l. Phosphate concentrations in Cheney Reservoir were generally <0.5 mg/l.

The five divisions of freshwater algae are (1) Chlorophyta (grass green algae), (2) Euglenophyta (motile green), (3) Chrysophyta (diatoms and others, yellow green to golden brown), (4) Pyrrophyta (motile greenish tan to golden brown), and (5) Cyanophyta (blue green algae). Euglenophyta grow best in a rich NH_3 medium. Cyanophyta prefer high *p*H and/or high soluble inorganic ion concentrations.

Algae are autotrophic organisms in that they are able to use inorganic compounds for their synthesis. The mineral requirements for algae protoplasm are similar to those for bacteria protoplasm. Carbon often comes from CO_2, as it does for the autotrophic bacteria. Available phosphorus is always in the orthophosphate ($PO_4^{=}$) state, whereas S is usually $SO_4^{=}$. The normal trace elements of Na, K, Ca, Mg, iron, cobalt, molybdenum, and so on are all required. Some algae prefer low *p*H or soft water.

For Cheney Reservoir the noncritical nutrients appear to be Ca^{++}, Mg^{++}, $SO_4^{=}$, and Na^{+}. Because no analyses were made for potassium, iron, cobalt, and molybdenum, no statement can be made with regard to whether they were critical nutrients or not. For Cheney Reservoir the critical nutrients appear to be nitrogen, phosphorus, and SiO_2, because apparent reductions in concentration were observed.

For purposes of classifying algae with respect to water temperature the following grouping is used (from lowest to highest water temperature): diatoms (3), green (1 and 2), blue green (5), and Pyrrophyta. No Pyrrophyta were observed in Cheney Reservoir, which was expected because they usually grow best when water temperatures exceed 40°C.

Table 6 was constructed from the observations made on Cheney Reservoir. The maximum concentration of algae was observed at a water temperature of 15°C. This was also the point at which the diatom percent was a minimum (15%) and the green percent was a maximum (85%). The water temperature is 15°C at the end of April and about the middle of October. Algae numbers reflect also the visible sunlight available for photosynthesis. At temperatures of about 15°C, bacterial competition for nutrients probably has some effect on algae numbers. The effect of fish on algae numbers could not be determined because there were no fish data available.

Table 6 is a very rough approximation, but it appears to be the best that can be done with the observed data. It should give a fair qualitative idea of the effect of water temperature on algae composition and concentration.

The net weight of oxygen produced daily would be directly proportional to the intensity of visible solar radiation if the efficiency of energy conversion were constant. An efficiency of 1% being assumed, the daily increase in DO concentration would be expected to be $\leqq 1.47$ mg/l/day. The actual efficiency is likely to be substantially <1%, because values as low as 2% have been reported for oxidation ponds. The lower limit of photosynthesis being 5 meters, the top 5 meters encompasses about 72% of the total volume of Cheney Reservoir.

The biological activity in this reservoir did not seem to affect the water quality materially. Odor appears to have stabilized at a threshold odor number of about 5 and is characteristically musty, like the odor of decomposing straw. The effect of the interaction between microorganisms

TABLE 6. Concentration and Composition of Algae as a Function of Water Temperature for Cheney Reservoir

Water Temperature, °C	Number of Algae per ml	Percent Composition		
		Blue Green Algae (5)	Diatoms (3)	Green Algae (1 + 2)
3	300	0	57	43
4	400	0	47	53
5	510	0	40	60
6	660	0	35	65
7	850	0	31	69
8	1100	0	28	72
9	1400	0	26	74
10	1850	0	23	77
11	2400	0	21	79
12	3100	0	19	81
13	4000	0	18	82
14	5100	0	16	84
15	6600	0	15	85
16	5400	0	17	83
17	4500	0	19	81
18	3700	0	20	80
19	3100	1	22	77
20	2600	1	23	76
21	2050	2	25	73
22	1750	3	27	70
23	1450	4	29	67
24	1200	5	31	64
25	1000	6	33	61
26	840	8	36	56
27	690	11	39	50

and nutrients was characterized in the analysis of the phosphates, nitrates, and silica concentrations in Cheney Reservoir.

CONCLUDING REMARKS

The evaporation excess is defined as lake evaporation minus precipitation. The importance of the evaporation excess is that it indicates the type of water quality problem that is likely to be of paramount importance in a given area. In other words, if the evaporation excess is positive, dissolved solids concentration is likely to be the major water quality problem. Furthermore, the magnitude of the evaporation excess indicates the intensity of the dissolved solids concentration problem. For example, the evaporation excess at Cheney Reservoir is 142 − 81 (61) cm/yr, and this excess was sufficient to cause an increase in dissolved solids concentration in one reservoir of 170%.

On the other hand, where evaporation excess is negative, the major water quality problems are likely to be something other than dissolved solids concentration. In fact, the mere construction of a reservoir in a negative evaporation excess area reduces the dissolved solids concentration.

Because most of the population of the United States is currently (1973) in a negative evaporation excess area, the water quality problems receiving the most attention have not been dissolved solids concentration. However, most of the United States has a positive evaporation excess, and therefore the major water quality problem would appear to be dissolved solids concentration.

The data collected and used in the analysis have been adapted to the national water quality data storage and retrieval system and filed with the center in Washington, D. C.

Acknowledgments. With the exception of the heat budget (Tables 2 and 4) the work on which this article is based was supported by funds provided by the U.S. Bureau of Reclamation. The work reported as heat budget was supported by the U.S. Department of the Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379. The authors also wish to thank Dr. S. M. Morrison, Professor of Microbiology at Colorado State University, for his review of the entire manuscript and for the many useful contributions developed in the course of that review. In addition, the authors express their appreciation to Paul R. Tramutt, Head, and Dr. Dale A. Hoffman, Research Scientist, Chemistry and Water Quality Research Section, Chemical Engineering Branch, Division of Research, U.S. Bureau of Reclamation, Denver, Colorado, for their excellent comprehensive review and evaluation of the rough draft.

REFERENCE

Ward, J. C., and S. Karaki, Evaluation of the effect of impoundment on water quality in Cheney Reservoir, *Sanit. Eng. Pap. 4,* Colo. State Univ., Fort Collins, Sept. 1969.

Summary: Reservoirs in Relation to Man—Fisheries

ROSEMARY H. LOWE-MCCONNELL

Streatwick, Streat, Hassocks, Sussex, England

Reservoirs are created primarily for irrigation, water storage, flood control, or hydroelectric power and rarely for fisheries, but the rapidly increasing demands for protein, especially in developing tropical countries, and for sport fishing in the more affluent societies now call for the fullest use to be made of man-made lakes for fisheries development. Far above the often considerable cash value of the fish caught and of the numerous ancillary services associated with the fishing industry is the immense value of fishery development for the physical and mental health of the people in the countries concerned.

At present, some 60% of the people living in less-developed countries have nutritionally inadequate diets, and, to meet estimated protein and calorie needs throughout the world in 1985, at least 50% more food will be required [*Stroud*, 1970]. When *Holt* [1967] summarized world needs for protein, he pointed out that the best prospects for increased fish production now come from small lakes, reservoirs, and ponds, where management is possible. The increasing demands for sport fish in the United States have been assessed by *Jenkins* [1964]. In 1963, 1200 large reservoirs provided 86 million days of angling, and an 85% increase was expected by 1976. Management is therefore aimed at a 30% increase in fish yield, from 17.2 kg/ha/yr to 23 kg/ha/yr.

Some types of reservoirs lend themselves to fish production better than others do. Irrigation reservoirs, which run very low in dry years, obviously need different management from deep hydroelectric power lakes. The reservoir fishery biologist is concerned with finding out how best to manage each type of water.

The aim of fisheries management is to obtain the maximum sustained yield of desired fish species, be they food fish (which are often herbivorous plankton or benthos feeders) or sport fish (which are most often piscivorous species). For sport fishing the quality of the fishing is also important. In developing countries it may be more important to make employment available for a large number of fishermen than to aim purely at the highest fish production, but this paper is concerned with the more technical aspects of getting a good crop of fish.

For fisheries management in a new lake we need to be able to forecast the fish yield before the dam is completed. This yield will depend on the biological production of fish (which is dependent on the species present, the latitude, and the limnological conditions in the new lake) and on the fishing effort (which will involve sociologic and technological problems, such as the availability of able fishermen, gear and craft, transport, and markets). When the lake is formed, we have to be able to assess the fish stocks present (this assessment is generally based on age and growth rate data in temperate lakes) and to regulate the fishery to crop an amount equivalent to the fish flesh produced over a given period of time.

The biological production is the rate at which fish flesh is produced in contrast to the standing crop or biomass of fish in the water body, and the yield or catch (often miscalled 'production' in fishery publications) represents the proportion of fish removed from the lake as a result of the fishing effort. In a balanced fishery the annual yield should be made to approximate the annual production.

In addition to fishery development within a new reservoir we also have to consider how damming the river may affect fisheries already in existence in the river, both above and below the dam, and in the estuaries and neighboring seas. Damming a river will obviously stop fish movements upstream and downstream unless fish passes are provided, but subtler effects will also exist: changes in water level regime below the dam may affect both fish spawning rhythms and feeding and breeding areas, nutrients may be cut off from downriver stretches right to the sea, or salinity changes may affect marine fishes that come into the estuaries to spawn.

SEQUENCE OF BIOLOGICAL EVENTS AFTER A RIVER IS DAMMED

The general sequence of biological events after a river is dammed is now well known for temperate lakes, but each case presents its own problems and calls for preimpoundment surveys and continued monitoring of fish populations for successful fishery management. For large tropical reservoirs, which are relatively new phenomena, there is as yet rather little biological information.

As the dam is closed, the rising water level drowns the surrounding vegetation. This rots, and the resulting nutrients lead to an outburst of production among the bacteria, flora, and fauna. Fish populations expand rapidly, the abundant food and cover allowing high survival rates among juvenile fishes spawned at this time, and the fish grow fast. In temperate zone lakes, production slows down after 2–3 years, when nutrients are exhausted and fish are abundant. This 'trophic depression phase' lasts 25–30 years at high latitudes (north of 55°N in the USSR) but is over correspondingly quickly in 6–10 years in lakes further south (south of 55°N in the USSR) [*Lapitsky*, 1968]. Production increases slightly as the lake settles down. Lakes might stabilize more rapidly at the high temperatures of the tropics, where events proceed so fast, but data on this point are needed. Lake Kariba appears to be through this trophic depression phase 12 years after dam closure.

The fish fauna of the new lake will depend on the species present in the river (which will vary with biogeographic zone and latitude) and their response to the changed conditions. A new lake generally has far fewer fish species than the river did. The fishes have to face changes in (1) physical and chemical conditions (temperature, turbidity, current flow, and so on and deoxygenation as the submerged vegetation rots), (2) available food, and (3) spawning conditions.

Spawning under the new conditions presents great challenges. Stream spawners have to find a tributary stream in which to spawn, and the young fish have to be able to return to the lake. Among the lake spawners, fish with buoyant or semibuoyant eggs (such as the sciaenid freshwater drum) are able to spawn successfully, and year classes tend to be regular [*Benson*, 1968]. Fish that spawn deep enough not to be affected by water level fluctuations may spawn successfully too, but the many species that spawn in the littoral zone either on the bottom (cichlids and centrachids) or among aquatic plants (many forage fish) will be very much affected by water level fluctuations, and year classes will tend to be very irregular. Indeed, water level fluctuations can be used to control unwanted spawning in these species.

In many tropical fishes, spawning is triggered by rising water levels, and so water level fluctuations are likely to have correspondingly greater physiological effects on tropical fishes than on temperate zone fishes, which spawn according to water temperature or day length.

Riverine fishes tend to be facultative feeders, and so can often adapt to new foods within their trophic group. The increased plankton in the new lake presents special opportunities, and lakes that have plankton-feeding species in their riverine fauna (such as *Tilapia*, which feed on phytoplankton, and sardine clupeids, which feed on zooplankton) get a good start. The bottom fauna is much changed as the former riverbed is drowned. In thermally stratified lakes, much of the bottom will be deoxygenated and so will be unfit for habitation by fish. The establishment of a littoral flora and fauna depends very much on water level fluctuations. Drowned trees and bushes present important substrata for a flora and fauna of food organisms, as has happened in Volta Lake, where periphytic algae and the burrowing nymphs of the ephemeropteran *Povilla adusta* have had vital roles in the productivity of the new lake [*Petr*, 1971]. As the lake stabilizes, various niches will be filled by different species of fish. If a niche remains vacant, such as that for plankton feeders in open water, the lake will not be as productive as it would otherwise be. The establishment of new lake faunas has been well studied in temperate lakes (in the USSR particularly), and there is an extensive literature. In tropical lakes, such studies are in their infancy.

DIFFERENCES BETWEEN TROPICAL AND TEMPERATE LAKES

Most fishery research has been carried out in temperate waters, but how far can the management techniques worked out for these lakes be applied in tropical conditions?

First, events move much faster at the higher temperatures of the tropics. Fish grow faster and mature earlier (many commercial species maturing in <1 year), populations build up much more quickly, and good and bad spawning years show their effects sooner in the catchable population (and conversely their effects do not last as long). Also, production represents a higher proportion of the biomass (standing crop) of fish. For example, in Cuba, production was three quarters of the biomass, whereas in European reservoirs it was only about one third [*Holčik,* 1970*a*].

Second, tropical communities are very complex. Numerous species that look very much alike live together, and it is often difficult to identify the young stages. The fisheries are generally for fishes of diverse sizes and shapes, which complicate fisheries management and legislation.

Third, conditions are less seasonal. Many species spawn throughout the year, and so fish enter the catchable population continuously. This together with the lack of seasonal growth checks, which register the age on the scales and bones of temperate fish, makes the determination of fish ages and growth rates very difficult in many tropical waters. As such age and growth data are basic tools for population assessment in temperate lakes, new methods of stock assessment need to be devised for tropical waters.

SECTION PAPERS

The papers presented in this section on various aspects of fisheries come from both tropical and temperate waters, and each may be taken to illustrate a different problem. From Africa the paper from Kainji Lake on the River Niger is concerned mainly with preimpoundment and postimpoundment surveys. Another African paper comes from Lake Nasser on the Egyptian Nile, which has basically the same fish fauna as Kainji Lake, and is concerned with catches in the early years of the impoundment. Then, from Asia, there is a paper from Ceylon, where introduced exotic fish have greatly boosted the catch, and another from the Mekong River that raises questions on the importance of migrant fishes and on possible effects of the planned impoundments on the very valuable fisheries that already exist, both in the river and associated lakes and in the delta and the neighboring sea. From the United States, there are four papers, one that examines the effects of water level fluctuations on fish populations in Missouri main stem impoundments, another from Lake Apopka in Florida that deals with eutrophication, a third from the South Lake Tahoe area that demonstrates sophisticated treatment of waste waters to enable them to be used for sport fishing, and a fourth that concerns the gas bubble disease of fish, which results from exposure to an environment that is supersaturated with nitrogen, as experienced at the lower Columbia and Snake River reservoirs.

OTHER SOURCES OF INFORMATION

Reservoir fish studies in the United States. The United States had >1300 reservoirs (each >200 ha) by the end of 1968 totaling >3½ million ha with >50 types of fish. A bibliography of reservoir fishery biology for North America [*Jenkins*, 1965] indicates the large amount of research in progress: surveys, studies of fish population dynamics, age and growth, food habits, life histories and ecology, and management techniques. Some of the studies have been in progress for decades. Further research needs and techniques to obtain the desired information were discussed by *Jenkins* [1964]. More recently, the influence of environmental factors on standing crops has been explored by extensive multiple regression analyses using a computer. The results of these analyses have been summarized by the director of the National Reservoir Research Program [*Jenkins,* 1968*a, b,* 1970].

Data based on recovery following rotenone treatment and on sport and commercial fish harvests [*Jenkins*, 1968*a*, *b*] indicate that in 1968 the mean standing crop in 127 U.S. reservoirs was 204 kg/ha/yr, the mean sport harvest in 121 reservoirs was 24.8 kg/ha/yr, and the mean commercial harvest in 46 reservoirs was 11.2 kg/ha/yr. The environmental factors that appeared to exert the greatest positive influences were found to be dissolved solids, which influenced the standing crop and the sport fish harvest; the age of the reservoir, which influenced the commercial harvest and the clupeid standing crop; the storage ratio (i.e., lower water exchange rate), which influenced the sport harvest; and the shore development, which influenced the standing crop and the sport harvest. Factors of greatest negative influence were the age of the reservoir, which influenced the sport harvest; the storage ratio, which influenced the clupeid standing crop and the commercial harvest; the area, which influenced the sport harvest; and the mean depth and the shore development, which influenced the commercial harvest [*Jenkins*, 1968*a*].

In later analyses, factors such as outlet depths, growing seasons, and drainage areas were tested, and distinctions were made between reservoirs with or without a thermocline. Interspecific correlations between the standing crops of various fish species were also made [*Jenkins*, 1968*b*, Table 3] and were useful for designing stocking programs. As the environment changes, so will the interactions between the species.

Among the relationships that *Jenkins* [1970] considers most useful for fisheries predictions and management are the positive effects of increasing outlet depth, shore development, and dissolved solids on standing crops, of growing season and storage ratio on clupeid crops in hydropower reservoirs with a thermocline, of increasing shore development on total crops in nonhydropower reservoirs, and of the age of the reservoir on the total crop.

Management accomplishments in U.S. reservoirs summarized by *Jenkins* [1970] include stocking, liberalizing the angling season to allow year-round fishing for warmwater fish, control of forage fish (using rotenone) and of 'rough' fish (by netting, electrofishing, and so on), using the drawdown to ameliorate limnological conditions (and also to control the reproduction of undesirable species), timber clearing, and installing fish passes for migrating salmonids. In some places, fish are eradicated completely; then cooler waters are restocked with trout, or centrachids are reintroduced into warmwater impoundments.

Reservoir fish studies in the USSR. The USSR has more large reservoirs, due to hydropower development, than any other country. Fishery development is regarded as an important part of the use of these reservoirs, and so an immense amount of work is being done on the hydrobiological conditions, the establishment of new fish faunas, and fishery management to give maximum yields of high-quality food fish. Fortunately, the extensive Russian literature has been summarized in papers in English prepared for study tours of fisheries research and management in the USSR [*Food and Agriculture Organization*, 1968]. The reservoirs in the USSR totaled 5 million ha in 1968, and, when planned projects are completed, this area should be doubled. The Volga, Don, and Dnieper rivers are being transformed into cascades of reservoirs along their entire courses. Another large reservoir complex has been completed west of Lake Baikal on the Angara and Yenisei rivers, which drain to the Arctic Ocean. (These may one day be linked by the suggested huge Omsk and New Siberia reservoir and by canals to the northward flowing River Ob and west to the Caspian Sea.) By 1968 the USSR reservoir catch was circa 44,000 metric tons/yr, although only some of the reservoirs were in commercial use. On the basis of present catches the target is 20–30 kg/ha/yr of high-quality fish products, which, if it is achieved, should give circa 170,000 metric tons/yr of fish from these reservoirs. The USSR reservoirs are classified according to their hydrobiological characteristics and fish faunas by *Melnikov* [1962].

The development of fisheries and ways of raising fish productivity in big reservoirs were considered by *Lapitsky* [1968], who summarized what is known about patterns of ichthyofauna formation in reservoirs and reservoir management in the USSR. (He cited the history of fishery development in the Tzimljanskoye Reservoir on the River Don formed in 1952 as an example.)

The Russians have paid great attention to shaping hydrobiological conditions in large reservoirs [*Pirozhnikov and Miroschneichenko*, 1968]. They have done much work on fish passes and fish lifts for anadromous fishes, protection facilities to keep fish out of turbines, and so on [*Nusenbaum*, 1968]. They have also made great strides with induced spawning and rearing of migratory fishes for stocking when a river is completely blocked [*Vovk*, 1968]. Induced spawning has made possible the introduction of plant-eating silver carp or white tobilisk (*Hypophthalmichthys molitrix*) from the Amur River into the European part of the USSR [*Konradt*, 1968]. The grass carp is now breeding in the Kara Kum canal in Turkmenia. Sometimes the Russians advocate wiping out the indigenous fauna and stocking with a new fauna of more productive fish. Chemical methods of rehabilitation and propagation of new fish faunas are described by *Burmakin* [1968]. Stocking with invertebrates (crustacean mysids, mollusks, and polychaetes) is also advocated to boost fish food supplies during the trophic depression phase [*Lapitsky*, 1968].

In the USSR, where fish mature relatively slowly at the low temperatures, great stress is laid on encouraging the right fish populations to develop as the reservoir fills, for the fishery will be based on these populations for many years to come. Management measures taken include stocking the reservoir with spawners of valuable food fish, which are transferred from other waters to strengthen spawning stocks during the first year of filling, since an overwhelming abundance of fry can then inhibit the growth of trash fish; construction of fish hatcheries at the reservoirs to stock the new lake with the fry of valuable species; and planned fishing with protection of valuable species during the early stages of stock formation by a complete ban on fishing for them for 2 years prior to filling and during the first years after impoundment. This saves spawner stocks for use under favorable propagation conditions in the first year to obtain huge populations of fry. Trash fish are inhibited by selective fishing. Other measures include the acclimatization of food organisms to overcome the trophic depression phase, the preparation of the reservoir bottom for commercial fishing, ascertaining optimum water level regimes, and so on. Fishing for the valuable species may remain 'closed' until the first generation of lake fish matures.

Reservoir fish studies in India. India is a land of big rivers and small streams, which are in spate during the two monsoons and become straggling streams during the rest of the year. To conserve monsoon floods, most of the rivers (large and small) have been dammed at suitable places, and the waters have thus been stored for irrigation, water supply, pisciculture, and hydroelectric power. By 1969, India had 295 major reservoirs (211 of them >400 ha) [*David and Gopinathan*, 1970]. These Indian reservoirs are major ones formed by damming rivers and minor ones formed by damming vast depressions at their lowest level. These depressions are filled during the monsoon rains by rainfall and surface runoff and almost dry up during the hot weather. These two types of reservoirs are found scattered throughout India, and they are stocked with the fry and fingerlings of major Indian carps (*Catla catla, Cirrhina mrigala, Labeo rohita,* and *L. calbasu*).

At a seminar held in India at the Central Inland Fisheries Research Institute, Barrackpore, in 1969 on the ecology and fisheries of freshwater reservoirs, >50 papers were presented. Measures adopted for the development of reservoir fisheries in India were summarized by *Jhingran and Tripathi* [1970]. Other published abstracts indicate that the supply of fish fry 'seed' to stock the many reservoirs is of major concern. The rivers in which the major carps spawn have been mapped [*David*, 1959, Figure 1], and their spawning seasons and biology are summarized by *Qasim and Qayyum* [1961]. Some species migrate upriver from the new lakes and move out laterally to spawn [*David*, 1959]; some spawn in the headwaters of the new dams (as they do in Lake Bhakra [*Bhatnagar*, 1964]). Yields of >45 kg/ha/yr are recorded from several reservoirs, though average yields may be much smaller (7.5 kg/ha/yr). The desirability of replacing 'wild' fish by more productive carps is advocated [*Bhimachar*, 1970], as is the importance of protecting the spawners of the valuable species, which are often fished heavily as they move into the shallows to spawn [*Jones*, 1970]. Fish yields in relation to primary production and various limnological conditions in Madras reservoirs have been studied by *Sreenivasan* [1970].

Reservoir fish studies in Indonesia. Some of the earliest studies on fish production in tropical man-made lakes were made in Indonesia, where herbivorous fishes contribute to very high yields. *Vaas and Sachlan* [1952] report 500–600 kg/ha/yr from a 25-km artificial lake in west Java (mainly *Cyprinus carpio, Puntius javanicus*, and *Helostoma temmincki*). A reservoir in central Java had previously been found to yield 250 kg/ha/yr [*Vaas and Schuurman*, 1949].

Reservoir fish studies in South America. Since South America has such a rich natural freshwater fish fauna with more endemic species than any other continent and since there are as yet so few large reservoirs, few studies of fisheries in man-made lakes have been made. In Lake Brokopondo, Surinam, the forest was not cleared, and no attempt was made to develop a commercial fishery, though the fish fauna was studied and collected intensively at the time of impoundment [*Leentvaar*, 1967]. In the Andes, rivers are being harnessed for hydroelectric power. Introductions of salmonids into these rivers were followed by the decimation and virtual disappearance of the endemic species flocks of large cyprinodontoid poeciliids. These were of the greatest scientific interest and also of considerable value as food fish for the indigenous Indian peasants. The salmonids were found to have carried a sporozoan parasite to the indigenous *Orestias* [*Villwock*, 1972]. Studies in Brazil [*de Godoy*, 1959] and Argentina [*Ringuelet et al.*, 1967] show that some of the important commercial fish make very long migrations upriver and downriver. Fish passes are likely to be needed here if rivers are dammed. The South American fish fauna is so complex that ecological studies need to be made well in advance of any impoundment schemes to gage the effects on the fish.

Marine areas turned into freshwater lakes. The development of freshwater fisheries in lakes that were formerly arms of the sea raises different problems. These are being studied mainly in Holland at the Delta Research Division of the Hydrobiological Institute, and their progress is reported in their annual reports [*Vaas*, 1968]. Feasibility studies on estuarine storage in the Morecambe Bay area of the United Kingdom are considered by *Gibb and Corlett* [this volume]. A freshwater reservoir has been created from an arm of the sea for Hong Kong.

SPECIAL PROBLEMS

Forecasting fish yields from reservoirs. In the early days of man-made lakes, predictions of yields had to be based on yields from natural lakes of comparable morphometry and at comparable latitudes. *Roundsell* [1946] working on this basis pointed out the decline in yield as the lakes increased in area and that overoptimistic estimates were often based on small areas. (The total fish population was likely to fall from around 300 kg/ha/yr in 0.4-ha ponds to 35 kg/ha/yr in 80-ha lakes, and between these sizes the annual yield of sport fish might vary from 82 to 10 kg/ha/yr.) The commercial fish catch can be much higher than the sport fish catch in large reservoirs. The yield per hectare, Roundsell suggested, is probably correlated with the relative area of fertile shallow water, which is larger in small lakes than in large lakes. He also noted that other factors, such as chemical nutrients, the fish species present, and the balance between them, will also affect fish production.

In recent years, many attempts have been made to find indices to predict yields from reservoirs. Some of these were reviewed by *Ryder* [1965], who reckoned that the 'morphoedaphic index,' i.e., the total dissolved solids divided by the mean depth of the lake, as a simple regression on fish production allowed him to predict yields for lakes of various sizes in the temperate zone of North America, and he has since attempted to apply this method to African lakes. The multivariate computer analyses of data from U.S. reservoirs [*Jenkins*, 1968*a*, 1970], already considered above, also help predictions to be made.

In the tropics, there is as yet far less comparable work to provide base lines for predictions. *Holden* [1969], who has reviewed problems of forecasting yields for tropical lakes, suggested that the growth of indicator species (such as *Tilapia nilotica*) might be helpful. For Lake Kariba the highest annual catch, circa 5400 metric tons in 1963–1964 [*van der Lingen,* this volume; Zambia Republic, unpublished report, 1968], was far short of the least optimistic estimate of circa 8200 metric tons (quoted by *Jackson* [1960], who also mentioned another estimate of 28,000 metric tons). The low yields in Lake Kariba seemed to be the result of a combination of human and biological factors. Fishermen evidently returned to their gardens instead of fishing owing to marketing difficulties, controversy over fish prices, and poor roads. *Salvinia* cover over the mouths of tributary streams [*Begg*, 1969] might have affected spawning runs and the recruitment of fish.

Volta Lake, on the other hand, has been much more productive than was expected. About twice the area of Lake Kariba, Volta Lake has produced 10 times the amount of fish (>60,000 metric tons in 1969–1970). As a shallower lake it was likely to be relatively more productive, but the happy accident of the presence of both *Povilla adusta* and clupeid fishes seems to have contributed greatly to its productiveness. As the lake rose gradually, new areas were flooded year by year, and so production remained high. *Petr* [1971] observed that production will fall when the trees rot and are no longer able to support large *Povilla* populations. Indeed, catches have already fallen (to circa 38,000 metric tons according to *Kalitsi* [this volume]), and, if Ryder's morphoedaphic index predictions are applicable to tropical lakes (which is by no means yet certain), they may fall to about one-half this amount again before they stabilize.

The extent to which the predicted yield can be realized depends on whether the new lake is fishable with the gear available and whether preparations have been made to develop and regulate the fisheries [*Holden*, 1969]. At present, many opportunities are probably being missed. Helping the fishermen to exploit species of fish other than the usual commercial ones would assist them during the inevitable period of decline after the initial burst of production.

The extent to which the potential yield should be cropped in the early years of impoundment needs consideration in each individual case. In the USSR, as was already mentioned, great care is taken to protect the spawners of desirable fish species until stocks have had time to build up. In tropical lakes, on the other hand, the desirability of cropping the fish hard during the initial high production phase has been advocated not only to make use of the fish and to demonstrate to the indigenous people the advantage to be gained from having a lake but also to remove the excess nutrients from the system, which might lead to an outburst of weed growth.

Nutrient buildup will depend on other factors, such as the flushing rate of the lake, the speed with which the lake fills, and so on. In tropical waters, fish populations can build up so quickly that there will probably be less need to prohibit fishing for valuable species for some years than there is in the USSR. However, selective fishing for undesirable species should be encouraged in the early years, less desirable predators, such as *Hydrocynus*, be fished hard. *Bowmaker* [this volume] suggests that they can be cropped as they migrate up to spawn. The large predator *Lates*, on the other hand, is a valuable food fish, capable of adding greatly to the yield from a lake. The uncleared bush-covered areas provide protection for fish such as *Tilapia* in many lakes (as they do in Kainji Lake).

The rate of fish production is dynamic and will itself change according to the numbers of fish in the lake. Fish grow faster when populations are sparse in relation to food supply, and production is reduced as a lake gets overcrowded and growth slows down. The situation is, however, complex. *Beauchamp* [1958] pointed out that, since breakdown of plant matter in the bottom mud of tropical lakes is slower than breakdown through herbivores, the removal of large numbers of herbivores, such as *Tilapia*, from a lake will itself decrease productivity by slowing down production cycles.

Bush clearance and fisheries. At the time that the Volta Dam was being built, bush clearance in the area of the new lake was considered advisable if it could be afforded to enable fishing nets to be used; to avoid a high level of nutrients, which might lead to an aquatic plant cover problem, as it had in Lake Kariba, where *Salvinia* growth was so high after the decomposition of the bush; and to avoid deoxygenation, which might have damaging effects on fish stocks.

As it happened, only small areas of bush were cleared because of the high cost of clearing. It now seems from *Petr*'s [1971] studies that one of the main reasons for the unexpectedly high fish production in Volta Lake is that the uncleared bush offers a substratum for periphytic algae and the wood-burrowing nymphs of the ephemeropteran *Povilla adusta*. These have both provided extensive food resources for the fish, the periphyton for *Tilapia* and other algal feeders and the *Povilla* (which itself feeds on periphyton) for fishes that were formerly bottom feeders (such as *Schilbe*) and also for the small clupeid sardines (*Pellonula*), which have multiplied fast in the new lake.

The ability of bushes to increase the yield of fish from these tropical lakes might have been predicted from (1) experiments in fishponds in which screens used to increase the growth of periphytic algae improved the growth rate of herbivorous fish, (2) the use of the 'acadja' or fish park indigenous fishing method in the lagoons of the coastal areas of Dahomey, west Africa, which consists of planting bare branches in an area of lagoon to increase the algal area and provide cover for the fish, the result being greatly increased yields of fish, mainly *Tilapia* [*Welcomme*, 1972], and (3) observations in the Great Lake of the Khmer Republic, where *Hickling* [1961] noted that production was spectacularly high because the fishes fed in the submerged forest on periphytic plant matter on the trees.

Clearing the bush does help fishing operations and is very necessary for some of them, but the Volta Lake experience suggests that clearance might be done in lanes, as was suggested by *Bowmaker* [1970], areas of bush being left for increased fish production. In Kainji Lake, there are reports of shoals of large *Tilapia* in the bush-covered area, but it is very difficult to catch them. New fishing methods need to be devised to do so.

Introductions: transplants and exotics. To get the maximum yields from a new lake, it may be necessary to supplement the fish fauna either by stocking with fry, fingerlings, or spawners of indigenous fish (transplants) or by introducing exotic species from outside the drainage basin. The introduction of an exotic species may boost the yield from a new lake (as it did in Ceylon), but it carries many dangers with it, and each case needs careful examination both of the limnological conditions and of the biology of the fish to be introduced. There are numerous examples of introduced fishes affecting native species to the point of extinction either directly (through predation, competition, hybridization, or introduction of disease or parasites) or indirectly by altering the habitat. Great care is needed to ensure that the most suitable and most productive species is introduced, since once fish are liberated in open waters it may well prove impossible to eradicate them. Tropical faunas present special difficulties here, since the young of so many species live together and look so much alike but may have very different growth potentials. Expert supervision is essential to see that the desired species do in fact get stocked without a whole lot of undesirable accessory species being introduced too. Numerous small cichlids, for example, have been carried around in Africa with *Tilapia* in this way, and, indeed, *Tilapia leucosticta* gained access to Lake Victoria when other larger growing *Tilapia* were introduced.

Either introduced fish may be very aggressive and oust local species, or they may not 'take' (as *Tilapia macrochir* and *T. melanopleura* did not take in Lake Kariba). Russian experience suggests that it is often no good to introduce a fish unless there is a vacant niche for it, since an introduced species will suffer not only from predators but also from competing species, which eat their food, eggs, and so on. When a local species is available, it would seem more likely to do well in a new lake. On the other hand, there is something to be said for using species for which management techniques are already known.

Certain species have been regarded as fish of golden promise because they are very productive in their home areas or where they were first introduced (often by accident), and so they have been moved around a great deal. These include carp (*Cyprinus carpio*) from Eurasia (introduced into the United States in 1872 according to *Miller* [1961]) and *Tilapia*, the mainstay of African lake fisheries. But introductions of even these species often have undesirable side effects. Carp make the water so turbid that they alter the habitat for indigenous species, and therefore they are now banned in parts of Africa and Australia. *Tilapia* too are now unwelcome in certain areas, for they runt badly and they compete with the more desirable milkfish (*Chanos*) in milkfish ponds [*Food and Agriculture Organization*, 1968]. Results may be somewhat unpredictable even for 'well-known' species.

Man-made changes, such as lakes and canals, are allowing fish increasingly free movement from one water system to another, and any introduced species may now spread over a very wide area in most continents. The zoogeographic role of reservoirs was considered by *Dzyuban* [1962], who cited the progress of the smelt *Osmerus eperlanus* from freshwater around the Baltic southward through the Volga reservoirs.

Fish parasites and diseases may spread from introduced fishes to local fishes not resistant to them. The decimation of the Lake Titicaca endemic cyprinodontoid fishes since the introduction of salmonids to Andean streams (already mentioned) is an example.

Sport fishermen are particularly prone to carry fish around. *Miller* [1961] pointed out that in the southwestern United States about 36 exotics have been introduced, mainly from the eastern United States, as intentional plants of game fishes during the construction of major dams between 1930 and 1950. These established aliens have led to the virtual extinction of about 20 species (20% of the indigenous fish fauna). Exotic fishes in Southern Rhodesia, about 17 species, are listed and discussed by *Toots* [1969]. It is very important that reliable records of introductions be kept.

In some cases (the United States, the USSR, and India) the total destruction of the indigenous fauna is advocated, and the lakes are stocked with new fish: trout in cooler waters, centrachids in warmer waters in the United States, and major carps in India. The use of chemicals such as rotenone, toxaphene, or others may have serious consequences for local species, local extinctions being brought about. Some chemicals may affect the fish flesh of the stocked fish [*Konar*, 1970]. Chemical poisoning is not a step to be undertaken lightly. In the USSR it is found really useful only for fry-rearing ponds not for commercial fishponds.

The present fish of golden promise are the Chinese carp; the grass carp or white Amur, *Ctenopharyngodon idella* (a herbivore); the silver carp or white tobilisk, *Hypophthalmichthys molitrix* (primarily a phytoplankton feeder); and the bighead, *Aristichthys nobilis* (primarily a zooplankton feeder). These three have very high growth rates, are tolerant of a wide range of temperature conditions, and make good complementary species producing very high yields. Grass carp can grow to 5 kg in a year [*Hickling*, 1965]. They do not, however, breed in many places in the wild (they come from the Amur

River, bounding the USSR and China), and, until spawning could be induced by pituitary injections, the supply of young fish for stocking limited their use in other water bodies. Grass carp are now known to be breeding in the Kara Kum canal in Turkmenia [*Konradt*, 1968] and in one river in Japan. The grass carp is remarkably effective in clearing weeds. In the USSR their use in coolant reservoirs of power stations is advocated, they are also stocked to keep channels and canals open, and they are now stocked in southern reservoirs and in impoundments as far north as around Leningrad. An enormous amount of research has been carried out with these fishes in the USSR both where they are in their natural habitats and where they have been introduced or used as pond fish.

Grass carp and silver carp do escape. They are now turning up in rivers in east and central Europe [*Holčík*, 1970*b*; *Holčík and Par*, 1970]. Grass carp have been imported into several hatcheries in the United States, but the policy is, very wisely, to wait and see what side effects there may be before liberating them into open water [*Lachner et al.*, 1970]. It is being found in England that their copious feces cause water blooms unless they are stocked with other species. There is already considerable literature about this species [*Nair*, 1968].

Fish passes, locks, and screens. Although gravity pool fish passes have long been used alongside dams, particularly in areas where salmonids are important, the scientific design of more ambitious fish passes and fish locks has only come to be studied since about the 1950's. This study is of increasing importance in view of the increasing number of river barrages. Most of the work has been and is being done in the United States and the USSR by biologists in cooperation with engineers.

The types of fish passes, locks, and other devices for lifting fish over dams in the United States are well summarized by *Eicher* [1970]. The Bonneville Fishway Laboratory of the U.S. Bureau of Commercial Fisheries, funded by the U.S. Army Corps of Engineers, has since 1956 been looking at the economics of various constructions (such as shorter pools, smaller flows, and less costly entrances). The Bonneville Dam fishway, built on the Columbia River in 1938, was 12 meters wide with 0.3-meter rises between 5-meter pools and flow velocities kept down to 0.6 m/sec in the channels. Other types of fish pass described by Eicher include Denil fishways, which were developed in the late 1950's and have vanes set in straight chutes to reverse the flow (aluminum sections 55 cm wide and 62 cm high based on this principle are being flown into Alaska to aid fishes over natural obstacles), and vertical slot fishways, in which a vertical opening of constant width from the top to the bottom of a pool directs the water through a constriction to release its full energy away from the next slot. These operate very well at varying water levels. They have been used so successfully at Hell's Gate on the Columbia River that it is estimated that they have increased the salmon runs so much that the initial cost of installation is recovered many times over every year.

Locks, either at atmospheric pressure or pressurized, have been tried in the United States but are not used much (in contrast with the USSR). Many fish, of course, must slip through locks that are opened for navigation. Many other devices have been tried, such as tramways and trolleys and other forms of trapping and hauling fish around dams.

However, getting downstream migrants safely downstream is proving much more difficult than getting upstream migrants past dams, and getting juvenile downstream migrants through impoundments (with their very different oxygen, temperature, and flow conditions) is just as important as moving them through turbines, over spillways, and around dams. Devices used in the United States are discussed by *Eicher* [1970]. These include louvers, mechanical screens (a drum or screen panels on a belt, success varying depending on the ability of the screen to clean itself), and devices known as 'skimmers,' 'gulpers,' and gate wells. If the young fish go through the turbines, mortalities can amount to 5–100% depending on factors such as cavitation in the back of the turbine blades, and, as a result of study, turbines can be operated with least injury during migration periods. Mortalities over a spillway are reduced if a ski jump type of free fall is arranged. Trapping and transportation from the head of a lake are used sometimes.

The passage of fishes up or down fishways presents opportunities for them to be counted. Visual techniques have long been used, sometimes in underwater observation chambers, and various photographic or photocell techniques have been developed.

Fish passage facility studies in the USSR are summarized by *Nusenbaum* [1968]. Again, there is a special laboratory to study fish passage facilities and screens staffed by biologists and engineers. Fishways provide facilities for the independent passage of fish from a lower to an upper level, but, on the very high dams on the Don and Volta, special fish locks have been constructed. Fish are attracted and accumulated in fish collectors (80 meters long) for 2 hours; then they are impelled by a moving lattice into a square lock chamber (8.5 m^2). A horizontal impellent screen then lifts the fish into the outlet chute (95 meters long and 12 meters wide). The passage time from tail water to headwater is about 40 min.

The fish lock on the Volga hydroelectric station has since 1961 taken up very large numbers of migrating sturgeon, herrings, and other species (including sheatfish, *Silurus glanis*; bream; carp and other cyprinids; and perch), which accumulate temporarily in a dam zone. Up to 600 sturgeon and 12,000–15,000 herring have passed during one locking (the period of attraction being 2 hours). Every year, 25,000 sturgeon and 1 million herring and other fishes were said to pass at this site. A great deal has been learned about the migrating behavior of these fishes. The intensity of the fish run varies within the season, and different species run at different times of day, sturgeon mainly in the dark and herrings by day. In the River Ob, which flows to the Arctic Ocean, it was found that many 'resident' (i.e., nonanadromous) fish spread over a wide area during feeding and spawning migrations, the ide (*Leuciscus idus*), pike (*Esox lucius*), and *Acipenser ruthenus* migrating over 400–600 km.

A great deal of work on fish screens to keep fish out of turbines and the wrong channels has been carried out in the USSR. Electrical and mechanical screens give the best results, though the use of lights, sounds, chemicals, and so on have been tested. Electrical screens are, of course, only useful to stop or steer upstream moving fishes. Details are given by *Nusenbaum* [1968].

In South America, *de Godoy* [1959] has shown by marking experiments that the commercially important *Prochilodus scrofa* migrate very long distances (>400 km) up the rivers of southern Brazil and return to their original river at comparable times each year. The valuable *Salminus* migrate upriver in Argentina and Brazil [*Ringuelet et al.*, 1967], and many other species make spawning runs upstream (references given by *Lowe-McConnell* [1969]). In Africa, *Bell-Cross* [1960] has shown that indigenous freshwater fishes, even *Tilapia* and nonbreeding fishes, move upstream and downstream more than was formerly believed. In India, some major carps run upriver to their spawning grounds. Some very large Mekong species are reputed to move long distances upstream and downstream [*Smith*, 1945].

The question of the need for fish passes on tropical rivers has perhaps been too easily dismissed in the past. However, where there is a whole series of impoundments, fish passes may become obsolete for some species. They appear to have become obsolete to some extent on the Volga, where the sturgeon can no longer find spawning grounds above the Volgograd Dam and so induced spawning and hatchery rearing is needed [*Vovk*, 1968].

Effects of impoundments on fisheries in other parts of the river system and in the estuaries and neighboring sea. From the case histories and papers in this section we have already seen examples of effects from impoundments downstream of a dam. Thus, below the Kainji Dam, catches have fallen to about half their former value in the River Niger and its associated swamps for a considerable distance. The change from annual flooding to short-term irregular water level fluctuations seems to be the potent factor here.

In the River Niger in areas upstream of the dam (the French-speaking territories of Dahomey and Niger), catches have also declined (R. L. Welcomme, verbal communication, 1971), but the decline seems to be a reflection of the fishing effort. Fishermen no longer migrate north as they used to do from March to October to tap these stretches while water was receding from the floodplain. Some of these fishermen are perhaps fishing in the new lake, but the imposition of controls on fish imported from the French-speaking territories into Nigeria and Ghana has apparently affected fish sales and lessened the incentive to fish further upriver. There seems to be a case here for treating fishery development on a regional basis.

Petr [1969] noted that migratory species disappeared from Volta Lake in later years. These presumably went upstream and did not return, but we know little about the changes in fish populations above the dam. Controls on fish imports from the north may also have obscured the situation here. Downstream of Volta Lake the oyster fishery has apparently diminished.

Jackson [1961] suggested that Lake Kariba might improve the fisheries below the lake by turning this stretch of the Zambezi into a 'reservoir' type of river with regulated flow rather than a 'sandbank' type of river with greatly reduced flow in the dry season. The effects of the discharges from Lake Kariba, which are 'ecologically speaking wrongly timed,' on the wildlife below the dam have been considered, but there appears to be no published information about the effects on the fish.

The effects of dams on the fisheries downstream of them are considered for the Mekong and mentioned for Lake Nasser in this section. We need a great deal more information on the effects of dams on other fisheries in the river systems and neighboring seas.

STATE OF THE ART CONCLUSIONS

1. The development of a fishery in a new reservoir has in most instances been regarded as an 'optional extra.' The world demands for increased protein and also for increased sport fishing mean that the potential of a reservoir for fishery development now needs to be taken seriously. Furthermore, recent experience in Thailand has shown that sometimes the value of a reservoir fishery can almost equal that of the hydroelectric power produced.

2. It is therefore essential to learn how to manage reservoir fisheries to give maximum sustained yields of desired species and to ensure that damming the river does not affect already existing fisheries in the river system, both upstream and downstream of the new lake, and in the estuaries and neighboring sea.

3. To achieve these ends, fishery biologists need to be included in planning teams from an early stage and to work closely with the engineers and others concerned with the project. Biological problems involve so many variables that getting answers to them generally takes longer than finding answers to engineering questions does, and so biological surveys must be started in good time if they are to provide reliable indications of fish production. Two years of planning followed by 3 years for a feasibility survey are now considered advisable in the United States [*Stroud*, 1966]. Cooperation between biologists and engineers is needed for fish pass design, for practical points such as the advisability of constructing the lake outlet below the future thermocline to draw off hypolimnion water, and for determining the amount of bush clearing that is desirable.

4. After the completion of the dam, continued monitoring of fish populations is essential for sound management, and fishery biologists must continue to work in close cooperation with those responsible for water levels because water level adjustment can be a powerful management tool. Computer studies can now speed up prediction processes.

5. The yield of fish also depends on planning the fishery well in advance, including biological measures to build up populations of desirable fish species, clearing the bottom for use of suitable gear to catch them, and well-organized transport and marketing, which are vital to commercial fishery development in remote areas.

6. The papers in this section have shown that each new impoundment needs a preimpoundment and postimpoundment survey and continued monitoring. Basic research into fish biology at all stages of life history is needed. Information should be collected and made available as soon as possible to allow more accurate predictions for other new impoundments. Information banks are particularly important for tropical reservoirs, where relatively little information is as yet available. Management techniques worked out for temperate lakes may have to be altered considerably for application to tropical waters, since changes occur so much faster there. The complex communities and the difficulty of determining the ages and growth rates of the fishes call for new methods of stock assessment to be developed in tropical waters.

7. Where suitable fish are lacking in the fauna, introductions can make a big contribution to fishery development. It is, however, first necessary to determine the capabilities of local species. It is essential to make very thorough studies of the limnological conditions and to know the biology of the proposed fish very well before attempting an introduction. Introductions often lead to extinctions of local species. Also, it is very important to introduce the best possible fish. Once fish are introduced, they generally prove impossible to eradicate and may spread through a wide area with the aid of man-made canals and lakes. The young of many tropical species live together and may be very difficult to distinguish. Expert care is needed to ensure that only the desired species is in fact in-

troduced. It is very important that reliable records be kept of all introductions.

8. We need more information about the upstream and downstream migrations of tropical species and the economics of the fisheries and potential fisheries for them. When large rivers with rich faunas, such as the Mekong and South American rivers, come to be dammed, fish passes may be advisable. In temperate waters (where salmonids are important), fish passes can pay for their construction very quickly. We also need to know the reproductive biology of such fishes to enable induced spawning and hatchery rearing to be used, if they become necessary.

9. Fishes do change their food spectra in impoundments, whether it be salmonids in Wales or fishes changing to a new food source in *Povilla* in Volta Lake. Foods used are affected both by foods available and by other fish species present.

10. Water level fluctuations affect both food resources and reproductive biology by direct effects on fish physiology and by indirect effects on the habitat. Tropical fishes are likely to be even more sensitive to water level fluctuations than temperate fishes are. Fishes with buoyant eggs will be less affected than littoral zone spawners will be.

11. Eutrophication is an increasing problem. Game fish, such as salmonids, give way to rough (coarse) fish, such as pike or perch, unless preventive steps are taken. The use of waste waters at South Lake Tahoe shows what can be done provided that there is a will to do it and expense is not spared.

In brief, a great deal of basic information about fish ecology is still needed, especially in the tropics where fish populations are as yet hardly monitored. Experience already gained could be used more fully to help plans for new lakes.

REFERENCES

Beauchamp, R. S. A., Utilizing the natural resources of L. Victoria for the benefit of fisheries and agriculture, *Nature London, 181*, 1634–1636, 1958.

Begg, G. W., Observations on the water quality and nature of the affluent rivers of Lake Kariba with reference to their biological significance, *Limnol. Soc. S. Afr. Newslett., 13*, suppl., 26–33, 1969.

Bell-Cross, G., Observations on the movements of fish in a fish ladder in Northern Rhodesia, *Publ. 63*, pp. 113–125, Cons. Sci. pour Afr. au Sud du Sahara, Comm. de Coop. Tech. en Afr. au Sud du Sahara, Publ. Bur., London, 1960.

Benson, N. G., Review of fishery studies on Missouri River main stem reservoirs, *Res. Rep. 71*, 61 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1968.

Bhatnagar, G. K., Observations on the spawning frequency and fecundity of certain Bhakra Reservoir fishes, *Indian J. Fish., 11*, 485–502, 1964.

Bhimachar, B. S., The problem of fish seed in relation to productivity in reservoirs (abstract), *Advan. Abstr. Contrib. Fish. Aquatic Sci. India, 4*(1), 22, 1970.

Bowmaker, A. P., A prospect of L. Kariba, *Optima, 29*(2), 68–74, 1970.

Bowmaker, A. P., Potamodromesis in the Mwenda River, Lake Kariba, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Burmakin, E. A., The chemical methods of lake rehabilitation and propagation of new fish fauna in lakes, *TA 2547*, pp. 109–123, Food and Agr. Organ., Rome, 1968.

David, A., Observations on some spawning grounds of the Gangetic major carps with a note on carp seed resources in India, *Indian J. Fish., 6*, 327–341, 1959.

David, A., and K. Gopinathan, Reservoir resources in India (abstract), *Advan. Abstr. Contrib. Fish. Aquatic Sci. India, 4*(1), 38, 1970.

de Godoy, M. P., The age, growth, sexual maturity, behavior, migration, tagging and transplantation of the curimbata (*Prochilodus scrofa* Stdr, 1881) of the Mogi-Guassu River, Sao Paulo State, Brazil, *Ann. Acad. Brasil. Cienc., 31*, 447–478, 1959.

Dzyuban, N. A., Reservoirs as a zoogeographic factor, in *Proceedings of the Zonal Conference on Water Bodies of the South of the U.S.S.R.* (in Russian), pp. 105–110, Kishinev, 1962.

Eicher, G. J., Fish passage, in *A Century of Fisheries in North America, Spec. Publ.*, vol. 7, edited by N. G. Benson, pp. 163–171, American Fisheries Society, Washington, D. C., 1970.

Food and Agriculture Organization, First and second group fellowship study tours on inland fisheries research, management and fish culture in the U.S.S.R., *TA 2547*, 183 pp., Rome, 1968.

Gibb, O., and J. Corlett, Estuarial storage in the United Kingdom: Morecambe Bay, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Hickling, C. H., *Tropical Inland Fisheries*, Longmans, Green, Toronto, Ont., 1961.

Hickling, C. H., Biological control of aquatic vegetation, *Pestic. Abstr. News Sum., 11*(3), 237–244, 1965.

Holčík, J., Standing crop, abundance, production and some ecological aspects of fish populations in some inland waters of Cuba, *Vestn. Cesk. Spolecnosti Zool., 34*(3), 184–201, 1970*a*.

Holčík, J., Discovery of the Chinese grass carp—*Ctenopharyngodon idella* (Valenciennes, 1844) in the Morava River, Czechoslovakia, *Vestn. Cesk. Spolecnosti Zool., 33*(4), 334–336, 1970*b*.

Holčík, J., and O. Par, First record of the silver carp—*Hypophthalmichthys molitrix* (Valenciennes,

1884) in the Danube River, *Vestn. Cesk. Spolecnosti Zool.*, *34*(2), 107–109, 1970.

Holden, M. J., Problems in forecasting sustainable yields from man-made lakes, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 190–194, Ghana Universities Press, Accra, 1969.

Holt, S. J., The contribution of freshwater fish production to human nutrition and well-being, in *The Biological Basis of Freshwater Fish Production*, edited by S. D. Gerking, pp. 455–467, Blackwell, Oxford, 1967.

Jackson, P. B. N., Ecological effects of flooding by the Kariba Dam upon middle Zambezi fishes, *Proc. Fed. Sci. Congr. 1st*, 277–284, 1960.

Jackson, P. B. N., Ichthyology, The fish of the middle Zambezi, in *Kariba Studies*, pp. 1–36, Manchester University Press, Manchester, Eng., 1961.

Jenkins, R. M., Reservoir fishery research strategy and tactics, *Circ. 196*, 12 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1964.

Jenkins, R. M., Bibliography on reservoir fishery biology in North America, *Res. Rep. 68,* 57 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1965.

Jenkins, R. M., The influence of some environmental factors on standing crop and harvest of fishes in U.S. reservoirs, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, Jr., pp. 298–321, American Fisheries Society, Washington, D. C., 1968*a*.

Jenkins, R. M., National reservoir research program, Progress Sport Fisheries Research, 1967, *Resour. Publ. 64,* pp. 135–139, U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1968*b*.

Jenkins, R. M., Reservoir fish management, in *A Century of Fisheries in North America, Spec. Publ.*, vol. 7, edited by N. G. Benson, pp. 173–182, American Fisheries Society, Washington, D. C., 1970.

Jhingran, V. G., and S. D. Tripathi, A review of the measures adopted for the development of the fisheries of reservoirs in India (abstract), *Advan. Abstr. Contrib. Fish. Aquatic Sci. India,* *4*(1), 39, 1970.

Jones, S., Destruction of fish in reservoirs by man (abstract), *Advan. Abstr. Contrib. Fish. Aquatic Sci. India,* *4*(1), 28, 1970.

Kalitsi, E. A. K., Volta Lake in relation to the human population and some issues in economics and management, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Konar, S. K., Use of chemical control in freshwater fishery reservoir management (abstract), *Advan. Abstr. Contrib. Fish. Aquatic Sci. India,* 1970.

Konradt, A. G., Introduction of plant-eating fish into the fish fauna of the European part of the USSR and means of reproducing them, *TA 2547,* pp. 58–67, Food and Agr. Organ., Rome, 1968.

Lachner, E. A., C. R. Robins, and W. R. Courtenay, Jr., Exotic fishes and other aquatic organisms introduced into North America, *Smithson. Contrib. Zool.*, *59*, 1–29, 1970.

Lapitsky, I. I., Development of fishery and ways of raising fish productivity of big reservoirs, *TA 2547*, pp. 124–134, Food and Agr. Organ., Rome, 1968.

Leentvaar, P., The artificial Brokopondo Lake in the Suriname River, Its biological implications, in *Atas Sympósio Biota Amazônica*, vol. 3, *Limnologia*, pp. 127–140, Conselho Nacional de Pesquisas, Rio de Janeiro, 1967.

Lowe-McConnell, R. H., Speciation in tropical freshwater fishes, *Biol. J. Linn. Soc. 1*, 51–75, 1969.

Melnikov, G. B., The question of classification of reservoirs in the USSR, in *Proceedings of the Zonal Conference on Water Bodies of the South of the U.S.S.R.* (in Russian), pp. 155–160, Kishinev, 1962.

Miller, R. R., Man and the changing fish fauna of the American southwest, *Pap. Mich. Acad. Sci. Arts Lett.*, *46*, 365–404, 1961.

Nair, K. K., A preliminary bibliography of the grass carp *Ctenopharyngodon idella* Valenciennes, *FRi/302*, pp. 1–15, Food and Agr. Organ., Rome, 1968.

Nusenbaum, L. M., Fish passage and fish protection facilities—Biological and technical aspects, *TA 2547*, pp. 89–108, Food and Agr. Organ., Rome, 1968.

Petr, T., Fish population changes in the Volta Lake over the period January 1965–September 1966, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 220–237, Ghana Universities Press, Accra, 1969.

Petr, T., Lake Volta—A progress report, *New Sci.*, *49*(736), 178–182, 1971.

Pirozhnikov, P. L., and M. P. Miroschneichenko, Shaping the hydrobiological conditions for large reservoirs, *TA 2547,* pp. 66–78, Food and Agr. Organ., Rome, 1968.

Qasim, S. Z., and A. Qayyum, Spawning frequencies and breeding seasons of some freshwater fishes with special reference to those occurring in the plains of northern India, *Indian J. Fish.*, *8,* 24–43, 1961.

Ringuelet, R. A., R. H. Aramburu, and A. Alonso de Aramburu, *Los peces Argentinos de agua dulce*, Comision de Investigacion Cientifica, Buenos Aires, 1967

Roundsell, G. A., Fish production in lakes as a guide for estimating production in reservoirs, *Copeia*, *1*, 29–40, 1946.

Ryder, R. A., A method for estimating the potential fish production of north-temperate lakes, *Trans. Amer. Fish. Soc.*, *94,* 214–218, 1965.

Smith, H. M., The freshwater fishes of Siam, or Thailand, *Smithson. Inst. Bull. 188*, 1–622, 1945.

Sreenivasan, A., Limnology of tropical impoundments: A comparative study of the major reservoirs of Tamil Nadu (abstract), *Advan. Abstr. Contrib. Fish. Aquatic Sci. India,* 15, 1970.

Stroud, R. H., Comments on the symposium in the light of the biology of the U. S. reservoirs, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 205–208, Academic, London, 1966.

Stroud, R. H., Future of fisheries management in North America, in *A Century of Fisheries in North America, Spec. Publ.*, vol. 7, edited by N. G. Benson, pp. 291–308, American Fisheries Society, Washington, D. C., 1970.

Toots, H., Exotic fishes in Rhodesia, *Limnol. Soc. S. Afr. Newslett.*, suppl., *13*, 70–82, 1969.

Vaas, K. F., Annual report of the Division Delta-

Research of the Hydrobiological Institute of the Royal Netherlands' Academy of Sciences for the year 1967, *Neth. J. Sea Res.*, *4*(2), 268–281, 1968.

Vaas, K. F., and M. Sachlan, Notes on fisheries exploitation of the artificial Tjiburuj in west Java, *Contrib. 128*, pp. 1–22, Gen. Agr. Res. Sta., Bogor, Indones., 1952.

Vaas, K. F., and J. J. Schuurman, On the ecology and fisheries of some Javanese freshwaters, *Comm. 97*, pp. 1–60, Gen. Agr. Res. Sta., Buitenzorg, Java, 1949.

van der Lingen, M. I., Lake Kariba: Early history and south shore, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Villwock, W., Gefahren für die endemische Fischfauna durch Einbürgerungsversuche und Akklimatisation von Fremdfischen am Beispiel des Titicaca Sees (Peru-Bolivien) und des Lanao Sees (Mindanao-Philippinen), *Verh. Int. Ver. Theor. Angew. Limnol.*, *18*(2), 1227–1234, 1972.

Vovk, F. I., The biological basis of reproduction of migratory fish when the river is controlled, *TA 2547*, pp. 152–160, Food and Agr. Organ., Rome, 1968.

Welcomme, R. L., An evaluation of the acadja method of fishing as practiced in the coastal lagoons of Dahomey (west Africa), *J. Fish Biol.*, *4*, 39–55, 1972.

Ecological Comparison of the Preimpoundment and Postimpoundment Fish Faunas of the River Niger and Kainji Lake, Nigeria

A. LELEK AND S. EL-ZARKA

UNDP/FAO Kainji Lake Research Project, Lagos, Nigeria

The impacts of impoundment have been studied widely throughout the temperate zone; in the tropics, however, much less study effort has been made. The present investigation deals with the River Niger and the new lake above Kainji Dam (for maps, see *El-Zarka* [this volume] and *Lelek* [1973]).

METHODS EMPLOYED

Gill net catches of a graded fleet of multifilament nets of 5.08, 6.35, 7.62, 8.89, 10.16, 12.70, and 17.78 cm (stretched mesh) set both on the surface and on the bottom were the main source of information concerning fish occurrence. Each net was 30 meters long and 3 meters deep. Other sampling gear were also used: light attraction with gasoline lanterns, floating 100-watt electric bulbs, and electrofishing with direct current operating at 600 watts and 1.5–2.6 A with a pulse rate of 120/sec. Inshore stations were fished with electricity twice for 2 min at each visit. In addition to the gear above, cast nets with a mesh size of 12.7 mm (stretched mesh) and baited longlines with no. 7 and no. 9 hooks were used. Differences in catch over time disclose the changes of the fish population and were based mostly on 18 collection stations distributed throughout the lake. Catches were recorded by weight and by fish families and/or groups of economically important species.

Downstream, collections were made at three evenly distributed stations at Jebba, Pategi, and Lokoja. Since the number of fishing days differed from 12 to 27 during the various months of the study, the catch is expressed in kilograms per unit of effort for comparative purposes. The catch computed for 20 days in 1 month is considered the unit of effort at all three stations.

AREA UNDER EXAMINATION

The area surrounding the lake has been classified as northern Guinea savanna [*Keay*, 1965]; however, closer observation of the Niger Valley [*Clayton*, 1957] reveals that part of the Kainji Lake area vegetation can be considered sub-Sudan savanna. Northern Guinea savanna applies to the southern part of the lake from the western bank almost up to Shagunu across now submerged Foge Island to the eastern bank opposite the upper peak of Foge Island. The sub-Sudan savanna extends northward from the line described above.

The fishing grounds of indigenous fishermen below the dam differed by region. In the Pategi area, most of the fishery was in the swamps, and only a little was on the floodplains and in the river itself. At Jebba the river itself was the fishery, only a small percent of the catch coming from the swamps. Around Lokoja the fishery depended mostly on the river but also significantly on the swamps, and it was influenced by the tributary River Benue.

CHANGES OF THE FISH FAUNA IN THE LAKE

Knowledge of the process of change of fish population starts with preimpoundment studies. One of these studies [*Banks et al.*, 1965] was in the river near Shagunu, where the lake now attains its greatest width. Here, the most abundant fish families were the Citharinidae and Mochokidae, followed by the Mormyridae and Schilbeidae. Cichlids composed only 4% of the catches by numbers. Another preimpoundment survey took place in rocky stretches of the cutoff channel of the River Niger in 1966 near the damsite [*Motwani and Kanwai*, 1970]. Here, the species composition was much different from that at Shagunu. The Characidae were the most abundant group, followed by the Mormyridae, Mochokidae, and Schilbeidae; cichlids were not recorded at all. In spite of physical differences between the two stations the fish composition is comparable to that of recent collections in the most northern part of the lake. There, riverine conditions prevail throughout the year, most markedly so during the drawdown period. The Citharinidae were most abundant, and the Mochokidae and Characidae were almost as abundant as the Mormyridae. The cichlids were scarce and composed only 3% of the catch. The fish occurrence in the lake was much different with the exception of the two upstream stations. The Citharinidae were the most common, followed by the Characidae, Centropomidae, and Mochokidae. Although the Mormyridae and Cichlidae were formerly important and abundant in the river, they composed only 1% of the lake samples; the cichlids continued to be scarce, also at 1%.

Both important and interesting is the ratio of predators to other fish species. Before impoundment the predators composed only 4.5–5.0% by numbers and 15–17% by weight of the catches from the River Niger. After impoundment the ratio of predatory to nonpredatory fish increased considerably to 18–31% by weight.

Until fish sampling with light attraction began, it was not fully clear which of the forage fishes was maintaining the high population of predators. Light attraction combined with a small mesh dip net revealed the small clupeids *Sierrathrissa leonensis* and *Pellonula afzeliusi*. *S. leonensis* was recorded by *Daget and Bayagbona* [1961], probably as *Potamothrissa miri*. *P. afzeliusi* was common in the open water of the lake. Subsequent electrofishing proved *Sierrathrissa* to be lake-wide in its distribution, even in shallow (<1 meter deep) areas, except where floating aquatic vegetation was present. Food habit studies revealed that the small clupeids were eaten by almost all carnivorous fishes, particularly by the tiger fish, *Hydrocynus* (Dr. D. Lewis, personal communication, 1971).

The explosive rise of predatory fish populations in Kainji Lake followed the generally known pattern of such populations in both temperate and tropical man-made lakes. For example, in the temperate zone, *Domanevsky* [1962] found the pike, *Esox lucius*, to make up 43% of the catch by numbers and 55% by weight in the first year of a new impoundment (Cimljansk Lake), and *Sharonov* [1962] described the highest level of pike in commercial catches from the Kujbyshev Lake as 64.3% by weight. In the tropics, *Harding* [1964] described a marked increase of *Hydrocynus* in Lake Kariba during the first years after impoundment. Data given by *Petr* [1968] for Volta Lake indicate the substantial occurrence of predators (*Hydrocynus* and *Lates*) in the central parts of the lake, where they composed 20–38% of the catch in the first year of impoundment. Later, *Petr* [1969] found that 2.5 years after the initial filling of the lake the percent occurrence of the predators reached almost 50% in the southern part of the lake (Ampem). The data from Volta Lake correspond roughly with those from Kainji Lake, particularly in indicating that in the uppermost parts of both lakes, where there are still to some extent lotic conditions, the occurrence of predators is much lower than it is in the lake itself. As for Lake Kariba, there is also a similarity in the increase of predators. When preimpoundment data [*Jackson*, 1961] are compared with data collected 2 years later, a 17% increase of predators was observed.

In spite of an early abundance the future of predatory fishes such as *Hydrocynus* is uncertain. The future of the most desired and appreciated species, *Lates niloticus*, is perhaps better than that of *Hydrocynus*, since it is a pelagic spawner [*Hopson*, 1968]. Furthermore, the future of the key prey organisms, *Sierrathrissa* and *Pellonula*, is also uncertain, as it is in Lake Tanganyika [*Coulter*, 1970].

From the beginning of our observations, *Citharinus* species were the most common in both experimental and commercial catches. *Citharinus citharus* and *C. distichodoides* were common in the river before impoundment. The rising waters of the River Niger in September 1968, i.e., at the end of the rainy season, enabled the spawn of the year to survive in continuously improving conditions of food and shelter. In addition, flooded organic material provided an almost unlimited food supply for these species, which are adapted for feeding on organic detritus [*Bakare*, 1970; *Imevbore and Bakare*, 1970]. The second generation of *Citharinus* species, which originated after the first rise of the lake (in 1969), is much less abundant in comparison to the generation spawned in 1968. Thus it seems unlikely that Kainji will continue to be dominated by citharinids [*Lelek*, 1970].

Cichlids, in spite of their negligible position in gill net catches in the early history of Kainji Lake, cannot be ruled out as being potentially of economic importance, since they are desired highly by consumers. Observations in cleared areas near the damsite indicated a rapid increase in the occurrence of cichlids, particularly those of the genus *Tilapia* (Table 1). In addition, *Tilapia* *galilaea*, the mouth brooder, composed 40–70% of the shoreline catches by numbers. Theoretically, the littoral zone pattern of reproduction of this fish may be advantageous in habitats lacking established aquatic vegetation. *Hemichromis* and sometimes *H. fasciatus* made up as much as 25% of the shoreline catches by numbers. With the slow but progressive stabilization of the littoral zone in the lake as well as the growing occurrence of clusters of floating vegetation in some parts of the lake, shelter and feeding grounds for cichlids are improving. The importance of floating vegetation for cichlids in early stages of Volta Lake is well documented [*Ewer*, 1966], as it also is in Lake Victoria, where the rapid extension of the littoral zone following the raised water level resulted in increased catches of *Tilapia* [*Welcomme*, 1969].

Shoreline sampling at the 20 stations also showed cichlids to be widespread. They were found at all stations except three where the banks are almost vegetation free and the shore is barren and wave washed. In places with established rooted aquatic vegetation and/or floating vegetation, cichlids composed up to 81.5% of the catches. At eight of the remaining stations, cichlids made up >15% of the catch, and at the last eight stations the cichlids were <15% by numbers. By weight, cichlids reached a maximum 92.9% of the catch. At six stations they composed >15%, and at the 10 remaining stations they were <15% of the catch.

The most abundant families summarized for the whole lake are the Characidae, followed by the Clupeidae, Cichlidae, Cyprinidae, and so on by numbers caught. The most abundant by weight are the Characidae, followed by Cichlidae, Citharinidae, Clupeidae, and Cyprinidae (Table 2).

FACTORS OF DISTRIBUTION OF FISH

Up to the present (1971), some 90 taxa have been recorded from the lake. Although Kainji Lake is not very large (only 1270 km^2), it exhibits a rather distinct variety of characteristics and habitats. Some of the most important characteristics include: (1) the replacement of the water volume 4 times in 1 year, (2) the wide fluctuations of water level, the high level in November–March dropping about 10 meters to the low level in July–August, and (3) the division of the lake into three natural basins, the uppermost being strongly under the influence of inflowing mainstream water, the middle basin consisting of shallow water that covers the largest central part of the lake, submerged Foge Island, and the lowest basin being narrowest and deepest of all. In addition, two different types of River Niger water fill the lake. In September–October the white flood originates in the area surrounding the lake as a result of the local rainy season, and in February–March the receding white flood is succeeded by the black flood. The black flood originates in upstream catchment areas in Guinea and the Ivory Coast some months before it arrives at Kainji Lake via the River Niger.

TABLE 1. Percent Occurrence of Fish Families in Samples along the Cleared Shoreline of Kainji Lake

Families	1968	June 1969	August 1969	1970
Characidae	88	40	37	21
Cichlidae	9	22	38	79
Citharinidae	2	3	...	...
Cyprinidae	1	31	21	...
Other families	...	4	4	...

For the present, there is not enough information to explain or predict completely the distribution of the fishes. However, four different distributional zones seem discernible. Zone 1 is under the influence of inflowing water, lotic conditions being dominant throughout the year. Zone 2 consists of the deep areas over or near the drowned river channel, depths being 15 meters and more. Zone 3 consists of the cleared areas of the central part of the lake, depths not exceeding 15 meters. Zone 4 is the bottom formed by the

TABLE 2. Percent Occurrence by Numbers of Individuals and by Weight of Fish Families along the Shoreline of Kainji Lake Based on Samples from 20 Stations from October 12 to October 14, 1970

Families	Percent in Catch: By Numbers	Percent in Catch: By Weight, grams	Mean Weight per Individual, grams
Characidae	27.5	61.8	4.73
Cichlidae	10.3	18.9	3.85
Citharinidae	0.1	11.1	399.5
Cyprinidae	3.8	2.7	1.51
Clupeidae	17.8	3.6	0.13
Bagridae	0.4	1.8	10.9
Other families	0.1	0.1	0.4

former bush, which is now submerged, depths not exceeding 15 meters.

The abundance of fish in the four zones (Table 3) expressed as catch per unit of effort (i.e., standard fleet of gill nets set overnight) varied as follows: zone 1 was the least inhabited at 14.6 kg, zone 2 was only slightly more so at 18.5 kg, zone 3 was next highest at 24.6 kg, and zone 4 was highest at 30.3 kg.

The occurrence of species varied significantly in different zones. In zone 4 (submerged bush) the herbivores, periphyton, and detritus eaters composed 60% of the catches by weight. Slightly lower was the occurrence of primary consumers in zone 3 (shallow cleared areas), where they composed 56% by weight. In contrast to the shallow areas (i.e., zones 3 and 4), in the deepwater zone 2 the group of primary consumers was at minimum, composing only 6% by weight. In zone 1 (lotic conditions) the fish occurrence corresponded almost with the preimpoundment condition except for the Mormyridae; there, the primary consumers composed 19%, and the secondary consumers composed 59% by weight, the secondary consumers being almost the same by percent as those in zone 2 (deep water). The secondary consumers in zones 1 and 2 made up 59% and 60%, respectively, of the catch in contrast to those in zones 3 and 4 (shallow areas), which composed only 10% and 9%, respectively. Tertiary consumers occurred in zones 2, 3, and 4 in almost the same relative amounts, 31%, 29%, and 28% by weight. In the lotic conditions of zone 1, however, the predators composed only 18% by weight.

CHANGING FISHERIES BELOW THE DAM

Although each of the three study stations downstream from the dam had different habitats and markedly different fisheries, the rate of water level fluctuation affected all of them but most expressively the station nearest Kainji Dam.

The average water level measured daily at Jebba revealed that the River Niger had consistent

TABLE 3. Occurrence and Trophic Classification of Most Important Fish in Kainji Lake (by Percent of Weight) in Different Zones Based on Gill Net Catches in 1969

Major Food Preferences	Genera and Species	Percent Occurrence by Weight in Habitat Zones 1	2	3	4
Primary consumers					
Herbivores	*Alestes macrolepidotus* *Distichodus* spp. *Synodontis schall*	1	...	2	7
Periphyton	*Labeo* spp. *Synodontis* spp.	4	...	2	8
Detritus	*Citharinus* spp. *Labeo* spp. *Auchenoglanis* spp.	14	6	52	45
Secondary consumers					
Zooplankton	*Schilbe mystus* *Eutropius niloticus* *Chrysichthys* spp. *Alestes dentex* *Alestes baremose* *Alestes nurse* *Heterotis niloticus* *Synodontis membranaceous* *Synodontis resupinatus* *Synodontis sorex*	59	60	10	9
Tertiary consumers					
Carnivores	*Lates niloticus* *Hydrocynus* spp. *Bagrus* spp. *Clarias lazera* *Heterobranchus* spp.	18	31	29	28
Unknown or dubious	rare species and those with little known food habits	4	3	5	2

and predictable yearly flow patterns with two annual peaks as described previously. From the ecological point of view the most significant factor of these changes of water level is the regular and smooth decrease after both the white and the black floods. The fishes, particularly after the white flood, can follow the retreating water back into the mainstream with little loss through standing. The following movements of the fishes were described as 'local' or 'lateral' migrations by *Svenson* [1933] and were confirmed by *Wellman* [1948] and later by *Reed et al.* [1967] and others.

The River Niger water level fluctuation in 1968 at Jebba followed the historic pattern until the middle of July. From then on, however, sharp changes in water level occurred every month due to engineering and mechanical tests related to dam construction. The stability of the water level did not improve in 1969. Quite often the amplitude between maximum and minimum levels exceeded 0.9–1.2 meters or more within 2- to 3-day intervals. This unpredictable and continuous change of water level had definite effects on the natural reproduction of the fishes [*Lelek and El-Zarka*, 1973].

DOWNSTREAM RIVERINE FISH CATCH

The landing of fresh fish in the downstream riverine fishery changed in 1967–1969. At Jebba the catches decreased as follows: from 19.6 metric tons in 1967 to 17.2 metric tons in 1968 to 12.2 metric tons in 1969. At the Pategi station the decline was greater over the same years: from 27.9 metric tons in 1967 to 21.0 metric tons in 1968 to 10.9 metric tons in 1969. At Lokoja the fluctuation of catch was not so sharp perhaps owing to the ameliorating action of the River Benue on both the riverine and the swamp fisheries there. The catches were 60.2 metric tons in 1967, 80.4 metric tons in 1968, and 78.0 metric tons in 1969.

COMPOSITION OF THE DOWNSTREAM RIVERINE CATCH

Although the weight of the catch dropped considerably at the two downstream study stations nearest the dam after the river was harnessed, none of the commercially important fish groups disappeared completely from the catch. However, some of the families were more sensitive than others to the changes in the water regime.

The group most affected was the Mormyridae. At Jebba in 1967, 1968, and 1969 this family composed, respectively, 6.5, 3.1, and 1.8% of the catch by weight. At Pategi and Lokoja the occurrence of the mormyrids after the changes in water discharge was insignificant. *Heterotis niloticus* became less frequent at both Jebba and Pategi in the landings from the second half of 1968 and those from 1969. The decline of the family Clariidae was observed only in the two upstream stations during the last 2 years. They were 4.2% in 1967, 2.4% in 1968, and 1.0% in 1969.

Lates niloticus, in contrast, increased in the catches of all stations. At Jebba it represented 22.1% of the catch in 1967, 28.8% in 1968, and 57.0% in 1969. At Pategi the catches of this species increased from 5.5% in 1967 to 13.4% in 1968 to 25.1% in 1969. Even at Lokoja, there was a slight increase of occurrence from 9.4% in 1967 to 9.8% in 1968 to 13.5% in 1969.

SUMMARY

The fish fauna in the River Niger responded rapidly to changes of the water regime during and following construction of Kainji Dam.

1. In the newly created lake the Mormyridae almost disappeared. In the first year, probably because of successful spawning during the filling of the lake, fishes of the genus *Citharinus* became the most important commercial species.
2. Predatory fishes increased in the lake because of the rise in the abundance of the small clupeids.
3. Although cichlids were not numerous in the former river, they were on the increase along the shore because of the slow but gradual buildup of the new littoral zone.
4. The distribution of fish in the lake is to some extent dependent on the structure of the bottom and the depths of the water. The lake is divisible into four different zones according to fish occurrence and abundance.
5. The fish species populations of the lake are far from being stabilized after only 2 years of lake history.
6. Downstream from the lake, there was an overall decline in fish catch upstream from the mouth of the River Benue.
7. The Mormyridae were sensitive to fluctuations of the water regime and nearly disappeared from the commercial catches in the two downstream stations nearest the dam.
8. Only the predatory *Lates niloticus* was observed to increase in catches downstream of the dam.

Acknowledgments. The authors wish to express their thanks to the Ministry of Natural Resources of Kwara State for their cooperation in the studies downstream from Kainji Dam. Also, our gratitude is extended to the many fishermen, and particularly to Mr. I. Yaro, for their enthusiastic help in the field. Special thanks go to Mr. P. Fregene, Niger Dams Authority hydrologist, for consultations and data on the water regime in the River Niger. For the determination of some fish species the authors are grateful to Dr. D. F. E. Thys Van den Audenaerde, Dr. P. H. Greenwood, and Mr. P. White. The valuable help of the above mentioned individuals and organizations and particularly of the United Nations Development Program, Food and Agriculture Organization is greatly appreciated. The views expressed in this paper are those of the authors and do not necessarily represent the views of the United Nations Development Program, Food and Agriculture Organization.

REFERENCES

Bakare, O., Bottom deposits as food for inland fresh water fish, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 65–85, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Banks, J. W., M. J. Holden, R. H. McConnell, Fishery report, in *The First Scientific Report of the Kainji Biological Research Team,* edited by E. White, pp. 21–42, University of Liverpool, Liverpool, Eng., 1965.

Clayton, W. D., Secondary vegetation and the transition to savanna near Ibadan, Nigeria, *J. Ecol., 46,* 217–238, 1957.

Coulter, C. W., Population changes within a group of fish species in Lake Tanganyika following their exploitation, *J. Fish. Biol., 2*(4), 329–353, 1970.

Daget, J., and M. E. Bayagbona, *Niger Dams Project,* vol. 8, pp. 1–14, Federal Government of Nigeria, Lagos, Nigeria, 1961.

Domanevsky, L. N., The influence of predators on the formation of Cimljansk man-made lake fish fauna, in *Proceedings of the Zonal Conference on Water Bodies of the South of the U.S.S.R.* (in Russian), pp. 279–284, Leningrad, 1962.

El-Zarka, S. E.-D., Kainji Lake, Nigeria, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.,* vol. 17, edited by W. D. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Ewer, D. W., Biological investigations of the Volta Lake, May 1964 to May 1965, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 21–30, Academic, London, 1966.

Harding, D., Hydrology and fisheries in Lake Kariba, *Verh. Int. Ver. Limnol., 15,* 139–149, 1964.

Hopson, A. J., A description of the pelagic embryos and larval stages of *Lates niloticus* (L.) (Pisces: Centropomidae) from the Lake Chad, with a review of early development in lower percoid fishes, *Zool. J. Linn. Soc., 48,* 117–134, 1968.

Imevbore, A. M. A., and O. Bakare, The food and feeding habits of non-cichlid fishes of the River Niger in the Kainji Reservoir area, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 49–64, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Jackson, P. B. N., Ichthyology, The fish of the middle Zambezi, in *Kariba Studies,* pp. 1–36, Manchester University Press, Manchester, Eng., 1961.

Keay, R. W. J., *An Outline of Nigerian Vegetation,* Government Printer, Lagos, Nigeria, 1965.

Lelek, A., Possible trends of the development of the fish fauna in the Kainji Lake, Nigeria, paper presented at Symposium on Ecology of Kainji Lake, Univ. of Ife, Ife, Nigeria, June 1970.

Lelek, A., Sequence of changes in fish populations of the new tropical man-made lake, Kainji, Nigeria, west Africa, *Arch. Hydrobiol., 71*(3), 381–420, 1973.

Lelek, A., and S. El-Zarka, Preliminary observation on the effect of Kainji Dam on the downstream fisheries, *West Afr. Sci. Ass., 16*(2), in press, 1973.

Motwani, M. P., and Y. Kanwai, Fish and fisheries of the coffer-dammed right channel of the River Niger at Kainji, in *Kainji, A Nigerian Man-Made Lake,* edited by S. A. Visser, pp. 27–48, Nigerian Institute of Social and Economic Research, Ibadan, Nigeria, 1970.

Petr, T., The establishment of lacustrine fish population in the Volta Lake in Ghana during 1964–1966, *Bull. Inst. Fondamental Afr. Noire, Ser. A, 30*(1), 257–269, 1968.

Petr, T., Fish population changes in the Volta Lake over the period January 1965–September 1966, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 220–237, Ghana Universities Press, Accra, 1969.

Reed, W., et al., *Fishes and Fisheries of Northern Nigeria,* Ministry of Agriculture, Zaria, Nigeria, 1967.

Sharonov, I. V., General notes about the formation of the ichthyofauna of the Kuibychev man-made lake, in *Proceedings of the Zonal Conference on Water Bodies of the South of the U.S.S.R.* (in Russian), pp. 397–404, Leningrad, 1962.

Svenson, G. S. O., Freshwater fishes from the Gambia River, *Kgl. Sv. Vetenskapsakad. Handl., 12*(3), 1933.

Welcomme, R. L., The effect of rapidly changing water level in Lake Victoria upon the commercial catches of *Tilapia* (Pisces: Cichlidae), in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 242–250, Ghana Universities Press, Accra, 1969.

Wellman, J. B., *Preliminary Survey of the Freshwater Fishes of Nigeria,* Government Printer, Lagos, Nigeria, 1948.

Catch of Fishes from Lake Nasser, Egypt, in the Early Years of Impoundment, 1966–1969

A. F. A. LATIF AND M. M. RASHID
Lake Nasser Development Center Project, Aswan, Egypt

Lake Nasser is a large reservoir in Egypt formed by the construction of the High Dam. The storage of water began with 637 km² in 1964 and grew to 2590 km² in 1969. By May 1970, there were 3484 fishermen. Over the years, cotton gill nets have been replaced by nylon nets. Fish collection and transportation facilities have been progressively augmented, and, as a result, fishermen have spread toward the remote southern parts of the lake.

SPECIES COMPOSITION OF THE CATCH

Seventeen kinds of fishes in six families have been most important in the early years of the Lake Nasser fishery (Table1).

The total catch has increased annually from 1966 to 1969 (Table 2), and there have been some changes in composition by family of fishes (Tables 3 and 4). Moreover, the quantities converted to salted fish amounted to >40% of the catch in the different years, the highest amount being recorded in 1966 (about 55% of the landed catch).

Tilapia nilotica has consistently been the most common species and constituted 60% or more of the commercial fresh fish landings in each of the 4 early years. Cyprinidae represented by *Labeo* spp. and *Barbus* spp. was second from 1967 to 1969.

The characins are the main fishes that are salted and have accounted annually for 60% or more of the salted fish, the cyprinids being second at about 25%. The other fishes that are salted include mainly *Schilbe* spp., mormyrids, and sometimes *T. nilotica, L. niloticus*, and other species. Among the silurids, *Bagrus* spp. has predominated over *Synodontis* and *Clarias* spp. Among the salted characins, *Alestes dentex* and *A.*

TABLE 1. Commercially Important Fish Species of Lake Nasser

Family	Vernacular Name	English Name	Latin Name
Cichlidae	bolti	Nile bolti	*Tilapia nilotica*
Cyprinidae	bynni	leatherfishes	*Barbus bynni*
	bynni	carp family	*Barbus perince*
	lebis	carp family	*Labeo niloticus*
	lebis	carp family	*Labeo forskali*
Siluridae	karmout	catfish	*Clarias lazera*
	karmout	catfish	*Heterobranchus bidorsalis*
	bayad	catfish	*Bagrus bayad*
	docmac	catfish	*Bagrus docmac*
	schilba	catfish	*Schilbe mystus*
	schilba	catfish	*Schilbe uranoscopus*
	schilba	catfish	*Eutropius niloticus*
	schall	catfish	*Synodontis schall*
	schall	catfish	*Synodontis serratus*
Centropomidae	samous or eshr bayad	Nile perch	*Lates niloticus*
Mormyridae	kannume	elephant fish	*Mormyrus kannume*
	saweya	elephant fish	*Marcusenius isidori*
Characinidae	kalb	tiger fish	*Hydrocynus forskalii*
	raya	tiger fish	*Alestes dentex*
	raya	tiger fish	*Alestes baremose*

TABLE 2. Commercial Fish Landings in Different Years for Lake Nasser

	Salted Fish in Terms of Fresh Fish		Fresh Fish			
Year	metric tons	%	metric tons	%	Total, metric tons	Progressive Increase, %
1966	420	55.0	344	45.0	764	100
1967	633	44.5	789	55.5	1422	186
1968	1163	50.1	1157	49.9	2320	305
1969	1839	40.5	2706	59.5	4545	595

baremose are the main species, and their contribution in the catch is much greater than that of *Hydrocynus* spp.

SEASONAL VARIATIONS IN CATCH

Fresh fish landings by month in 1966 were highest during August. However, the catch had two peaks, one in February–March and the other in August. The landings increased from January to February, remained the same in March, decreased gradually up to June, increased in July, and peaked in August. There was a gradual decrease from September through November. December showed somewhat higher fresh fish landings than November did. In the years 1967 and 1968, two similar catch peaks appeared in April and July. In 1969, there was a gradual increase in landings from January, a peak in March, and a gradual decrease from April to December. Landings of various kinds of fishes have also shown differences.

Tilapia nilotica. The landings of this species showed a trend that is nearly comparable to that of the total landings of the different months in various years. This similarity is rather expected since the catch of this species is dominant among the fresh fish species. It contributed about 60% or more of their landings in 1969.

Carps (Labeo spp. and Barbus spp.). After 1966 the landings of these cyprinids showed only a slight tendency to bimodality but more were caught in July–August of 1967–1969 than were caught in other months. Their landing was 5.5 metric tons in December 1966, which was 31% of the landing for the year.

Catfishes (silurids). The highest landings of the silurids in 1966, 1967, and 1969 were in July, whereas the highest landing in 1968 was in June. In general, there is a tendency for an increase in the landings from January toward the summer months matching the peaks in the above mentioned months, which are mostly followed by a decrease up to the end of the year.

Lates niloticus. The highest landings of this species took place in July of 1966, 1968, and 1969 and in April of 1967. For 1968 and 1969, there was a gradual increase from January to July,

TABLE 3. Fresh Fish Landings from Lake Nasser by Families

	1966		1967		1968		1969	
Family	metric tons	%	metric tons	%	metric tons	%	metric tons	%
Cichlidae	276.7	80.45	471.2	60.32	697.0	60.23	1851.9	68.45
Cyprinidae	18.0	5.19	149.7	19.18	241.2	20.84	386.6	14.25
Siluridae	44.5	12.93	131.7	16.87	142.9	12.34	169.9	6.28
Centropomidae	4.9	1.43	38.4	3.63	76.1	6.57	297.0	10.98

TABLE 4. Commercial Salted Fish Landings by Families

	1966		1967		1968		1969	
Family	metric tons	%	metric tons	%	metric tons	%	metric tons	%
Characidae	270.39	64.33	443.57	70.05	688.88	59.2	1175.37	63.92
Cyprinidae	126.23	30.00	171.45	27.10	447.59	38.5	582.20	31.66
Others*	23.72	5.65	18.05	2.80	26.43	2.3	81.29	4.42

*Mainly *Schilbe* spp.

which was followed by a gradual decline in the landings up to the end of the year.

CATCH IN THREE DIFFERENT SECTORS OF THE LAKE

The lake was divided into three sectors (1–3 from north to south), each sector having a large lagoon or khor, as it is called locally (Kalabsha khor, Al-Allaqi khor, and Toshka khor).

Fresh fish landings were highest in the northern sector, sector 2 being second and sector 3 being the lowest. The reverse is true for salted fish landings. The total commercial catches from sectors 1 and 2 have been nearly the same, but that of the third sector is highest mainly owing to the production of salted fish. Sectors 1 and 2, which are collectively less than half the length of the lake, contributed about 74% of the fresh fish, whereas sector 3 contributed about 71% of the salted fish. Such differences can be attributed to the fact that irregularities in transportation partly oblige the fishermen to salt their catch in sector 3. Moreover, most of the characins, which are largely salted, were taken in the southern part of the lake.

FISHING GROUNDS

The formation of Lake Nasser has resulted in the formation of many lagoons or khors, which vary greatly in area and depth. In general, the khors are fished most intensively toward their heads, which are usually shallow and calm and are apparently spawning concentration areas for species such as *Tilapia nilotica*. On this account the khors contribute the largest part of the commercial fish catch. For example, the total catch in sector 1 from October 1965 to September 1966 was 49.3 metric tons. Mariya khor contributed 38.5 metric tons or 78.09% of this amount. During the same period the total catch in sector 2 was 125.2 metric tons. Al-Allaqi khor contributed 81.5 metric tons or 65.09% of this amount.

TABLE 5. Total Fish Landings in Relation to Volume and Surface Area

Year	Approximate Volume of Lake, km^3	Approximate Surface Area of Lake, km^2	Landings per km^3, metric tons	Landings per km^2, metric tons
1966	17.72	1121.19	43.1	0.68
1967	31.99	1988.81	72.5	1.16
1969	53.48	2581.8	84.9	1.75

SUMMARY

The fish production of Lake Nasser has increased from 764 metric tons in 1966 to 4545 metric tons in 1969 in terms of fresh fish. The fishes are landed either fresh or salted.

There has been a progressive increase in commercial fish landings from the beginning of Lake Nasser in 1964 through 1969 (Table 5). The landings in 1969 per square kilometer were more than twice those in 1966, almost in proportion to the increase in surface area.

Tilapia nilotica, *Labeo* spp., *Bagrus* spp., *Clarias* spp., *Heterobranchus bidorsalis*, *Synodontis* spp., and *Lates niloticus* are the main species consumed as fresh fish. *Alestes* spp., *Hydrocynus* spp., *Labeo* spp., *Barbus bynni*, and *Schilbe* spp. are the main salted fishes.

Lagoons (khors) are the main fishing areas, and they are more productive than the deepwater areas are.

Fresh fish are produced mostly in the northern half of the lake, whereas salted fish are produced mostly in the southern half of the lake.

Fish landings generally increase from January onward reaching a peak in March–April for *Tilapia* and in June–August for cyprinids, silurids, and *Lates niloticus*. The monthly variation of the landings is highly significant.

Man-Made Lakes of Ceylon: A Biological Resource

C. H. FERNANDO

Department of Biology, University of Waterloo, Waterloo, Ontario, Canada

Ceylon is situated 6°–10°N of the equator and has an area of 70,000 km². It has a very varied climate from hot wet tropical to mild almost temperate. The maximum elevation is about 2300 meters, but much of the country is below 300 meters above sea level. The whole island is well supplied with rivers; 103 major rivers drain basins of varying sizes and flow radially from the central highlands or the northern plains. However, there are no natural lakes. Reservoirs for irrigation have been built from ancient times for rice cultivation, and about 10,000 of these exist today in various states of repair. Since the turn of this century, additional reservoirs have been built, and some ancient reservoirs have been repaired or enlarged. Reservoirs have also been built for hydroelectric power. The present reservoir area is about 125,000 ha. With the new multipurpose reservoirs planned this figure will increase to about 250,000 ha, an average of 3.5 ha of reservoir area for every square kilometer. The reservoirs are, however, concentrated in the dry zone (<200 cm of annual rainfall) (Figure 1).

Although the multipurpose nature of reservoirs for irrigation, flood control, hydroelectric power, and raising the water table has been recognized, hardly any attention has been paid to reservoirs as a biological resource. In fact, freshwater fisheries are not even mentioned by *Hickling* [1961] in his book on tropical inland fisheries. It might also be mentioned in passing that the recreational value of reservoirs has been neglected too. The accidental success of *Tilapia mossambica*, introduced into open waters in Ceylon in 1951, increased the negligible fish catch from only 400 metric tons annually in 1956 to 8000 metric tons in 1969 [*Fernando*, 1970]. This phenomenal increase has made for optimism as shown in a *Food and Agriculture Organization* [1968] estimate of a further twentyfold increase to 134,000 metric tons annually, a figure that is higher than the total marine and freshwater catch of the island now. In a series of papers I have analyzed some of the causes of the phenomenal increase in fish production [*Fernando*, 1965, 1970; *Fernando and Indrasena*, 1969]. This paper examines the reservoir complex in Ceylon as a source of freshwater fish in the future and discusses some measures that will possibly increase fish production on the basis of data available. Until now there has been little investment of money in developing freshwater fisheries in reservoirs. Also hardly any biological work either basic or applied has been done on reservoirs. I hope this presentation together with my previous papers will stimulate the investment of money in the research and management of this valuable source of cheap protein.

TYPES OF RESERVOIRS

Fernando and Indrasena [1969] tentatively divided the reservoirs of Ceylon into five types on the basis of their morphometry: (1) shallow and heavily silted with an even depth, (2) shallow with a gently sloping bottom, (3) shallow with undulating bottom contours, (4) deep and encompassing one valley, and (5) deep and encompassing several valleys. Small reservoirs (<300 ha) fall mostly in types 1 and 2. A high proportion of their area is littoral. Although morphometry is of considerable importance in fish production, many other factors, including elevation with its concomitant temperature regime, water chemistry, and fluctuation of water levels, must be considered.

The vast majority of reservoirs are at elevations below 300 meters. Those above 300 meters are usually hydroelectric reservoirs. At present, the total area of the small reservoirs is about one-half the total reservoir area, and it will be less than one-fourth the total area when all the proposed reservoirs are completed. About 10,000 small reservoirs exist in comparison with 51 large reservoirs completed and about another 90 planned (Figure 1). The areas, depths, and capacities of the large reservoirs (>300 ha) are given in Table 1. The fluctuations of water levels in some small and large

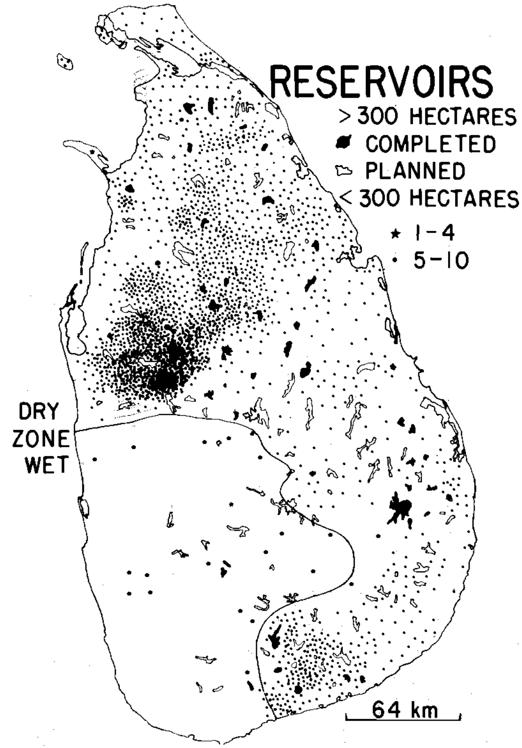


Fig. 1. Reservoirs in Ceylon from *Fernando* [1970].

reservoirs are shown in Figure 2. We know little about the water chemistry except that acidic waters predominate only in the wet zone [*Fernando and Indrasena*, 1969].

PRESENT FISH PRODUCTION

The total fish catch from freshwaters is about 8000 metric tons annually. By far the largest part of this comes from a few large low-country reservoirs. One reservoir, Parakrama Samudra (2262 ha), has had a catch of over 500 metric tons a year from 1961 to 1969. The fish catch in these reservoirs varies from 14–225 kg/ha/yr. In deep low-country reservoirs the catches are lower, 0–20 kg/ha/yr, whereas in deep up-country reservoirs the fish catches are negligible (Table 2).

The small reservoirs (<300 ha) in the low country are highly productive in fish, as is shown by a number of examples in Table 2, but these examples are all special. Beira Lake is a highly enriched lake unique in Ceylon for the level of 'pollution.' The other three reservoirs were stocked with *Tilapia mossambica* shortly after the monsoon rains [*Fernando and Ellepola*, 1969]. In general, small reservoirs of this type have a very low fish catch. *Fernando and Indrasena* [1969], however, noted a 'naturally stocked' small reservoir with a fishery.

The questions that must be raised are whether the fish production of these different types of reservoirs can be raised significantly and if so by what means. To answer these questions, I wish to deal first with some factors influencing fish production in reservoirs and then with measures to increase fish production.

SOME FACTORS INFLUENCING RESERVOIR FISH PRODUCTION

Ceylon has an indigenous fish fauna of only 54 species, a low number for a tropical island considering its size, closeness to the continental mass, and relatively recent separation (Miocene) from the Indian subcontinent, which has a rich and varied fish fauna [*Fernando*, 1970]. *Fernando and Indrasena* [1969] have shown that there are few large fish species and that the fauna, essentially a stream and marsh type, colonized the alien habitat of the reservoirs. These two things caused the low fish production, not the lack of herbivores as some previous workers [*Willey*, 1910; *Amirthalingam*, 1949; *Schuster*, 1951] have stated. These views were discussed by *Fernando* [1956], who argued that *Tilapia mossambica* was phenomenally successful because it was a 'lake' species [*Fernando*, 1965]. However, *Tilapia mossambica* is found only in shallow low-country lakes, and no large-sized deepwater species of fish is available in the indigenous fauna. Thus deep reservoirs have a negligible fish production. A few such reservoirs with some fish production have considerable areas of shallow water, e.g., Senanayake Samudra (Table 2). In this lake, fishing is restricted to the shallow areas [*Fernando and Indrasena*, 1969]. The Ceylonese fish fauna is particularly lacking in low-temperature-tolerant large fish, and thus no economically important species are found in the up-country reservoirs. It is likely that the invertebrate fauna and the flora of the reservoirs are deficient in lake forms, although the extent of this deficiency remains to be studied.

An important feature of reservoirs is the fluctuation of water levels determined by irrigation and hydroelectric power needs. Seasonal droughts and rainfall affect the patterns of these changes too. In general, three basic situations exist in Ceylon if one views these changes from the fisheries aspect. Since spills limit the upper level of the reservoirs, only exposure of the reservoir bed by lowered water levels

TABLE 1. Reservoirs >300 ha in Ceylon

Name	Area at Full Supply Level, ha	Depth at Sluice,* meters	Capacity at Full Supply Level, $m^3 \times 10^3$
Nalanda Reservoir†	273	22.9	15,293
Kandalama Tank	983	12.2	30,344
Yodawewa	607	4.9	7,740
Yodakandiya Tank	621	4.9	12,359
Ridiyangama Tank	888	7.0	26,828
Giants Tank	1840	4.3	32,806
Iranamadu Tank	2327	13.4	101,147
Pavatkulam	1202	9.5	33,045
Akkaryankulam	841	9.8	20,854
Vavanikulam	1275	9.5	43,107
Thannimurrippu Tank	607	5.8	18,502
Senanayake Samudra	7770	38.1	949,795
Irrakamamkulam	821	6.7	19,818
Amparaikulam	363	5.5	8,807
Kondavattavankulam	355	7.9	11,264
Rugam Tank	983	7.6	19,884
Unichchi Tank	1012	10.1	31,774
Vakaneri Tank	453	7.3	12,890
Kaddukkamunai Tank	361	2.7	6,199
Kantalai Tank	1912	14.3	85,345
Vendarasankulam	445	11.0	24,670
Tabbowa Tank	461	7.6	9,744
Kalawewa	2582	12.2	89,648
Minneriya Tank	2550	13.1	135,685
Siyabalagamuwa Tank	758	6.4	27,137
Kariyalai Nagapuduwa Tank	582	3.0	9,497
Nachchaduwa Tank	1784	10.3	55,690
Nuwarawewa	1198	10.1	44,466
Parakrama Samudra	2262	9.4	102,380
Huruluwewa	1113	10.7	67,842
Mahawillachchiya Tank	969	7.6	40,088
Soraborawewa	400	8.8	4,414
Wirawila Tank	562	3.7	12,359
Allai Tank	704	2.1	8,387
Morawewa	751	8.8	33,551
Padaviya Tank	2347	6.7	89,428
Makakandrawa Tank	1174	5.8	32,071
Udawalawe Reservoir	1091	15.2	222,030
Chandrikawewa	439	11.6	26,351
Castlereagh Reservoir	368	35.0	54,069
Kaudulla Tank	2428	9.1	128,286
Maskeliya Reservoir	720	26.2	115,949
Nagadeepa Tank	320	9.1	16,775
Muthiyankaddu Tank	1303	6.7	51,807
Rajangana Reservoir	1598	10.7	99,913
Hakwatuna Oya Tank	334	7.9	19,736
Dewahuwa Tank	344	8.2	9,436
Badagiriya Tank	354	1.8	6,389
Angomuwa Tank	422	6.1	13,691
Muruthuwela Tank	522	15.0	48,106
Dewalawewa	389	8.2	10,854

Tank is English, kulam is Tamil, wewa is Sinhalese, samudra is Sinhalese for sea, and a reservoir is a deep artificial lake.

* The maximum depth is 2 to 8 meters greater.

† Included because of its large storage capacity.

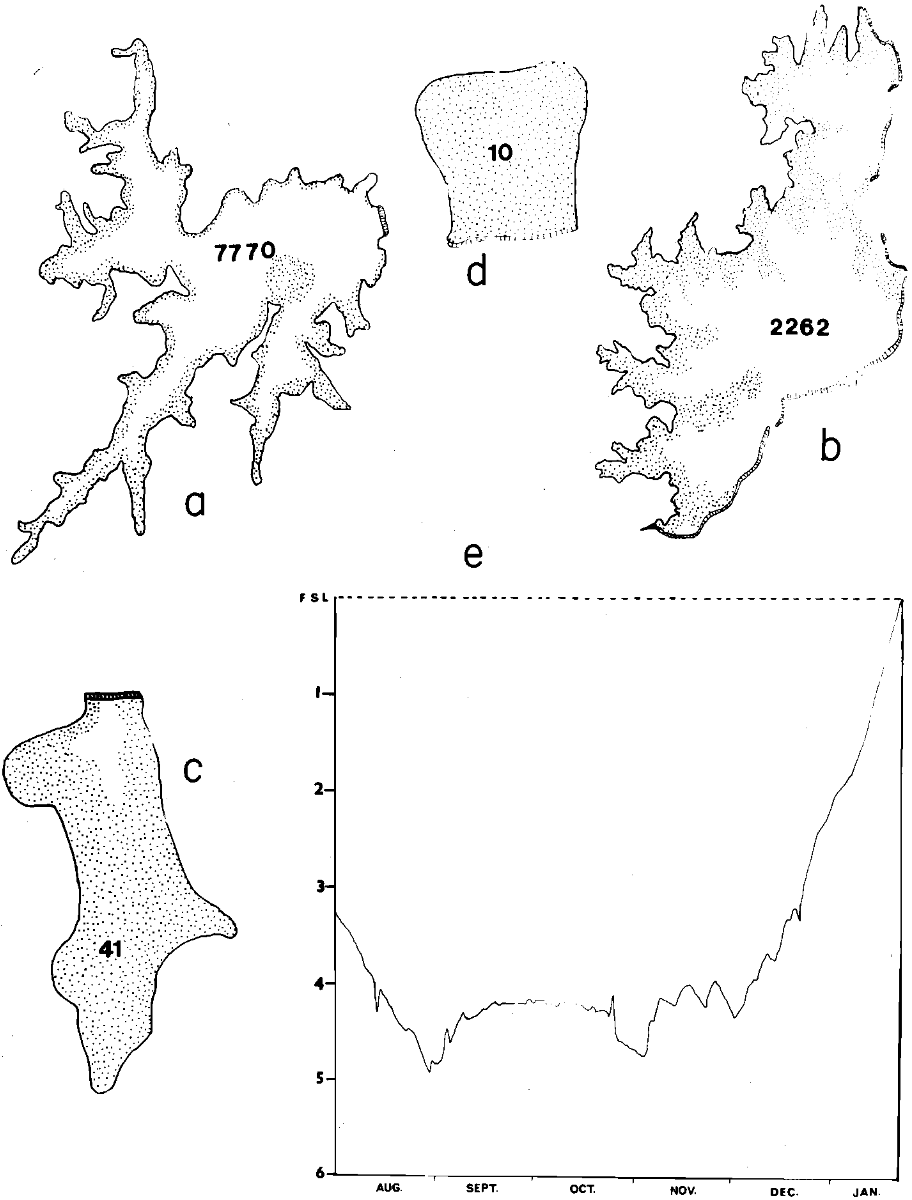
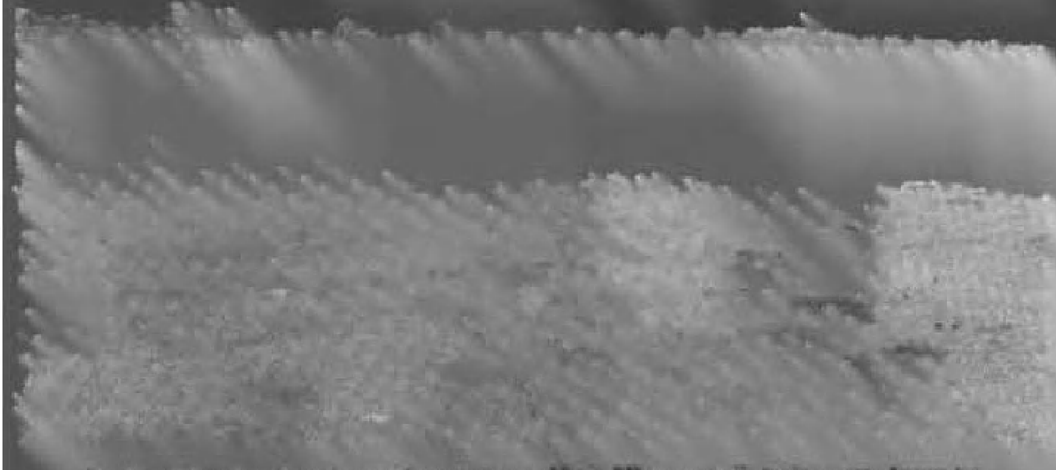


Fig. 2. Fluctuations of water levels in reservoirs: (*a*) total area of Senanayake Samudra, a deep low-country reservoir, in hectares, (*b*) total area of Parakrama Samudra, a shallow low-country reservoir, in hectares, (*c*) total area of Dalukanawewa, a small shallow low-country reservoir, in hectares, (*d*) total area of Thimbirgaswewa, a small shallow low-country reservoir, in hectares, and (*e*) changes in the water level of Parakrama Samudra from August to January (the changes during the rest of the year are slower). Levels below the full supply level (FSL) are marked in meters. The stippled parts of the figure are exposed at low water levels.

will be considered. In most large reservoirs, although the area exposed at low water levels is considerable, an appreciable area is still covered by fairly deep water (Figure 2*b*). The relative area exposed is smaller in deeper lakes (Figure 2*a*). Also the changes in water levels in larger reservoirs are not too rapid (Figure 2*e*). In smaller reservoirs the area exposed accounts for almost the total area

[illegible]

[illegible]



[illegible]

material normally submerged is to increase its rate of decomposition [*Visser and Imevbore*, 1969]. This could add considerable amounts of nutrients to the reservoirs. In small reservoirs, where complete exposure of the bed takes place, the fish (except for air breathers) are eliminated. Thus these reservoirs can be converted into fishponds. Fishing is also affected by changes in water level. *Fernando* [1967] found that beach seines are most successful when water levels are rising.

There are certainly many other factors influencing fish production and catches. For one thing the reservoirs in any group are quite variable in fish production at present. Reservoirs in the wet zone are as a general rule less productive. In the dry zone, fish production in some large reservoirs is high, and in others it is quite low. Intensive and extensive studies of biology are urgently required to assess the situation.

RESERVOIR MANAGEMENT

For the proper use of reservoirs as a biological resource it is important that more attention be given to this aspect by planners, engineers, and biologists. Coordination of work on reservoirs will have perhaps the most profound effects on reservoir fisheries in the long term. Reservoirs differ greatly in their biology; hence studies on different types of reservoirs should be undertaken. Only then will the measures adopted to improve production be more realistic. Measures that can be initiated immediately for the improvement of the fisheries will be considered, namely, fish introductions, fish culture, and fishing methods. Besides these the important aspects of research and extension will be mentioned.

FISH INTRODUCTIONS

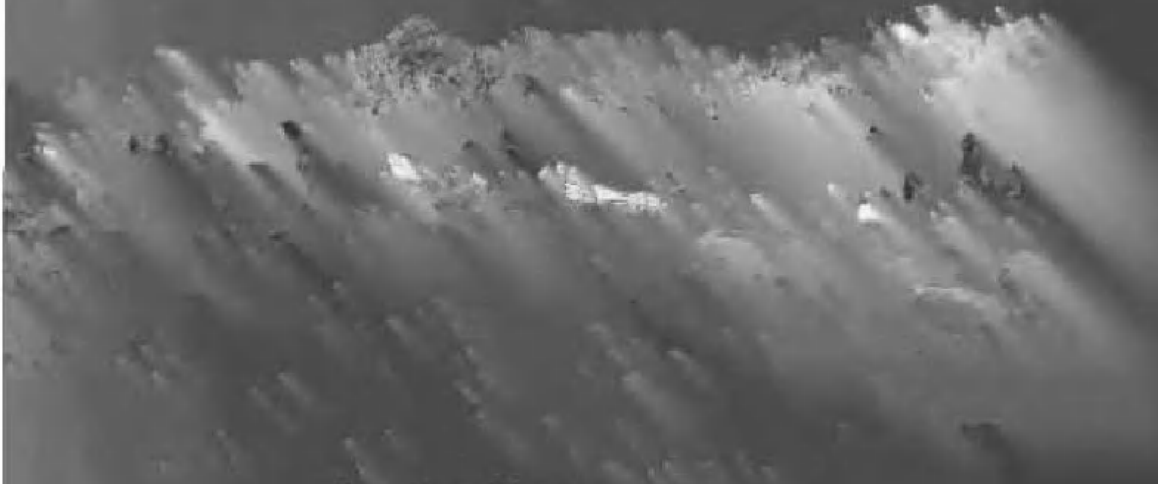
The role of introduced species in the freshwaters of Ceylon has been discussed in detail by *Fernando* [1970] and *Fernando and Indrasena* [1969]. At present, only one species, *Tilapia mossambica*, has had a marked effect on raising fish production. On the recommendation of *Fernando* [1965], three other species of *Tilapia* were introduced in 1969, but their impact has not been evaluated as yet. All the species introduced so far are suitable only for shallow low-country reservoirs. Two types of reservoirs have a poor fish fauna, namely, deep low-country reservoirs and up-country reservoirs with lower temperatures. *Fernando* [1970] has recommended additional *Tilapia* spp. for these habitats plus a predator for up-country reservoirs (>300 meters in elevation). In India, where a rich indigenous fauna exists, the introduction of *Tilapia mossambica* into open waters has been discouraged at times, since these fish compete with the indigenous carps [*Chandhuri*, 1964]. In Ceylon, there are only two valuable carps (*Labeo dussumieri* and *L. porcellus*), and these are of limited importance in the fisheries. One could consider the large Indian carps or *Tilapia* spp. for introduction into Ceylon. The fish production in Indian reservoirs (mainly major carps) is of the order of 50 kg/ha/yr [*Indian Council on Agricultural Research*, 1969]. On the other hand, some African lakes with cichlid fishes have a production of over 200 kg/ha/yr [*Hickling*, 1961], a figure reached in some lakes in Ceylon mainly owing to *Tilapia mossambica*. If a choice has to be made between Indian carps and African cichlids, African cichlids would seem a more satisfactory alternative. Therefore there is a chance, thanks to historical reasons, of introducing the highest yielding fishes in Ceylon. However, careful studies are necessary before introductions are multiplied.

FISH CULTURE

Ceylon has no tradition of fish culture, although *Willey* [1910] mentions a primitive and not too efficient form of culture. Attempts to introduce fish culture practices have failed so far [*Fernando*, 1965]. It appears, however, that the small lake can be made to serve the purpose of fish culture in addition to irrigation. *Alagaratnam* [1956] points out that the restoration of ancient tanks is too costly to be justified on the basis of their value for irrigation. However, *Fernando and Ellepola* [1969] have shown that small reservoirs stocked with fish can yield good harvests (about 150 kg/ha/yr). Perhaps restoration and management of small reservoirs may be economic if they are used as fishponds too! A fish fry industry based on local carps, introduced species, and brackish water species of fish and prawns (*Chanos chanos, Mugil cephalus,* and *Macrobrachium rosenbergi*) is a necessity if fish culture is to be a success. In India a thriving carp fry industry exists [*Alikunhi*, 1957]. Fry of *Labeo* spp. are available in Ceylon. Fry of *Tilapia* spp. can easily be raised or captured from large reservoirs. *Chanos chanos* fry is available in Ceylon. *Mugil cephalus* may soon be bred in the laboratory on a commercial scale [*Tang*, 1964; *Yashouv*, 1966]. *Macrobrachium rosenbergi* has been raised in the laboratory [*Ling*, 1962; *Fujimura*, 1966].

FISHING METHODS

Gill netting is the method of choice in reservoirs [*Fernando and Indrasena*, 1969]. However, beach



[illegible]

Fernando, C. H., The development of Ceylon's fisheries, 11, The role of inland waters in relation to the development of Ceylon's fisheries; and a note of the pearl oyster fishery, *Bull. Fish. Res. Sta. Ceylon, 17,* 291–297, 1965.

Fernando, C. H., The beach seine fishery in Ceylon's freshwaters, *Indo Pac. Fish. Counc. Curr. Aff. Bull. 50,* 1–12, 1967.

Fernando, C. H., The role of introduced fish on fish production in Ceylons fresh waters, in *The Scientific Management of Animal and Plant Communities for Conservation,* edited by E. Duffey and A. S. Watt, pp. 295–310, Blackwell, Oxford, 1970.

Fernando, C. H., and W. B. Ellepola, A preliminary study of two village tanks (reservoirs) in the Polonnaruwa area with biological notes on these reservoirs in Ceylon, *Bull. Fish. Res. Sta. Ceylon, 20,* 3–13, 1969.

Fernando, C. H., and H. H. A. Indrasena, The freshwater fisheries of Ceylon, *Bull. Fish. Res. Sta. Ceylon, 20,* 101–134, 1969.

Food and Agriculture Organization, Fisheries in Asia and their development prospects, *Publ. 79507 E/E,* 25 pp., Rome, 1968.

Fujimura, T., Notes on the development of a practical mass culturing technique of the giant prawn *Macrobrachium rosenbergi, Indo Pac. Fish. Counc. Proc., 47*(09078), 1–4, 1966.

Hickling, C. F., *Tropical Inland Fisheries*, Longmans, London, 1961.

Indian Council on Agricultural Research, The ecology and fisheries of freshwater reservoirs, paper presented at Seminar of the Indian Council on Agricultural Research, Barrackpore, India, Nov. 27–29, 1969.

Ling, S. W., Studies on the rearing of larvae and juveniles and culturing of adults of *Macrobrachium rosenbergi* (De Man), *Indo Pac. Fish. Counc. Curr. Aff. Bull. 35,* 1–11, 1962.

Mendis, A. S., A contribution to the limnology of Colombo Lake, *Bull. Fish. Res. Sta. Ceylon, 17,* 213–220, 1964.

Mendis, A. S., A preliminary survey of 21 Ceylon lakes, 2, Limnology and fish production potential, *Bull. Fish. Res. Sta. Ceylon, 18,* 7–16, 1965.

Schuster, W. H., Report on a survey of the inland fisheries of Ceylon, *Ceylon Govt. Sess. Pap. 24,* 1–15, 1951.

Tang, Y.-A., Induced spawning of striped mullet by hormone injections (in Japanese with English summary), *Gyoruigaku Zasshi, 12,* 23–28, 1964.

United Nations Educational, Scientific and Cultural Organization and the International Biological Program, Lake George, Uganda, Studies on a tropical freshwater ecosystem, *Productivity Problems of Freshwater,* Warsaw, 1970.

Visser, S. A., and A. M. A. Imevbore, Physical and chemical changes observed in a mixture of dried or burnt *Detarium microcarpum* leaves decomposing in the presence of clay or sand and under different water regimes, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 305–319, Ghana Universities Press, Accra, 1969.

Willey, A., Note on the freshwater fisheries of Ceylon, *Spolia Zeylan., 7,* 88–106, 1910.

Yashouv, A., Inducing of spawning of the grey mullets (*Mugil cephalus* and *M. capito*), *Progr. Rep. 3(10),* U.S. Bur. of Commer. Fish., Washington, D. C., 1966.

Fishery Problems and Opportunities in the Mekong

V. R. PANTULU

Mekong Secretariat, Economic Commission for Asia and Far East
Sala Santitham, Bangkok, Thailand

The Mekong is one of the world's great rivers and Southeast Asia's largest single natural resource. Originating in the perpetual snows of the great Tibetan plateau, it traverses a winding course of 4200 km through six countries before finally draining into the South China Sea off Vietnam. The stretch of the river from the point of its entry into the territory bordered by Laos and Thailand to its ultimate merger with the sea is termed the Lower Mekong. A comprehensive regional project for the development of resources of the Lower Mekong basin, currently under implementation, is managed by the Mekong Committee, a body consisting of plenipotentiary representatives of the governments of the Khmer Republic, Laos, Thailand, and South Vietnam with the assistance of a United Nations supported secretariat, the Mekong Secretariat. As part of this great venture, many significant studies were made, and a vast amount of data relevant to water resources development was collected. A few dams on the tributaries of the Mekong either have been completed or are under construction, and several development-oriented projects in the fields of agriculture, fisheries, navigation, industries, and social welfare have been implemented. All these projects have contributed to the accrual of valuable and at times unique experience and information.

Development of the Lower Mekong basin has in recent years accelerated rapidly and reached the stage where serious consideration is being given to the harnessing of the main stem of the river. There are several sites on this large river (Figure 1) that have a high potential for power development, flood control, and irrigation. Concomitant with the progress in the implementation of the Mekong basin development projects, increasing concern is being felt and expressed in knowledgeable quarters as to the ecological consequences of these projects, particular reference being made to fisheries, public health, wildlife, watershed, and social aspects. Often, parallels are drawn with experiences in the Pacific Northwest of the American continent or with the more recent African experiences. More often 'a lack of realization or concern, by the riparians about spatially far reaching consequences of the Mekong regulation' is assumed, and dire consequences are predicted.

Fishery resources of the Mekong basin are of considerable economic importance to the riparian countries. The yearly harvest from the Lower Mekong River and its tributaries is estimated to be of the order of 200,000 metric tons, benefiting directly around 20 million people and representing a value of US$100 million. As fish, in theory at least, are a renewable resource, the benefits above could be realized in perpetuity if the ecology of the river remains unchanged and exploitation is maintained at a rational level.

Nutritionally also, fish are very important in that they provide 50–80% of the animal protein in the diet of the people of the region (V. R. Pantulu and J. Bardach, unpublished report, 1969). In this context it is urgently necessary to examine carefully whether dam construction would result in a decline of fish harvests in a region known to be chronically deficient in protein nutrition.

It is therefore the object of this paper to analyze critically the Mekong fishery problems in their proper perspective and to set forth ideas and experiences gathered during the course of the brief period of implementation of fishery projects within the basin itself. Admittedly, the information available on various facets of life histories of the Mekong fishes and the environment is limited. Where there is a lack of specific information, conclusions have been drawn based on the knowledge of bionomics of the very same or

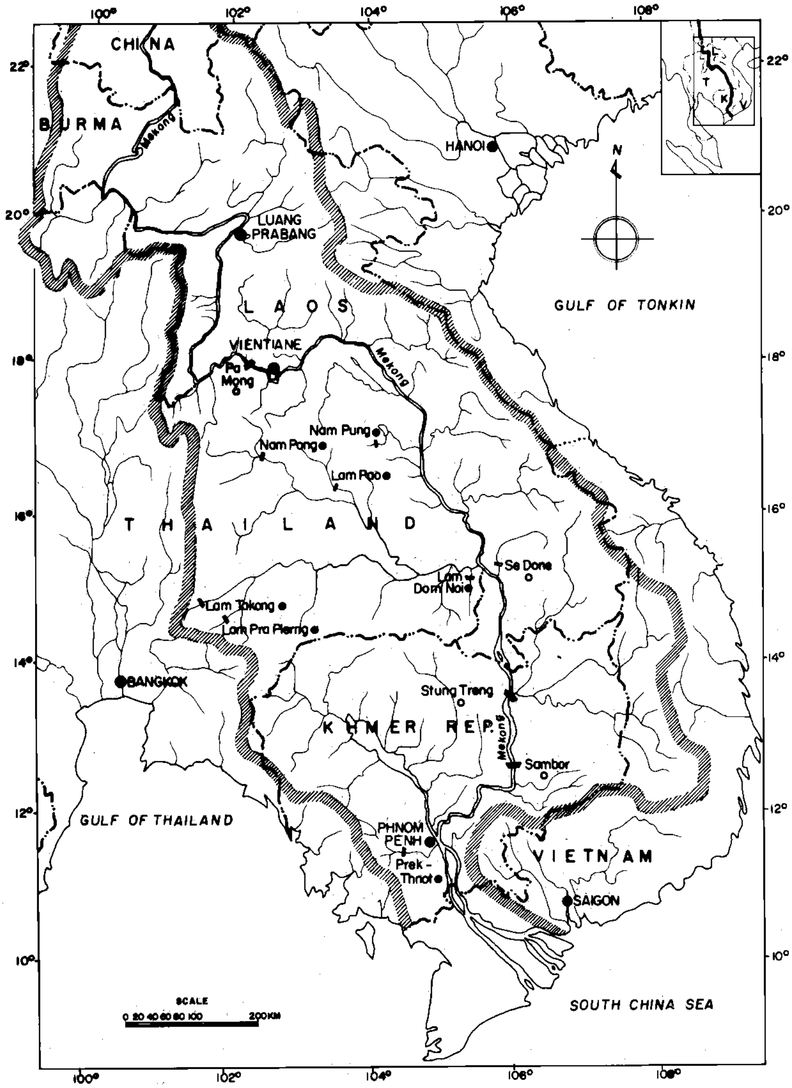


Fig. 1. The Lower Mekong basin. Open circles represent proposed mainstream dams, and closed circles represent dams that are completed or under construction.

similar species occurring in other tropical rivers in neighboring countries.

FISHERIES PROBLEMS RELATIVE TO THE CREATION OF MAN-MADE LAKES

The facts that are fundamental to the understanding of the modern concept of protection and management of fisheries relative to the creation of man-made lakes through dam construction have emerged largely as a result of the vast experience in the Pacific Northwest of the American continent.

1. Impoundment drastically alters the riverine environment by bringing about substantial changes in the morphoecological nature of rivers. Fast-flowing sections are converted into relatively lentic environments, long-established interrelations between organisms being transformed radically. Changes in temperature regimen, volumes of discharge, velocity of current, gradient, temperature, substrate, mineral contents, and so on take place. Changes in spawning biotopes, resultant on flow and substratal changes, inhibit propagation and the develop-

ment of both lythophilous and rheophilous species, which may even completely disappear. Both qualitative and quantitative changes take place in the trophic environment. Fish, being a balanced compromise of adaptations to a particular set of environmental conditions, cannot withstand environmental fluctuations beyond rather narrow limits; hence riverine fish fauna are adversely affected by these drastic changes.

2. In each species of fish, there are races or populations that are perpetuated from a specific spawning area or 'home.' Dam construction for the creation of man-made lakes would cause some runs to lose access to spawning areas and would result in the decimation of those particular races.

This basic philosophy places rigid restrictions on the latitude available for modification of the riverine environment [*Larkin and Pantulu,* 1958]. The evaluation of fishery problems by most of the scientists visiting the Mekong basin is conditioned by this philosophy. Mention is often made by them of 'migrations of hundreds if not thousands of kilometers,' 'blocking of fish runs outright,' and subtle changes of 'characteristics of flow and water temperature that upset swiftly, long standing, biological adjustments.' With this philosophy as the background an evaluation of the Mekong situation is attempted in the following pages.

MEKONG SITUATION

Preimpoundment environment. The Lower Mekong and its tributaries are typical tropical rivers subject to a monsoon-conditioned regimen and having a violently fluctuating environment. Individual environmental features exhibit a wide range of variation both in space and in time, as they do in any other tropical river. In the main Mekong the annual amplitude of variation in flow is between 1764 m^3 during the dry period and 52,000 m^3 during floods (averages of readings at Kratie, Khmer Republic). Flash floods and large-scale inundation are a common feature in several areas. Because of the continued scouring action of floods over a long period of time, depressions or 'pools' are formed in the riverbeds at several places. Such pools often assume considerable proportions; some several kilometers long and >50 meters deep were located in the Mekong near Pa Mong damsite. In the stretch of the river in the Khmer Republic, F. D'Aubenton (unpublished report, 1963) located several 'troughs 40 to 60 m deep.' These pools retain water year round and offer a sort of 'transient lacustrine' environment during the dry months. February–May usually constitutes the low-water period, when the wetted perimeter in the river is at its lowest. During this time, fluviatile sections of many of the tributaries are reduced to mere trickles of water, and the only relatively stable aquatic environment is provided by the pools in the stream beds.

Water temperatures in the river are high and fluctuate within the wide range of 20° to 37°C at different points during different months of the year. The *p*H values range between 7.0 and 8.2, and the dissolved oxygen values vary between 5.2 and 7.5 ppm in different sections of the river [*Sidthimunka,* 1970; *Le van Dang,* 1970; *Overseas Technical Cooperation Agency,* 1969]. The water level in the river starts rising by about the end of May, reaches its peak in August or September, and finally subsides in November. With the onset of floods, water temperatures rise, and dissolved oxygen and *p*H levels fall [*Le van Dang,* 1970; *Overseas Technical Cooperation Agency,* 1969] mainly as a result of the decomposition of the vast amount of organic debris brought in by the floods. Turbidity increases sharply owing to the mass of alluvial silt in the floodwaters. The increase in turbidity brings down plankton levels at least temporarily. Later, as a result of the allochthonous nutrients brought in by the floods, plankton blooms appear in the flood-inundated zones. It is estimated that in the Vietnam delta alone an area of about 1 million ha is inundated and the water level rises 4–5 meters during floods [*Le van Dang,* 1970]. Average current velocities increase from 0.2 m/sec in February to about 1.4 m/sec in August [*Overseas Technical Cooperation Agency,* 1969]. Flood-induced changes in the environment return to normality, and dry-period conditions begin to set in by December or January.

The fluviatile sections of the river itself are not very productive owing to the relatively high turbidity, fast current, and sandy nature of the bottom. Plankton production in this lotic environment is relatively low. The pools in the riverbeds, the oxbows, and the other inundated regions beside the rivers are the true pockets of productivity. Table 1 gives comparative figures of plankton production in the main river, in a deep pool in the riverbed, and in an inundated oxbow near the Mekong collected during a recent preim-

TABLE 1. Abundance of Plankton and Benthos in Three Locations

Place	Protozoa, number/m^3	Rotifers, number/m^3	Nauplius, number/m^3	Copepods and Cladocera, number/m^3	Annelids, mg/ft^2	Chironomids, mg/ft^2
Main river	2000	0	500	500	0	0
Main river pool	3500	500	3000	500	20.2	1.2
Oxbow lake	9000	7500	1500	20,000	119.2	11.4

This table is by *Sidthimunka* [1970].

poundment fisheries survey conducted by the Mekong Secretariat [*Sidthimunka,* 1970; V. R. Pantulu and J. Bardach, unpublished report, 1969].

Fish. Over 150 different species of fish have been recorded from the Mekong basin, 141 species of fish were recorded from the Mekong near the Pa Mong damsite (V. R. Pantulu and J. Bardach, unpublished report, 1969), and 74 species were represented in the samples drawn from the tributaries of Cheon and Pong prior to impoundment [*Sidthimunka et al.,* 1968]. In the Mekong during the dry months of the year, carps (Cyprinidae, 54%), catfishes (Siluridae, Clariidae, Schilbeidae, Bagridae, Sisoridae, and Akysidae, 19%), and murrels (Ophicephalidae, 8%) constitute about 81% of the fish fauna. The other 19% is composed of feather backs (Notopteridae), herrings (Clupeidae), climbing perches and gouramis (Anabantidae), and other miscellaneous groups. This composition varies slightly during different seasons but remains substantially the same (V. R. Pantulu and J. Bardach, unpublished report, 1969). Tributaries of the Mekong have a more or less identical distribution of the different groups of fishes [*Sidthimunka et al.,* 1968].

The life cycles of a vast majority of the fish in the Mekong depend prominently on the annual inundation cycle, as do those of fish in other tropical rivers. With the onset of floods and the concomitant submergence of rice fields, ditches, swamps, oxbows, and other low-lying areas over a considerable distance on either side of the riverbank a predominant section of the fish population 'migrates' from the rivers to the inundated areas, mostly for spawning. These migrations, barring a few exceptions, are more 'lateral' (toward and into the inundated riverbanks) than upriver or downriver (from estuaries to headwaters or vice versa). The distances traversed in the 'lateral migrations' and the duration of sojourn in the inundated zone differ with different species depending on their environmental requirements and tolerances.

Fishes with low oxygen requirements or those with accessory respiratory mechanisms, like murrels, some catfishes, and anabaenas, occupy and tarry for longer periods in the peripheral zones of inundation, where dissolved oxygen and *p*H are generally low owing to decomposing organic matter and terrestrial vegetation. Most cyprinids, which have higher oxygen requirements and a lower tolerance to *p*H fluctuations, occupy the proximal zone of inundation, spawn there, and move riverward with receding floods much earlier than the preceding groups of fishes [*Le van Dang,* 1970]. If the flood recedes quickly, as it does during years of relatively sparse rainfall, large numbers of eggs and hatchlings die from desiccation; if, on the other hand, floodwaters stand for a relatively long period, as they do in years of heavy rainfall, the large-scale mortality of fry and fingerlings occurs from deoxygenation and drastic changes in *p*H resulting from the decay of organic matter in floodwaters [*Le van Dang,* 1970]. Thus flood regulations that eliminate very high or very low floods might actually be beneficial to fisheries. The observed high fecundities in most of the tropical river fishes (except those exhibiting parental care) are an adaptation to survive these periodic large-scale mortalities. Some of the young that result from the spawning activity in the inundated zone enter the main river and repopulate it. Others are left behind in the water bodies inland, grow there, and provide a rich crop of fish. Thus a sort of natural restocking of the water bodies on either side of the river in the flood-covered plain takes place annually. The fact that the fish fauna represented in these stagnant waters and the riverine fauna are essentially the same is an indication that most of the riverine species in the Mekong and its tributaries can thrive in lentic environments.

The fish fauna of the Mekong are well adapted to this violently fluctuating environment. Their tolerance ranges for various critical environmental factors such as temperature, *p*H, dissolved oxygen, and so on are very wide, unlike those of temperate fishes. Some of these fishes have evolved exceedingly interesting adaptations to survive an inhospitable milieu and frequent abrupt environmental changes. Accessory respiratory organs or modifications in the epithelium of the suprabranchial cavity to enable the fish to use atmospheric oxygen are found in catfishes of the families Clariidae and Heteropneustidae; climbing perch, *Anabas* spp.; and murrels, *Ophicephalus* spp. These organs enable these fishes to survive the periods of deoxygenation of water that usually occur in the peripheral zones of inundated areas during flood seasons. Another interesting adaptation is the faculty of locomotion over wet land for appreciable distances in fishes like *Anabas* spp., *Clarius* spp., and *Ophicephalus* spp. This adaptation ensures survival when habitats dry up because of either a suddenly receding flood or the failure of precipitation. These few instances are cited to emphasize and underline the point that fishes of the Mekong basin have adapted themselves in manifold ways to changes and amplitudes of various often harsh environmental features.

In addition to the lateral migrations, 'up-and-down the river' migrations are suspected to take place in a few species, mainly on the basis of their seasonal appearance in fish catches in different sections of the river at different times of the year. Important among the suspected long-range or medium-range migrants that presumably pass through the proposed mainstream damsites are the following seven species [*Overseas Technical Cooperation Agency,* 1969; V. R. Pantulu, unpublished report, 1968].

Carps (Cyprinidae)
  Cirrhinus auratus Fowler
  Cirrhinus jullieni Sauvage
  Thinnichthys thinnoides (Bleeker)
  Probarbus jullieni Sauvage
Catfishes (Schilbeidae)
  Pangasianodon gigas Chevey
  Pangasius pangasius (Hamilton)
  Pangasius sutchi Fowler

No positive evidence is available as to whether these species do in fact perform the suspected migrations over long distances and, if they do, what the time ranges and goals of such migrations are (V. R. Pantulu, unpublished report, 1970). Members of identical species occurring in different sections of the river could be merely discrete local stocks and not individuals of a migratory population. Another commercially important freshwater migrant that moves into estuaries for spawning is the giant freshwater prawn, *Macrobrachium rosenbergii.*

There are about 27 species of marine and estuarine fishes belonging to Carcharinidae, Pristidae, Clupeidae, Syngnathidae, Scombrosocidae, Polynemidae, Centropomidae, Sciaenidae, Scombridae, Solidae, and Tetradontidae that occur in the freshwater areas of the Mekong. Very little is known about their life histories, but available evidence indicates that some of them are permanent residents in freshwater stretches of the river or connected lakes [*Mori et al.,* 1958]. Of the 27 species of saltwater fishes mentioned above, only a few are of commercial value. Perhaps the only truly anadromous species is *Hilsa kanagurta,* which is suspected to migrate several hundred kilometers upriver. *Anguilla japonica* and *A. mauritiana* are the two known catadromes. However, all three species are of little commercial value in the Lower Mekong basin.

Changes on impoundment. As a part of the Mekong development program, seven tributary dams have so far been completed. Prior to their development, all these tributaries were seasonal streams, at least in the vicinity of the damsites. Consequent on impoundment a stable lacustrine environment is created in place of a violently fluctuating tropical stream environment. Table 2 gives some environmental characteristics in the Nam Pong Reservoir and the residual river below the dam (in Thailand) commencing 6 months after the completion of the dam. These environmental factors are within the normal range of fluctuations to be expected in natural rivers and tributaries in the preimpoundment phase. Studies in the Nam Pong Reservoir (maximum depth 19.52 meters, mean 15.75 meters) have also indicated [*Sidthimunka et al.,* 1968] a horizontal homothermy in the reservoir and no thermal stratification apart from slightly higher temperatures at the surface due evidently to the transient heating of surface waters. The trophic

TABLE 2. Some Environmental Factors in the Nam Pong Reservoir and Residual River

	Reservoir						Residual River				
	Aug. 1966	Nov. 1966	July 1967	Aug. 1967	Sept. 1967	Nov. 1967	Aug. 1966	July 1967	Aug. 1967	Sept. 1967	Nov. 1967
Temperature, °C											
Surface	31.00	28.00	29.00	27.00	29.00	26.50	30.50	29.00	27.50	29.00	26.50
10 meter depth	30.00	27.50	28.50	26.00	28.00	26.50					
Dissolved oxygen, ppm											
Surface	6.31	6.48	8.30	6.20	5.70	4.90	5.17	5.90	5.00	7.08	7.15
10 meter depth	5.79	5.70	4.60	5.80	5.00	3.80					
pH											
Surface	7.60	7.00	7.72	7.28	7.27	7.30	6.90	7.00	7.25	4.20	4.30
10 meter depth	7.20	6.80	6.95	7.26	7.20	7.20					

environment also appears more favorable in the postimpoundment phase than it did in the preimpoundment phase, judging from the abundance of plankton (9272 per m^3 at a depth of 8 meters) and benthic organisms (5.375 g/m^2 at a depth of 6 meters) in the reservoir [*Sidthimunka et al.*, 1968].

Fish fauna in the reservoir 1 year after impoundment comprised only 51 species in comparison with 74 in the preimpoundment phase, a reduction in the number of species being indicated. However, the total production of fish increased remarkably from negligible harvests in the streams prior to impoundment to about 1300 metric tons annually from the reservoir. There was also a significant increase in yield per unit area in the impoundment from average yields of about 12 kg/ha/yr in tropical rivers to 32 kg/ha/yr. Important among the species of fish that have 'disappeared' or migrated to the river section above the reservoir after impoundment are the carps *Cirrhinus jullieni* and *Labeo bicolor* and the catfishes *Wallagonia attu, Bagarius bagarius, Kryptopterus cryptopterus, K. apogoa,* and *K. bleekeri.* It is interesting that of these species *C. jullieni* and *B. bagarius* are known to perform long-range or medium-range migrations and the rest are sedentary species inhabiting the bottoms of rivers. All these species, with the exception of *C. jullieni,* are not of much commercial value in the Mekong basin. The relative abundance of different species also changed after impoundment. Although carps continued to be the most common in number of species, their relative contribution by weight to catches reduced from 55.9% prior to impoundment to 24.1%. On the other hand, populations of predacious murrels increased from 16.5% of the catches by weight before dam construction to 34.8%.

From also a socioeconomic point of view this impoundment had a significant impact. The lucrative nature of the fishery that developed attracted a large fishing community even from provinces hundreds of kilometers away. Farmers turned to fishing, since this occupation proved to be far more rewarding than agriculture. Erstwhile river fishermen eking a marginal subsistence from a seasonal stream have become prosperous harvesters of abundant fish crops.

Along with the streams Cheon and Pong the Nam Pong Reservoir impounded a number of swamps and oxbows with considerable fish populations. For stretches of river without connecting oxbows and swamps, postimpoundment fish production appeared to be considerably less, and the species composition tended to have a higher proportion of minnows. Thus both the species composition and the abundance of individual species in the preimpoundment phase are perhaps important factors in determining fish yields and species structure in the postimpoundment phase.

PROBLEMS AND OPPORTUNITIES

It would be obvious from the account above of the Mekong environment and its fish that the creation of man-made lakes does not bring about any environmental changes that are outside the range of fluctuations occurring in natural rivers but only removes or reduces the amplitude of fluctuations in environmental features. Even prior to impoundment these fishes are well adapted to and spend parts or all of their life cycles in the lentic environment of pools in the riverbeds or inundations beside the rivers. Thus for a vast majority of the riverine species the creation of man-made lakes makes the environment more favorable for their development. Nevertheless there are several other problems characteristic of a tropical river. In the discussion of problems and opportunities that follows the whole complex of biological consequences relating to fisheries in the entire river system, contingent on the creation of man-made lakes, is considered.

Fish migration. Perhaps the most important issue is the tenuous problem of whether the suspected seven species of migrants (listed above) do in fact perform the long-range migrations attributed to them or whether members of individual species reported to occur seasonally in far-removed sections of the river are only discrete stocks performing local migrations (Mekong Secretariat, unpublished report, 1970). If studies reveal that long-range migrations do occur, associated research on spawning biology and ecology should be carried out in detail. Another problem inextricably linked with fish migrations is the provision of fish passage facilities. The number of species possibly involved, the likely differences in the exigencies of water flow that would be required to entice them, and the economic value of their fishery would render the provision of fish passes technically difficult and economically infeasible. Big fish of the genera *Pangasius* and *Pangasianodon* are particularly difficult to convey over dams by means of conventional passes. Hence the solution to the problem, where a solution is warranted for economic reasons, should perhaps be sought by resorting to induced spawning of such species below the damsites and by rearing the larvae to sizes at which they would migrate downstream naturally. (Volga sturgeon fishery is now reported to rely on such practices.) For the success of such measures a thorough understanding of the reproductive biology of the species involved is essential [*Pantulu,* 1970].

Effects of impoundment on estuarine and coastal capture and culture fisheries. Based on experience in the Nile, some ecologists have surmised that 'judging from other rivers that carry similar burdens of silt and nutrients those (coastal) fisheries are or will be very important.' A parallel is drawn with the postulated disappearance of a sardine fishery in the eastern Mediterranean consequent on the Aswan Dam construction, and it is predicted that as a result of the Mekong regulation and the resultant reduction in silt carried into the sea the distribution and prevalence of fishes will change through the intermediacy of nutrient-dependent changes in plankton levels. We have no knowledge of the nature, distribution, and magnitude of seasonal inundation-associated fish congregations off the mouths of the Mekong. However, we do know that the Mekong is a relatively 'clean' river carrying a small quantity of alluvium (100 ppm in the dry season and 250–300 ppm in the rainy season) in comparison with the Nile (1500 ppm), the Ganges (1950 ppm), and the Mississippi (1750 ppm). Estuaries are rearing grounds for the young of several saltwater fishes and prawns. In the Mekong estuaries, fry of important species of fishes, like *Chanos chanos, Mugil cephalus, Lates calcarifer,* and *Polydactylus indicus,* and the prawns *Metapenaeus monoceros* and *M. brevicornis,* among others, are known to occur during certain seasons of the year. A detailed study of their ecological relationships and life history is essential for the evaluation of effects of impoundment on their distribution. In this context the Mekong Secretariat is presently organizing a survey to assess the probable effects of Mekong regulation on the offshore and estuarine fisheries in the region (Mekong Secretariat, unpublished report, 1970).

Macrobrachium rosenbergii, the giant freshwater prawn, is a very important species in the Mekong by virtue of both its contribution to the catches from the river and estuaries and its potential value as a cultivable species of prawn with a growing demand in world markets. This species is known to spend its adult life in the freshwater areas of the Mekong in the vicinity of estuaries and to migrate to brackish waters for spawning. Environmental salinity is an important factor in the reproduction and survival of the young of the species. Salinity regime changes in the estuarine areas induced by impoundments upstream are likely to affect this species in several ways yet unknown. One of the priority projects sought to be implemented (Mekong Secretariat, unpublished report, 1970) in this context aims at elucidating the problem and also at developing a large-scale culture of this species as a rehabilitative measure taken in advance of the onset of the anticipated adverse effects.

A problem less widely recognized but of equal if not greater importance is the effect of environmental changes on estuarine and coastal aquiculture. The importance of aquiculture in the deltaic region of the Mekong can be gaged by the fact that, in South Vietnam alone, aquiculture of a traditional type is being practiced in about 26,000 ha. An area of another 160,000 ha in South Vietnam and 50,000 ha in the Khmer

Republic exists with a potential for the development of aquiculture [*Ling,* 1970]. Aquiculture as practiced in the region consists of impounding fish fry that enter low-lying areas along with tidal waters or floodwaters and rearing them to marketable sizes. Such a culture practice depends for its supply of 'seed' entirely on the natural distribution of fry, which is likely to be affected by the changes in environmental features, particularly in salinity conditions, which are consequent on upstream impoundment. Further, desiccation of large water areas due to regulation of inundation is likely to render present and potential aquicultural sites inoperative. Fisheries of the Vietnam delta alone are estimated to be of an annual value of US$17.4 million [*Le van Dang,* 1970], excluding the value of fish converted into fish sauce and dry fish. In view of the immense economic value and the livelihood for many thousands of people that these fisheries provide, the Mekong Secretariat has taken cognizance of the problem and is seeking to undertake studies on questions involving brackish water prawns as a first step (Mekong Secretariat, unpublished report, 1970). Here again the project has both investigational and rehabilitational aspects, as it did in the case of the giant freshwater prawn. Further the formulation and implementation of specific projects on estuarine ecology are also contemplated.

Effects of inundation control on fisheries in the freshwater zone. Annual inundation is an important feature for the aquatic life in the Mekong. Many fishes perform lateral migrations into the inundated zones for spawning. Several tropical riverine carps and catfishes do not spawn in stagnant waters, despite the fact that their maturity cycle itself is not influenced by a lotic environment. Normally, these fish could spawn under a wide range of temperature, pH, and dissolved oxygen conditions with known optimums for the maximum survival of hatchlings. The all-important environmental factor that releases the chain of behavior patterns leading to spawning appears to be inundation. So the crucial question is to what extent is the spawning biology of commercially important species of fishes influenced as a result of inundation control both in residual rivers and in reservoirs? Studies should also be conducted to elucidate (1) the relations between the annual flood cycle and the abundance of populations of commercially important species and (2) the role of the floodplains, oxbows, and swamps connected to the river as rearing grounds and their contribution to recruitment to the mainstream fishery. These studies would enable a realistic assessment of the economic losses, if any, due to dam construction. As was mentioned elsewhere, the fecundity rates in these tropical river fishes are very high, and the loss of a few spawning and rearing areas as a result of dam construction may not be significant, but the problem would assume serious proportions if a series of dams were constructed and several spawning and rearing sites were lost.

Mekong dams would provide irrigation to several million hectares of land. Within the areas that could be irrigated, there are several hundreds of thousands of hectares of agriculturally unsuitable low-lying lands that could be converted into fish farms to take advantage of the availability of irrigation water. Although development costs are high for dug ponds occupying valuable agricultural lands, conversion of the areas mentioned above with minimum excavation into fishponds would be highly beneficial from an economic point of view. A recent study by the Mekong Secretariat (V. R. Pantulu, unpublished report, 1970) in collaboration with the Pa Mong team of the U.S. Bureau of Reclamation has shown that the economic benefits derivable from such an enterprise could be about 4 times the benefits derivable from irrigated agriculture. Apart from the economic advantages, such a venture would also play an important role, where it was necessary, in the rehabilitation of species likely to be adversely affected by inundation control through artificial fish culture.

Reservoir ecology in relation to fisheries. The tributary reservoirs constructed so far have yielded fish harvests of a magnitude never realized in unimpounded rivers. Actual yields varied from one reservoir to another with a maximum harvest of about 31 kg/ha/yr realized from the Nam Pong Reservoir. Experience elsewhere has shown that yields 3 times this magnitude are possible with adequate management. With a view toward evolving an efficient management program, a more detailed study of the life cycles and ecological relationships of the commercially important species, which would permit meaningful inferences about the causative factors for the decline and disappearance of some species and the thriving of others, would be necessary. It is postulated that, morphoedaphic features being the same, the initial abundance of planktonophages, together with detritus and bottom-feeding fish populations, is the determining factor in reservoir fish production, since such a combination of species takes maximum advantage of the trophic environment that would develop in the new reservoir. Modern theories of fish population growth give only mixed reassurance with regard to the restoration of populations from low levels of abundance. Although it is generally true that, with favorable conditions, small populations have the mathematics of biological potential in their favor, it is also theorized on good evidence that other biological factors (predators, parasites, behavioral factors, and so on) may effectively block recovery from depressed levels. Hence it has become customary to transplant large numbers of fingerlings of desirable species, indigenous or otherwise, often with great success in newly formed reservoirs. A critical study on the need for transplantation embracing quantitative population studies of native species in the preimpoundment and postimpoundment phases and the performance of transplanted species in reservoirs is necessary. The question of transplantation of exotic species is very important in relation to the development of tropical reservoirs (V. R. Pantulu, unpublished reports, 1968, 1969). It is often easier and less expensive to introduce desirable exotic varieties whose habits are known and for which breeding techniques have been developed. At the same time, such introductions could sometimes be harmful, particularly when their ecological interactions with indigenous species are imperfectly understood.

Great Lake of the Khmer Republic. A very prominent feature of the Mekong watershed is the Great Lake of the Khmer Republic, which was known in the past as the site of one of the most productive freshwater fisheries of the world. The lake, which is connected to the Mekong through the Tonle Sap River, has a mean depth of <1 meter at low water and 8–10 meters at high water. Floods inundate a plain of 11,000 km^2 with a very special forest cover. At low water the lake covers about 2500 km^2. The high productivity of the Great Lake is attributed to this seasonal pattern of inundation. 'There is no doubt that this great productivity of the secondary and higher producers has been brought about by the inflow of organic matter into the lake from the vegetation on the flooded plain' [*Mizuno and Mori,* 1970].

Another characteristic feature of the Great Lake is the phenomenon of current reversal, which occurs during May to October, when waters from the Mekong enter the lake. During the other months of the year, water flows from the lake to the Mekong. This phenomenon of reversal is the result of the enormous water discharges in the Mekong during the rainy months. Fish movements and fishery operations in the lake are closely dependent on this unique current pattern. *Fily* [1963] states that, because of this flooding and recession and the considerable variations in the volume of water, all or almost all the fish in this region (Great Lake and the Tonle Sap River) exhibit a need to 'migrate.' The fish that feed and reproduce when the flood is at its highest in the lake, the flood forest, and other inundated areas move from the flooded areas into the lake as soon as the water begins to fall. As the water drains at increasing speed from the lake, fish escape into the distributaries and thence to the Mekong, 'where they find sufficient water and adequate living conditions' [*Fily,* 1963].

Upstream storage of 60 million m^3 at Pa Mong or Stung Treng would lower the highest water levels of the Great Lake (which occur once every 30 years) by about 80 cm and the once every 4 year highs by half of that or less. Mainstream dams at both Pa Mong and Stung Treng would increase the minimum dry-season water level of the lake to +4 or +5 meters in comparison with a minimum of about +1 at present. The minimum lake area would increase from the present 2500 km^2 to some 5000 km^2. All these changes would in turn affect the fisheries of the lake in a manner largely unknown. Some species might decline, whereas others might thrive. Increased water levels might render the habitat more attractive to big fishes [*Fily,* 1963], reduce turbidity, and increase productivity. These speculative statements are based on the known general effects of inundation control on fisheries. They also point to the need for an open mind in any consideration of the effects of upstream impoundments, or a barrage on the Tonle Sap itself, on the fisheries of the Great Lake. The Mekong Secretariat has on its program studies to gage the probable effects of Mekong impoundments on the fisheries of the Lake.

Aquatic weeds. The proliferation of aquatic weeds in reservoirs is one of the most serious problems that the Mekong impoundments share with other tropical reservoirs. The adverse effects of weed growth are already being experienced in most of the reservoirs constructed in the basin. Besides the usual well-known harmful effects of aquatic weeds a special undesirable feature observed in Mekong impoundments is that the weed-infested areas offer an ideal habitat for the swamp-inhabitating carnivorous species of murrels. Concomitant with the spreading of weeds is the increase of murrel populations, resulting in a high degree of predation on the carp species, which could better use the trophic environment of the reservoir. As is well known, a species structure composed of planktonophages and detritus feeders, which crop the food chain at the lowest levels, gives inordinately high yields. Change to a predator-prey species structure, which the increase of murrel populations would bring about, inevitably leads to a decline in yields.

Outlined above are some of the more important problems considered to be of special significance to the Mekong. There is an impressive array of other problems, technological, management, socioeconomic, and so on. If they are not mentioned here, it is not because they are less important, but because they are more universal and pertain to the development of reservoirs anywhere else in the tropical or subtropical region.

CONCLUSION

Fisheries and dam construction have always been considered incompatible resource uses, largely because of earlier experiences with salmon fisheries. In a violently fluctuating tropical riverine environment with well-adapted fish species, flood control measures within limits might well stabilize a changing environment and make it less rigorous and more hospitable. Mekong river fishes, with some exceptions, are adapted to lentic conditions by virtue of the fact that the natural rivers as well as the inundated plains offer transient lacustrine environments. With the exception of a few species, there are no long-range migrants. Hence it is perhaps reasonable to conclude that dams affect fisheries in other ways than by just obstructing the free passage of fishes and forging subtle changes in the environment.

By and large, isolated dam construction can be considered to be beneficial in the freshwater stretches of the river. A series of dams, on the other hand, might adversely affect fishes by completely eliminating or drastically altering the inundation pattern, so necessary for the spawning and rearing of fishes and the enrichment of the nutrient status of the water bodies. The environmental effects of upstream dam construction appear to be more important, particularly in estuaries and to a lesser degree in inshore areas.

The generalizations above are made on the basis of an admittedly brief experience in the operation of the Mekong fishery projects. It might appear to some readers that the tenor of the paper is to overemphasize the positive aspects of fisheries problems in relation to dam construction. If that be so, it is only to be taken as a reflection of the experience gained in the Mekong basin and in tropical areas elsewhere, which leads to the conclusion that it is unrealistic to hold the view that fisheries interests must necessarily suffer as a result of the dams on the Mekong and that it is in fact more likely that with proper planning and management the benefits from fisheries can be increased considerably. The objective of the Mekong Secretariat has been to examine the problems in their proper perspective to anticipate disfunctions, to implement measures for minimizing or offsetting adverse effects even before they set in, and then to use profitably the new environments created.

Acknowledgment. The author wishes to thank Mr. W. J. van der Oord, Executive Agent of the Mekong Secretariat, for his very helpful critical review of the manuscript.

REFERENCES

Fily, M., Description, operation and yield of fishing devices, Cambodia, Report on Fisheries Technology in Great Lake and the Tonle Sap, 1, Nat. Mus. of Natur. Hist., Paris, 1963.

Larkin, P. A., and V. R. Pantulu, Effects of hydroelectric development on the freshwater fisheries of British Columbia, *Can. Fish Cult., 25,* 12–23, 1958.

Le van Dang, Contribution to a biological study of the Lower Mekong, *Proceedings of the Regional Meeting of Inland Water Biologists in South-East Asia,* pp. 65–90, United Nations Educational, Scientific and Cultural Organization Field Science Office, Djakarta, 1970.

Ling, S. W., A review of the status and problems of coastal aquaculture of the Indo-Pacific region, *Indo Pac. Fish. Counc. Tech. Pap. 45,* 1970.

Mizuno, T., and S. Mori, Preliminary limnological survey of some South East Asian lakes, *Proceedings of the Regional Meeting of Inland Water Biologists in South-East Asia,* pp. 105–107, United Nations Educational, Scientific and Cultural Organization Field Science Office, Djakarta, 1970.

Mori, T., S. Nogusa, and E. Fujita, Fishes in Great Lake (Tonle Sap) Cambodia, Report on Expedition in Cambodia, *2*, pp. 51–56, 1958.

Overseas Technical Cooperation Agency, Sambor project report, Lower Mekong basin, *6*, Tokyo, 1969.

Pantulu, V. R., Some biological considerations related to the Lower Mekong development, *Proceedings of the Regional Meeting of Inland Water Biologists in South-East Asia*, pp. 113–119, United Nations Educational, Scientific and Cultural Organization Field Science Office, Djakarta, 1970.

Sidthimunka, A., A report on the fisheries survey of the Mekong River in the vicinity of the Pa Mong dam site, *Tech. Pap. 8*, Dep. of Fish., Bangkok, Thailand, 1970.

Sidthimunka, A., M. Patros, C. Boonsom, and M. Pawapootanon, Observations on the hydrology and fisheries of Ubolratana Reservoir (1965-1966), *Indo Pac. Fish. Counc. Tech. Pap. 15*, 1968.

Evaluating the Effects of Discharge Rates, Water Levels, and Peaking on Fish Populations in Missouri River Main Stem Impoundments

NORMAN G. BENSON
North Central Reservoir Investigations
U.S. Bureau of Sport Fisheries and Wildlife, Yankton, South Dakota 57078

Water management programs to produce power, flood control, navigation, and irrigation have reached a high level of precision in the Missouri River main stem reservoirs. Although these programs were not designed to fulfill the environmental requirements of fish, biologists should understand the effects of these programs on biotic production.

There are several reasons why fishery biologists are often ignorant about the consequences of many types of water management. First, our native fish species evolved in natural lakes and streams and have had to adapt to new environments when reservoirs were constructed. One cannot transpose directly our knowledge of the biology of fish in natural waters to fish in reservoirs. Second, we have inadequate knowledge of the environmental requirements of many fish species. It is difficult to distinguish between biological changes caused by natural conditions such as weather and those caused by man-made changes in the environment. Third, water management in a large reservoir system cannot always be programed for experimental purposes, and many years of data are frequently necessary to establish the relationships between water management and biological changes. It is much easier to document changes than to understand the causes. Fourth, each reservoir has about 25 common fish species with many predator-prey relationships. Fishery managers must understand the requirements of many fish species when they attempt to relate environments to fish populations. It would be irrational to program adequate spawning conditions for a predator species of sport-fishing value without considering the prey species that the predator must feed on. Also, we must consider the biological requirements of benthos and plankton, the primary fish foods. Finally, reservoir environments change owing to sedimentation, water management programs, and the quality and quantity of inflowing water. Much of our data in the Missouri River system was collected during the years of filling, and we must be cautious in projecting findings into the future. Although these limitations make it appear that the development of a firm understanding of the relations between water management and fish would be impossible, we have been able to attribute some biological changes to water management.

The research of North Central Reservoir Investigations, U.S. Bureau of Sport Fisheries and Wildlife, was designed, in part, to relate water management to fish, plankton, and benthos production. The objective is to provide basic knowledge for the use of state fish management agencies in managing recreational and commercial fishery resources. I will review some effects of water level fluctuation, discharge rates, and peaking on the biota of these reservoirs and describe some research in progress on modeling. Water level fluctuations refer to the changes in water levels in the entire reservoir, whereas peaking refers to the variations in water levels directly below dams that are caused by changes in discharge rates within a 24-hour period. The water management programs, engineering features, and fish populations of this system were described [*Bondurant and Livesey,* 1968; *Benson,* 1968], and the general morphometric features are shown in Table 1.

WATER LEVEL FLUCTUATIONS

Water level fluctuations will be viewed first in relation to the effects on the northern pike and next in relation to total fish populations. The reproduction of fish can be disrupted by water level changes prior to the time that eggs are deposited. *June* [1970] found that the sudden lowering of water

TABLE 1. Morphometry at Top of Annual Flood Control Pool and Average Storage Ratio in Missouri River Main Stem Reservoirs

	Fort Peck	Lake Sakakawea	Lake Oahe	Lake Sharpe	Lake Francis Case	Lewis and Clark Lake
Surface area, km^2	967	1489	1449	227	421	113
Volume, km^3	22.3	28.2	27.7	2.13	5.80	0.59
Average width, km	3.22	5.31	3.86	1.93	2.09	3.0
Maximum depth, meters	66	54	62	23	41	17
Average annual water level fluctuations, meters	3.0	3.0	1.5	0.6	10.7	1.2
Storage ratio	3.0	1.4	1.0	0.12	0.5	0.04

levels immediately prior to spawning was associated with large numbers of atretic eggs in the ovaries of northern pike; these resulted in intraovarian mortality. Abrupt decreases in water temperature also caused atresia. The interruption of spawning was associated with low year classes of pike for 3 years in Lake Oahe and Lake Sharpe. Also, northern pike require submerged vegetation for deposition of their eggs. *Hassler* [1970] found that the large year classes from 1959 to 1968 were associated with rising water levels over flooded prairie grass during the spawning and egg incubation period in Lake Oahe. If suitable vegetation on an exposed bottom is not available, it would be of no value to provide rising water levels during the spring spawning season.

Fish species that spawned during spring high-water periods in the river prior to the construction of reservoirs have had successful reproduction mostly during the early years of impoundment in these reservoirs and very irregular reproduction during normal reservoir operation. *Walburg and Nelson* [1966] documented this reaction for carp, river carpsucker, smallmouth buffalo, and bigmouth buffalo in Lewis and Clark Lake. Similar reproduction patterns for these species have taken place in Lake Francis Case [*Gasaway*, 1970], Lake Oahe, and Lake Sharpe [*Elrod and Hassler*, 1971]. Thus it appears doubtful that these fish species will remain dominant components of the fish population. Their major reproductive requirements are rising or constant water levels during the spawning and egg incubation periods plus suitable substrates. The fact that carp, river carpsucker, smallmouth buffalo, and bigmouth buffalo reproduce poorly may seem desirable to those concerned with the management of predator fish for recreational fishing. It is evident, however, that the young of these species serve as forage, and there is a direct relation between the total fish biomass and the growth and abundance of predators in these resevoirs.

There is a succession of spawning periods for those fish species in each reservoir that deposit adhesive eggs on the reservoir bottom or on submerged material at depths <1.5 meters. In general, spawning of the common fish species occurs from April 1 to July 1 in the following sequence: April to mid-May, northern pike, sauger, and yellow perch; May, river carpsucker, bigmouth buffalo, and smallmouth buffalo; May to mid-June, black crappie and white crappie [*Siefert*, 1969]; and June, white bass, freshwater drum, and emerald shiner. Times vary by year and among reservoirs. However, any decline in water levels during this reproduction period (April 1 to July 1) will reduce the spawning success of some species. The reproduction success of the species mentioned above has been very irregular on the reservoirs studied.

Those species that are less influenced by water levels during this same spawning period have had more consistent reproduction; these are walleye, freshwater drum, and goldeye. Walleye spawn at depths below the effects of water level fluctuation, and the eggs of freshwater drum and goldeye are buoyant or semibuoyant.

Benthos production on the bottom and on submerged trees is reduced when water levels are reduced in the late summer and fall [*Cowell and Hudson*, 1968]. Many forms (e.g., *Hexagenia*, a burrowing mayfly) that are important fish foods are rare in Lake Francis Case, a reservoir with a fall drawdown of 10 meters, but they make up >80% of the benthos biomass of Lewis and Clark Lake, a reservoir with little fluctuation. Chironomid larvae, the most abundant benthos group in Lake Francis Case, migrate with receding water levels, but large numbers are stranded and die each year. Submerged trees support a large assemblage of animals that live on the growth of periphyton (predominantly algae) on trees in Lewis and Clark Lake. The trees in Lake Francis Case become exposed in winter and lose the periphyton growth. It takes several weeks for plant life to develop on the trees after they become submerged in the spring, and the development of the animal population that lives on and within this plant community is delayed [*Cowell and Hudson,* 1968].

Periphyton growth also develops on plant stems that become submerged with rising water levels in the spring. After inundation it takes about 25 days for periphyton to develop and about 40 days for insects to inhabit this periphyton. If the plants are inundated too late or if the water level is lowered before the insect population can develop, there is a significant loss in fish food production. The development of this source of fish food is particularly important because much fish reproduction occurs during the spring period and there is a high food demand.

DISCHARGE RATES

The Missouri River main stem system first reached full operating levels in 1968, and large volumes of water had to be evacuated for flood storage during the spring of 1969. The effects of the increased discharge have been measured in reservoirs with high flushing rates, such as Lewis and Clark Lake and Lake Sharpe. The effects identified at this time are the reduction of zooplankton production, large losses of fish through the turbines, and increased mortality rates of small fish in the reservoirs.

Zooplankton production in Lake Sharpe was materially reduced with increased flushing rates in 1969. Oblique plankton samples were collected monthly at seven stations in Lake Sharpe from the dam to the Lake Oahe tail water from 1966 to 1969. From 1966 to 1968 the flushing rate ranged from 26 days to 50 days during June–October (Figure 1). In 1969 the high discharges reduced the flushing rate to 18 days in August and 22 days in September. Although the data for previous years showed that we can expect a decrease in abundance in August of the common zooplankton genera, the drop in 1969 was much more severe. The effects were most apparent on *Cyclops* and *Daphnia,* both important fish foods. The mean number of organisms per square meter (from surface to bottom) from July to October for the reservoir was 105,899 in 1966, 104,711 in 1967, 103,005 in 1968, and 57,974 in 1969. The decrease in production in 1969 could only be attributed to the increased flushing rate. The greatly reduced thermal stratification in the lower part of the reservoir in 1969 was associated with the low zooplankton abundance.

Further evidence of the importance of flushing

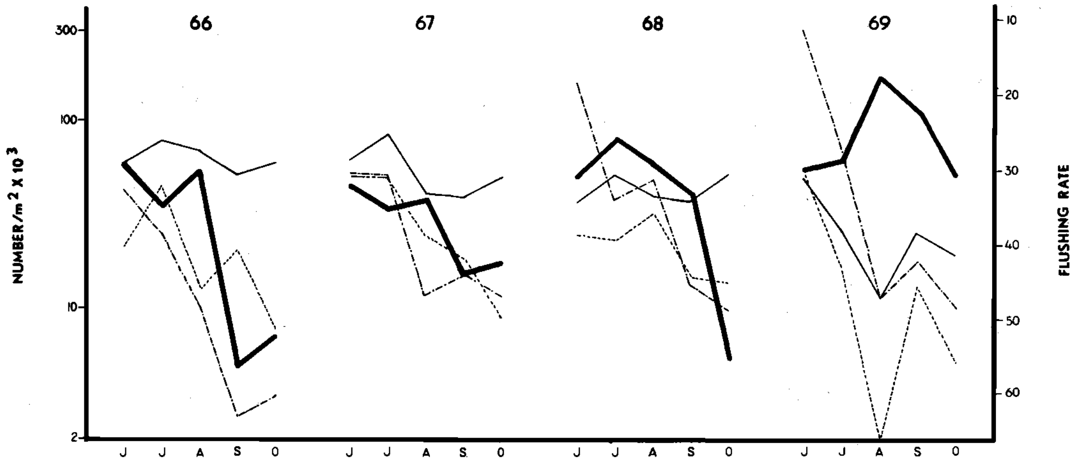


Fig. 1. Relations between flushing rate (heavy solid line) and abundance of important zooplankton genera (*Cyclops,* light solid line; *Daphnia,* dashed line; and *Diaptomus,* dash-dot line) in Lake Sharpe in June–October 1966 through 1969. Flushing rates in days for each month represent the mean daily reservoir volume divided by the mean daily discharge.

rates on the production of cladocerans (important fish food organisms) from 1964 to 1970 in Lewis and Clark Lake is available from D. B. Martin (unpublished data, 1973). Standing crops of *Daphnia galeata mendotae* and *D. schodleri* were significantly lower when flushing rates were high. *Daphnia retrocurva* and *D. pulex* were significantly more abundant as discharge rates increased, but this abundance was due to the fact that the small fish that feed on these daphnid species were being flushed from the reservoir (described in the second paragraph below) and predation on the daphnids was reduced.

The abundance of the spring (May–July) pulses of daphnids was analyzed as to whether production occurred within the reservoir or was carried in by inflows from the next reservoir upstream. The percents produced in the reservoir were 86% in 1964, 14% in 1968, and 42% in 1969. The flushing rates during these years were 8.6 days in 1964, 6.7 days in 1968, and 6.4 days in 1969. These findings strongly suggest that flushing rates had a significant bearing on the daphnid production in Lewis and Clark Lake.

The loss of fish through the turbines during periods of high discharge has a negative effect on the reservoir fish population. During June–August 1969 and 1970, losses were estimated by nets set directly above the intakes for 24-hour periods [*Walburg,* 1971]. Most fish were <25 mm long, but the numbers were high (Table 2). The most common species lost were sauger, freshwater drum, and emerald shiner. The estimated peak losses per 24-hour period were 10 million drum, 800,000 emerald shiner, 700,000 sauger, and 170,000 channel catfish. The number of fish lost was directly related to the flushing rate. Catch of age 0 fish from 1965 to 1970 by seine and trawl in Lewis and Clark Lake showed that the July–August flushing rate was inversely related to the August–September abundance of channel catfish, freshwater drum, gizzard shad, and emerald shiner. The estimated mortality rates for freshwater drum were directly related to the flushing rate in Lewis and Clark Lake from 1965 to 1969 (Figure 2). Freshwater drum are pelagic spawners, and the 18–34 mm size group is most abundant in the old river channel area [*Swedberg and Walburg,* 1970]. Currents in this area of the reservoir are higher than those in the floodplain, and freshwater drum would be extremely vulnerable to being flushed out of the reservoir.

TABLE 2. Estimated Mean Number (in Thousands) of Fish Species Lost per 24-Hour Period during Five 2-Week Periods from Lewis and Clark Lake in 1969 and 1970 and the Mean Flushing Rate for the Days Sampled

Date	24-Hour Samples		Carp		River Carpsucker		White Bass		Channel Catfish		Sauger*		Freshwater Drum		Emerald Shiner		Flushing Rate, days	
	1969	1970	1969	1970	1969	1970	1969	1970	1969	1970	1969	1970	1969	1970	1969	1970	1969	1970
June 1 to 15	4	7	...	1.1	...	...	...	...	...	...	222.5	48.5	...	...	5.2	3.8	5.7	5.6
June 16 to 30	7	9	...	24.3	...	11.1	...	0.6	...	...	18.0	13.7	...	3.2	32.0	6.3	6.5	5.9
July 1 to 15	7	8	5.0	94.6	4.6	32.7	3.8	2.0	...	10.2	0.8	2.7	1387.6	128.5	175.6	6.1	7.5	5.8
July 16 to 31	7	9	29.0	40.9	24.8	13.1	11.3	0.6	63.6	10.9	...	...	1800.0	117.0	240.7	6.1	5.7	5.7
August 1 to 15	6	8	1.7	...	1.7	0.8	...	...	13.3	0.8	...	...	82.7	29.9	21.2	11.8	4.5	5.5
Length range, mm			10 to 26	6 to 23	12 to 28	5 to 27	11 to 35	14 to 42	12 to 35	15 to 27	8 to 26	7 to 42	4 to 54	3 to 50	5 to 32	6 to 27		

*Includes a few walleye.

PEAKING

The only ecological effect that we have identified with peaking concerns sauger reproduction. Sauger from Lewis and Clark Lake move up the Missouri River and spawn 8–16 km below the dam of Lake Francis Case during late April or early May [*Nelson,* 1968]. Most spawning fish have been collected in water <1 meter deep, and most spawning has been observed in the early evening. Eggs are broadcast, adhere to the rubble, and incubate for 18–21 days. After hatching, larval fish move down to Lewis and Clark Lake. The time of spawning (1800–2100 hours) coincided with the maximum power release period, and many eggs became exposed to the air during the minimum release periods, which occurred within 12 hours after spawning. By eliminating the peaking operations during spawning and incubation (about 30 days), we were able to increase the abundance of sauger young by up to tenfold. This type of water management has been followed from 1966 to 1970. During some years a low water temperature during incubation caused egg mortality and reduced the effectiveness of this water management program. This type of water management to enhance fish reproduction needs to be studied for several years before the causes of failures and successes can be understood.

Another aspect of peaking that must have significance but has not been documented to our knowledge is the loss of immature insects from a reservoir at night. Drift measurements of insects below Lewis and Clark Lake show that the numbers of chironomids in night samples were 3–8 times those in day samples, and burrowing mayflies were collected only at night. The power plant at this reservoir does not peak, but large numbers of insects could be lost from a reservoir with peaking during the evening hours.

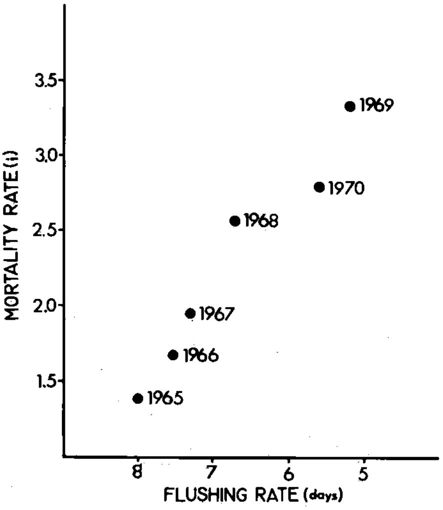


Fig. 2. Instantaneous mortality rates for 25- to 84-mm freshwater drum plotted against the mean July–August flushing rate for Lewis and Clark Lake in 1965 through 1969.

MODELING THE BIOTA OF A RESERVOIR

The complexities of the biological processes in reservoirs will always prevent us from precisely predicting the consequences of water management programs. Likewise, annual variations in runoff make it necessary for hydrologic programs to be flexible. Simple predictive models will have to be developed, and we have initiated research in this area on Lewis and Clark Lake. The general plan of this model is shown in Figure 3. We have data on about 40 variables collected over a 5-year period. The biological data include measurements of mortality, abundance, and growth rates of the common fish species; weekly abundances of plankton; and semiannual abundances of benthos. Nonlinear equations will be developed for relating various compartments. We know that natural or uncontrolled abiotic factors (e.g., air temperature and wind) will be significant factors in determining how this biological system functions. We also know what water levels and water exchange rates will be significant during some years. We have not included chemical and other physical parameters because they vary too little to warrant consideration. We assume that the biota will integrate many physical and chemical parameters. With this model we hope to answer questions such as the following.

1. What role does water management play in the relations among these biological compartments?
2. How will water management effects on the biology of a forage species be passed down to the survival, growth, and abundance of predator fish over time?
3. What benefits can we derive by modifying water management?

It becomes obvious that it will be difficult to program many fish environmental requirements into large reservoir systems. If fishery managers can predict what will occur, they can justify such fish management techniques as exotic or trans-

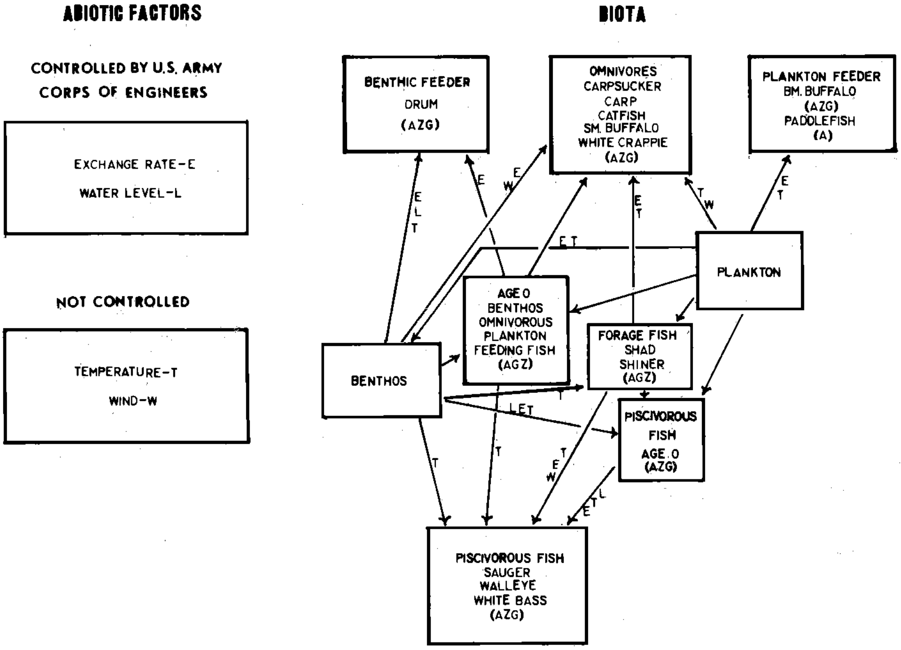


Fig. 3. Tentative simulation model to relate environmental measurements to biological measurements in Lewis and Clark Lake, A being abundance, Z being mortality, and G being growth rate.

planted fish introductions, maintenance stocking, or construction of spawning and nursery areas to compensate for losses caused by water management. The economics of modifying water management programs to benefit fish has not been discussed because the biological knowledge is too fragmentary. The amount of consideration that fish receive in future management programs will depend on the values that the public places on these fishery resources.

Acknowledgments. I wish to acknowledge the use of unpublished data from Fred June (zooplankton of Lake Sharpe), Dan Martin (zooplankton of Lewis and Clark Lake), and Patrick Hudson (benthos).

REFERENCES

Benson, N. G., Review of fishery studies on Missouri River main stem reservoirs, *Res. Rep. 71*, 61 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1968.

Bondurant, D. C., and R. H. Livesey, Operational problems associated with a basin reservoir system, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, pp. 47–53, American Fisheries Society, Washington, D. C., 1968.

Cowell, B. C., and P. L. Hudson, Some environmental factors influencing benthic invertebrates in two Missouri River reservoirs, in *Reservoir Fishery Resources Symposium*, edited by C. E. Lane, pp. 541–555, American Fisheries Society, Washington, D. C., 1968.

Elrod, J. H., and T. J. Hassler, Vital statistics of seven fish species in Lake Sharpe, South Dakota, 1964–69, in *Reservoir Fisheries and Limnology, Spec. Publ. 8*, edited by G. E. Hall, pp. 27–40, American Fisheries Society, Washington, D. C., 1971.

Gasaway, C. R., Changes in the fish population in Lake Francis Case, South Dakota, during the first 16 years of impoundment, *Tech. Pap. 56*, 30 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1970.

Hassler, T. J., Environmental influences on early development and year-class strength of northern pike in Lakes Oahe and Sharpe, South Dakota, *Trans. Amer. Fish. Soc.*, *99*(2), 369–375, 1970.

June, F. C., Atresia and year-class abundance of northern pike, *Esox lucius*, in two Missouri River impoundments, *J. Fish. Res. Bd. Can.*, *27*, 587–591, 1970.

Nelson, W. R., Reproduction and early life history of sauger, *Stizostedion canadense*, in Lewis and Clark Lake, *Trans. Amer. Fish. Soc.*, *97*(2), 159–166, 1968.

Siefert, R., Biology of the white crappie in Lewis and Clark Lake, *Tech. Pap. 22*, 16 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1969.

Swedberg, D. V., and C. H. Walburg, Spawning and early life history of the freshwater drum in Lewis and Clark Lake, Missouri River, *Trans. Amer. Fish. Soc.*, *99*(3), 560–570, 1970.

Walburg, C. H., Loss of young fish in reservoir discharge and year-class survival, Lewis and Clark Lake, Missouri River, in *Reservoir Fisheries and Limnology*, *Spec. Publ. 8,* edited by G. E. Hall, pp. 441–448, American Fisheries Society, Washington, D. C., 1971.

Walburg, C. H., and W. R. Nelson, Carp, river carpsucker, smallmouth buffalo, and bigmouth buffalo in Lewis and Clark Lake, Missouri River, *Res. Rep. 69,* 30 pp., U.S. Bur. of Sport Fish. and Wildlife, Washington, D. C., 1966.

Rise and Fall of Lake Apopka: A Case Study in Reservoir Mismanagement

ROBERT F. SCHNEIDER AND JOHN A. LITTLE

U.S. Environmental Protection Agency, National Field Investigations Center-Denver
Denver, Colorado 80225

HISTORY OF LAKE APOPKA

In recent years, Lake Apopka has been one of Florida's most studied lakes. Once known nationally as a recreational lake where record bass were caught it has now become excessively eutrophic and heavily overpopulated with trash fish. Perpetual algal blooms and extensive unconsolidated bottom deposits covering suitable fish spawning and feeding grounds have added to its many problems.

The lake, in central Florida, is located in Lake and Orange counties approximately 20 km west of the city of Orlando (Figure 1). The geologic life of Lake Apopka began before the mid-Wisconsin glacial recession, when the lake was formed from a bay. Freshwater life became established quickly because of a rich inorganic nutrient base. With time, organic matter accumulated on the lake bottom and provided a habitat along the shoreline for rooted vegetation. With an original surface area of approximately 18,000 ha the lake was the second largest natural lake in Florida. Banks of sandy soil formed a distinct southern shoreline, and a shallow marshy area developed on the northern border of the lake.

Evidence of man's influence on the character of Lake Apopka had begun by 1920 when citrus groves were being planted around the lakes of central Florida. The well-drained southern shoreline offered an excellent site for groves, but the marshland to the north was left undisturbed.

Small towns developed near the lake in the early 1900's. The largest, Winter Garden, was located on the southeastern shore. At first, a municipal sewerage system in Winter Garden was considered infeasible, but in 1920 the town constructed a sewerage system and two large septic tanks permitting wastes to enter the lake directly. This early use of the lake for disposal of inadequately treated wastes may have inspired the phrase 'dilution is the solution to pollution.'

Nutrients from municipal waste and runoff from the citrus groves seemed only to make the lake thrive at first. Grass beds in the shallows around the lake formed a dense cover for young fish, and marshlands along the northern shoreline provided excellent spawning grounds for a variety of sport fish. The lake became a popular fishing resort, and recreation abounded. At its peak, 13 fishing resorts and camps flourished around the eastern and southern banks. The annual income approached $500,000. Record size black bass, speckled perch, bluegill, and other panfish thrived in the big lake. Thousands of fish were caught each month. Commercial fishermen found Lake Apopka fertile for salable catfish also. More than 3 million kg (dressed weight) of catfish were caught commercially in one 8-month period.

Man had given little consideration to developing the marshy northern shore until the early 1940's. A few farmers at that time pointed the way toward draining small marsh areas near Lake Apopka and cultivating the newly exposed fertile soils. A plan for draining and farming part of Lake Apopka's marshland was formulated in 1942, and a dike was constructed near the northern shore. About 6000 ha of rich fertile lake bottom were exposed by draining away water north of the dike with large pumps (also used for irrigation). Because the land was extremely productive and several crops could be grown and harvested in 1 year, the conversion of marshland to cultivated land grew rapidly. In 1946 the waters of Lake Apopka were still described as being extremely clear.

In 1947, soon after large quantities of aquatic plants in the lake were uprooted by a hurricane, the first algal bloom was reported. The dense at-

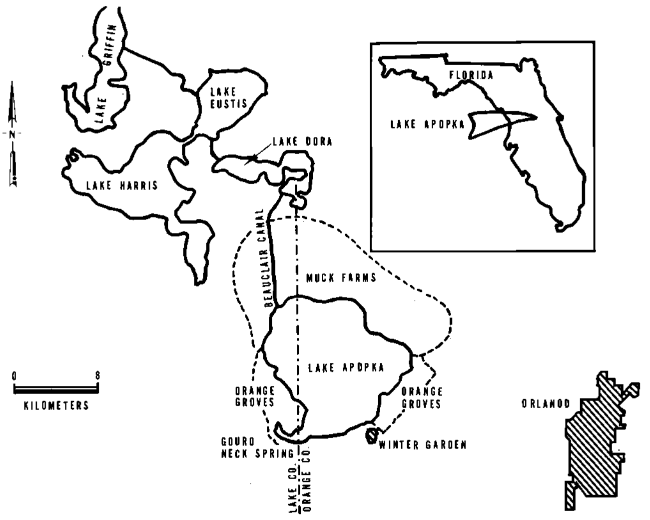


Fig. 1. Location map of Lake Apopka.

tached aquatic plants (*Vallisneria*) were never reestablished, probably because of a partial blackout effect caused by algal blooms, and the character of the lake was materially changed.

In the late 1940's, muck farm owners became increasingly concerned that future storms might weaken or destroy the dikes and reflood their croplands. The 1948 opening of Beauclair canal permitted better drainage of Lake Apopka to a downstream chain of lakes but at the same time lowered the lake several meters.

With the installation in 1952 of a control structure in the canal to regulate water levels the character of Lake Apopka changed from a troubled lake to a mismanaged reservoir. Lake drawdown for fish management was ignored. During periods of excess runoff the surrounding muck farms pumped water from their fertilized fields into the lake. Treated municipal waste and untreated citrus-processing waste water were poured into the lake at Winter Garden. Unknown acreages of water hyacinths were sprayed with herbicides and left to decompose. Algal blooms became persistent, and the lake visually resembled pea soup. Fishermen finally became irate and began to seek other fishing areas.

A 1956 Florida Game and Freshwater Fish Commission survey revealed the disappearance of game (sport) fish either by migration, death, or failure to spawn. The commission reported a species composition by weight of 82% rough fish (mostly shad) and 18% game fish.

In 1949 and 1950 the Game and Freshwater Fish Commission tried haul seining live gizzard shad out of the lake by the thousands to use them in a cat and dog food rendering plant. The seining, however, failed to change the balance of the fish population, and the commission decided to use poison as a control device.

Rotenone was used to poison gizzard and threadfin shad in November 1957, August 1958, and September 1959, during which an estimated 9 million kg of shad were killed. These fish were left to decompose in the lake, and the nutrients released triggered an extremely dense phytoplankton bloom following each treatment.

There were growing indications of the fall of Lake Apopka in May 1963, when 1,350,000 kg of fish were reported killed. A report released by the Florida State Board of Health in July 1963 indicated the cause to be gas (oxygen or nitrogen) embolism. A limnological survey during the following 2 years by the Florida State Board of Health showed that dense growths of floating phytoplankton were shading underlying phytoplankton, which were dying and sinking to the lake bottom, where they formed extensive unconsolidated deposits of organic material. These anaerobic flocculant deposits were not a suitable habitat for benthic biota; hence forage fish seeking food and spawning grounds were restricted to a small productive zone around the lake perimeter. This condition still exists. The Florida State Board of Health recently estimated the feeding and spawning grounds to be <800 ha in this 12,800-ha lake. Sport fishing is at a standstill.

On April 4, 1967, the governor of Florida appointed a technical committee to evaluate the restoration of the lake. Sixteen agencies, including the then Federal Water Pollution Control Administration (FWPCA), accepted the invitation to become active participants in the project.

FWPCA STUDY

In November 1967 the authors (representing the FWPCA) reviewed previous investigations of Lake Apopka. The review indicated that some special studies of the lake bottom and of certain nutrient sources entering the lake were needed before the technical committee could adequately evaluate the problems of the lake. A special study conducted by staff from the FWPCA Southeast Water Laboratory began in March 1968.

Sediment studies. The investigation revealed that unconsolidated bottom sediment (muck) covered 90% of the lake bottom. In some areas the deposit was 12 meters thick, but it averaged 1.5 meters. The anaerobic conditions and flocculant consistency of the sediment made these areas unsuitable for propagation of fish food organisms and game fish. Peat deposits were found along most of the lake shoreline, especially along the northern shore. (Peat deposits contain visible vegetable tissue and were distinguished from muck on this basis.) Although the peat deposits were more consolidated than muck, they were similarly anaerobic and provided little or no suitable substrate for desirable biota. Exposed deposits of sand, clay, and shell, which provided the only biologically productive bottom area, covered an area estimated to be 660 ha, about 5% of this 12,800-ha lake.

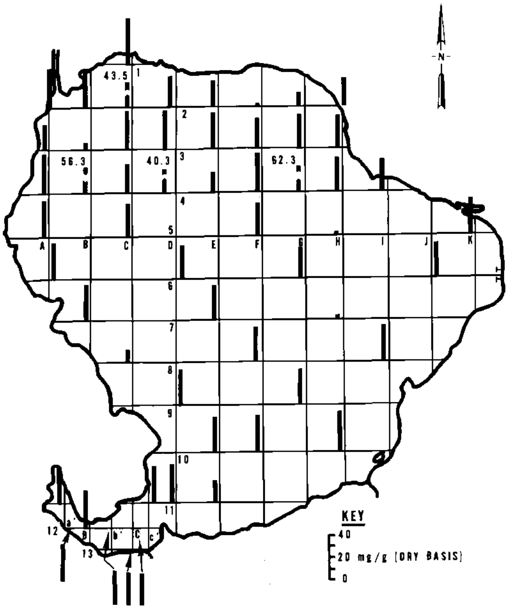


Fig. 2. Surficial nitrogen distribution in sediments.

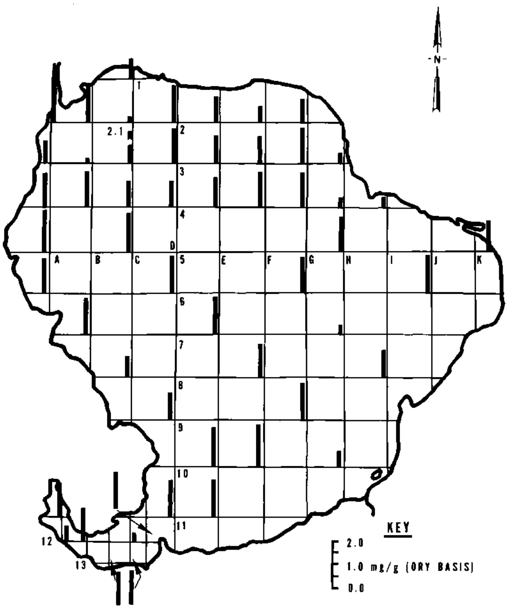


Fig. 3. Surficial phosphorus distribution in sediments.

Chemical analyses revealed that the top meter of lake sediments contained approximately 225 million kg of total nitrogen and 2¼–4½ million kg of total phosphorus. (Total nitrogen and phosphorus include inorganic and organic fractions.) Except for isolated bottom areas of shell, sand, or clay the surficial distribution of these nutrients was relatively uniform (Figures 2, 3). Individual values of total nitrogen ranged from 1 to 4% (dry weight) in muck deposits, whereas total phosphorus varied between 0.02% and 0.21%. Phosphorus concentrations usually decreased below the top few centimeters of the lake bed.

The average chemical oxygen demand value for muck samples (dry weight) was 1100 mg/g, whereas the solids content seldom exceeded 5% in surficial samples or 12% at a 1-meter depth. The volatile solids fraction composed 32–77% of the total.

The detailed study of bottom sediments emphasized the overall eutrophic state of Lake Apopka and pointed up a potential source of nutrients that could continue to enrich the lake long after external sources are eliminated.

External nutrient source studies. To determine the nitrogen and phosphorus input significance of all possible sources, certain unstudied or little-studied sources were included in the 1968 survey. Analysis of water collected from three shallow 'seepage' wells located along the citrus grove area of the shoreline showed a significant nitrogen and phosphorus content. The nitrate nitrite (as N) concentration ranged from 2.7 to 30.6 mg/l, and phosphate (as P) varied from 1.4 to 52.9 mg/l. These data showed that citrus grove drainage could be a significant nutrient source, although flow information would be needed for quantification.

On the basis of an annual precipitation of 1.25 meters and three rainwater analyses the nitrogen and phosphorus loading from rain falling directly on the lake was estimated as 6.75 kg/ha/yr total N and 0.8 kg/ha/yr total P. In comparison to the N and P entering the lake from other sources these amounts of N and P were considered significant.

Groundwater from the Floridian aquifer, which is the major water source for Lake Apopka, contained relatively low concentrations of nitrogen and phosphorus. The artesian aquifer generally had nutrient values ranging between 0.10 and 0.16 mg/l total N and 0.01 and 0.06 mg/l total P.

Upon completion of the FWPCA studies, abundant information was available to the technical committee for use in developing lake restoration plans.

RESTORATION PLANS

The FWPCA emphasized that any plan for the restoration of Lake Apopka must include a program of reducing the nutrient input. Point sources such as agricultural runoff pumped into the lake and municipal and industrial waste appeared to be the principal controllable nutrient inputs. Although the direct rainfall on the lake and the possible high nutrient input from citrus grove runoff were considered important, they were less amenable to control.

In addition to control of allochthonous nutrient sources, several solutions for improving the quality of the lake itself were considered.

1. Dredging would remove the richest deposits with disposal of the spoil to agricultural lands. The importance of nutrient recycling would be reduced by the removal of selected bottom deposits.
2. Lake drawdown would expose large areas of lake bottom to oxidization, compaction, or otherwise stabilization of the rich sediments. The actual removal of dried sediments could be accomplished. The lake would then be refilled.
3. Lake drainage combined with bypassing all inflows would allow the lake bottom to dry so that it could be converted to farmland. (This is a destruction scheme rather than a restoration scheme.)
4. Harvesting either by flotation, filtration, precipitation (not within the lake), or centrifugation would remove algae. The recovered algae could be used as a feed supplement.
5. Increasing the lake depth would reduce the importance of recycled bottom nutrients.
6. Hydroponic farming would remove dissolved nutrients.
7. The addition of an inert sealing material would stabilize bottom sediments.
8. Fish harvesting would remove nutrients on a large scale. The harvested fish could be used for protein supplement.

Other bizarre schemes were considered but not seriously.

The governor of Florida assigned complete responsibility for the restoration of Lake Apopka to the Florida Air and Water Pollution Control Commission, which decided to proceed with the lake drawdown scheme. The plan was to allow gravity drainage to lower the lake level 60 cm beginning December 1970. The effect of this lowering would be evaluated, and the lake level would then be drained further through pumping to 25% of its original area. This final drawdown would be effected in the spring of 1971. Water drained from Lake Apopka purportedly would be used to 'flush' the downstream chain of lakes. Hopefully, a suitable substrate for rooted shoreline vegetation would result from the drawdown and drying procedure, and the nutrient cycling capability of the exposed sediments would be reduced if not eliminated altogether.

In addition to the 1968 survey the Environmental Protection Agency (formerly the FWPCA) has contributed further to improving the quality of Lake Apopka and determining suitable means for restoring eutrophic lakes of this type. Specifically, municipal treatment at Winter Garden has been upgraded with federal funds, and research grants have been awarded for the treatment of citrus-processing wastes generated at a plant in Winter Garden and for laboratory and pilot studies of the drawdown proposal with emphasis on changes in the nutrient (carbon, nitrogen, and phosphorus) composition in aqueous and solid phases.

CONCLUSION

Lake Apopka was a typical clear shallow groundwater-fed lake in central Florida until man sought to render it more 'useful' for himself. Through his efforts the lake began to be a receiving water for wastes in the 1920's. In the 1940's the waste load increased rapidly as muck farming mushroomed along the northern shore. Control structures built in the 1950's were used to benefit land interests but not the lake itself. Even efforts to improve the fishery of the lake were mismanaged.

The history of Lake Apopka is not atypical. Other lakes in Florida and reservoirs all over the South are being subjected to similar attacks. Few of these are as large as Lake Apopka, but many are considered important recreational and/or water supply resources. Lake Apopka can be restored but only at great expense and with difficult decisions to be made, e.g., the extent to which a $10 million plus but marginal muck farming operation can expend money for nutrient removal.

The technical capabilities to prevent accelerated eutrophication are and have been available for some time. The planning foresight needed to prevent the early demise of our lakes, however, has come into being only lately. Today we must consider the full ecological impact of all our resource development activities if we are to eliminate the Lake Apopka syndrome from our aquatic environment.

Artificial Circulation Enhances Multiple Use of Reclaimed Water at South Lake Tahoe

GARY A. BOULIER

Hinde Engineering Company, Highland Park, Illinois 60035

Using the end product of a basic necessity to greatest advantage or even to advantage at all is a major and ever increasing role of man-made lakes for future waste water reclamation. Impoundment or storage of treated waste water provides advantages or benefits in the form of recreational fishing, boating, and water contact sports, new sources of water for lesser quality requirement uses such as golf course irrigation, and just plain decoration. Advancements in man's 'water pollution control technology' make treated waste water of sufficient quality available for these uses.

Indian Creek Reservoir, a man-made lake, is a prime example of waste water reclamation, i.e., environmental enhancement through man's technology. Born out of the Lake Tahoe pollution controversy, this Alpine County lake represents the ultimate in the concept of reusing water. To achieve maximum benefits from a man-made lake, such as Indian Creek Reservoir, water quality control is essential, from influent quality to in situ water quality. For this reservoir an exotic waste treatment plant provides influent quality control. Also, a unique method of in situ water quality control, a diffused aeration system, is being used. Emphasis, then, must be placed on the role of man-made lakes in waste water reclamation and the necessity of and methods for controlling their water quality to achieve maximum benefits.

LAKE TAHOE CONTROVERSY

Two occurrences in the early 1960's led to the water pollution controversy at Lake Tahoe. First, population pressure increased substantially, expansion of even basic waste treatment facilities being necessitated. Second, the overenrichment of Lake Tahoe, the ultimate receiver of nutrients in the basin, with the subsequent loss of its clarity and beauty came into public focus. It was recognized that continued and increased nutrient addition to the lake would accelerate eutrophication, the natural process of aging, and result in a great loss to the area's economy.

At the same time that consulting engineers for the South Lake Tahoe Public Utility District were designing the present advanced waste treatment plant, the local, state, and federal regulatory agencies and political entities involved made the decision to export all waste waters from the Tahoe basin. Before the waste water could be exported, however, it had to be treated to extremely high quality standards, and various political and mental blocks to shipping and receiving reclaimed water had to be overcome.

Indian Creek Reservoir would store water for agricultural irrigation and in-reservoir uses for water contact sports, including fishing, boating, and swimming.

ADVANCED WASTE TREATMENT

In the face of the Lake Tahoe controversy the South Lake Tahoe Public Utility District began in 1961 a long-range program to develop an advanced waste treatment process capable of overcoming the pollution problems cited above. The Tahoe process of purification and nutrient removal begins with the conventional and ends with one of the most, if not the most, advanced or exotic waste treatment plants in the world.

As is shown by Figure 1, the advanced treatment process begins with normal secondary plant effluent from an activated sludge process and proceeds to lime coagulation for chemical clarification to remove suspended matter and most of the phosphates. The high *p*H effluent is then pumped to a stripping tower for removal of ammonia nitrogen. The *p*H is then reduced to normal by recarbonation, or the addition of carbon dioxide. Filtration on mixed media separation beds removes the remaining turbidity, phosphates, and calcium carbonates. Final

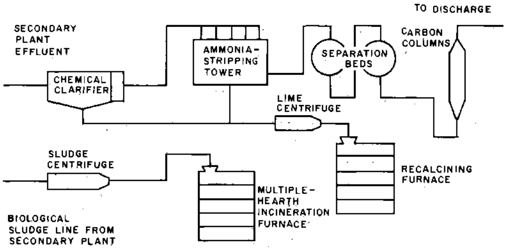


Fig. 1. Flow diagram of advanced treatment in South Lake Tahoe.

polishing is provided by granular activated carbon, which removes color, odor, and almost all the remaining organic matter. The costs of operating this exotic plant are minimized by reclaiming and reusing carbon, lime, and carbon dioxide.

RECLAIMED WATER QUALITY

Proof of the performance of this exotic waste treatment plant is shown in Tables 1 and 2 [*McGauhey et al.*, 1970]. Table 1 shows the overall treatment efficiency based on selected parameters from raw waste water quality to water reclamation plant effluent quality. Compare the normal 90% removal of biochemical oxygen demand (BOD), the common sanitary-engineering denominator for conventional biological treatment, in the activated sludge process to an overall removal efficiency of >99%. Comparable removal efficiencies were achieved with respect to the other parameters.

Table 2 summarizes plant performance with respect to local and state regulatory agency discharge requirements. Results prove 100% performance except for high suspended solids levels due to the flushing of fines from the new carbon columns. The suspended solids levels for 1969 were 0.

Dissolved oxygen (DO) concentrations in the influent reclaimed water, an extremely important factor in the DO budget within the lake, varied within 1–2 ppm.

Finally, and perhaps most important with respect to Indian Creek Reservoir, Table 3 summarizes the average values of total phosphorus and the nitrogen cycle components by month for 1969. Overall removal efficiencies for phosphorus were in the 99% range with average phosphate concentrations ranging from 0.08 to 0.29 ppm. Compare these removal efficiencies with phosphorus removal efficiencies of ≤50% in conventional treatment processes. High percents of nitrogen removal were also experienced.

INDIAN CREEK RESERVOIR

Located in Alpine County, California, on the eastern side of the Sierra Nevada Mountains, this man-made lake is the terminus for waste water reclaimed in the South Lake Tahoe area. This waste water is transported 43 km by pipeline, including a lift of 396 meters over 2397-meter

TABLE 1. Overall Efficiency of Treatment

Quality Parameter	Raw Waste Water Influent	Activated Sludge Plant Effluent	Water Reclamation Plant: Separation Bed Effluent	Water Reclamation Plant: Chlorinated Carbon Column Effluent
BOD, mg/l	200 to 400	20 to 40	<1	<1
COD, mg/l	400 to 600	80 to 160	30 to 60	3 to 16
Total organic carbon, mg/l	...	...	10 to 18	1 to 6
Suspended solids, mg/l	160 to 350	5 to 20	<0.5	<0.5
Turbidity, units	50 to 150	30 to 70	0.5 to 3.0	<0.5
Phosphates, mg/l	15 to 35	25 to 30	0.1 to 1.0	0.1 to 1.0
Alkyl-benzene-sulfonate, mg/l	2 to 4	1.1 to 2.9	1.1 to 2.9	0.002 to 0.5
Coliform bacteria, MPN/100 ml*	15,000,000	150,000	15	<2.2
Color, units	high	high	10 to 30	colorless
Odor	odor	odor	odor	odorless

*MPN means most probable number.

TABLE 2. Water Quality Data

Effluent Quality Parameter	Effluent Discharge Requirements: Alpine County	California Percent of Time: 50	California Percent of Time: 80	California Percent of Time: 100	Plant Performance Percent of Time: 50	Plant Performance Percent of Time: 80	Plant Performance Percent of Time: 100
Methylene-blue active substance, mg/l	0.5	0.3	0.5	1.0	0.01	0.03	0.06
BOD, mg/l	5	3	5	10	1.3	2.9	4.8
COD, mg/l	30	20	25	50	18	21	22
Suspended solids, mg/l	2	1	2	4	2*	5*	11*
Turbidity, Jackson units	5	3	5	10	1.3	1.6	2.0
*p*H	6.5 to 8.5		6.5 to 9.0			7.6 to 9.0	

Alpine County required the coliform bacteria (MPN/100 ml) to be adequately disinfected. California required the median number of coliform bacteria to be <2. The maximum number of consecutive samples >50 is 2. The median number of coliform bacteria at the plant is <2.2. The number of consecutive samples >50 is 0.

*High suspended solids due to activated carbon fines being flushed from new carbon columns.

Luther Pass, to the reservoir site at an elevation of 1707 meters above sea level. The reservoir, as formed by the main rock-fill dam, which is 18 meters in height, and a smaller saddle dam, has a surface area of 65 ha at maximum storage of 3,860,000 m^3. The site was prepared by first removing the vegetation and then stripping the soil to hardpan and rock to minimize available organics and nutrients.

Hydrology. Inflow to Indian Creek Reservoir is from two sources. Runoff from its 688-ha drainage area contributes about 1,000,000 m^3 of water per year, or about 18% of the total inflow. The remaining 82% consists of reclaimed water from the Tahoe area, reclaimed water that consistently meets the U.S. Public Health Service drinking water standards.

TABLE 3. Nutrient Concentrations in 1969

	Phosphorus, mg/l	Nitrogen, mg/l N: Ammonia	Nitrogen, mg/l N: Nitrate	Nitrogen, mg/l N: Nitrite
Jan.	0.18	2.7	0.22	0.04
Feb.	0.17	...	0.11	0.03
March	0.24	...	1.30	0.13
April	0.25	...	1.25	0.33
May	0.29	...	0.39	0.10
June	0.20	14.0	0.90	0.19
July	0.26	12.1	2.45	2.40
Aug.	0.12	15.7	2.20	0.26
Sept.	0.08	14.2	1.10	0.32
Oct.	0.13	15.9	1.10	0.26
Nov.	0.08	17.1	1.10	0.10
Dec.	0.17	19.4	0.30	0.06

Chemistry. Chemical analyses [*McGauhey et al.*, 1970] of impounded water showed good quality with little variation from top to bottom. The chemical quality of impounded water in Indian Creek Reservoir is summarized in Table 4 together with chemical analyses of Lake Tahoe water. Although the Indian Creek Reservoir water is of generally excellent quality, comparison with the higher quality Lake Tahoe water shows that the impounded water has a much higher level of biological productivity based on the available nutrients and carbon.

The clarity of the impounded water was typical of shallow impoundments of relatively good quality water with Secchi disk readings of ≤ 6

TABLE 4. Comparison of Selected Water Quality Parameters in Indian Creek Reservoir and Lake Tahoe in the Summer of 1969

Component and Unit	Indian Creek Reservoir June 4 to Aug. 12	Lake Tahoe
DO, mg/l	7 to 8	7.3 to 9.9
BOD, mg/l	2.6	...
COD, mg/l	35	$1^{\pm}$
NH_3-N, μg/l	3000^{+}	19
NO_3-N, μg/l	1550	7^{+}
Total N, μg/l	5900	123
PO_4, μg/l	25	4^{-}
Total P, μg/l	63	$8^{\pm}$
Ca, mg/l	37	9.3
Cl, mg/l	18	1.6
Fe, μg/l	14	<1
Alkalinity, mg/l	118	41
Hardness, mg/l	...	...
Total dissolved solids, mg/l	...	...
*p*H	8.0	7.7
Electrical conductivity, μΩ, at 25°C	319	$80^{\pm}$

meters in April 1970. Stratification was clearly evident during the summer months, temperature, DO, *p*H, alkalinity, and ammonia declining with depth. As evidence of stratification, Table 5 shows DO profiles taken during the summer of 1969. As was indicated, stratification, with a subsequent decrease in DO with depth, is most pronounced during the August sampling. Fall overturn with complete mixing was obviously achieved prior to the sampling on September 16, as is shown by the consistency of DO from top to bottom.

Limnology. Reclaimed water from the South Lake Tahoe plant was toxic to both fish and plankton with severely limiting nitrogen-phosphorus ratios of 150 : 1 and ammonia concentrations of about 1.5 mg/1. However, once the reclaimed water was in the reservoir, the mechanisms of dilution, nitrification-denitrification and ammonia stripping, and dissolution of phosphorus from the underlying soil provided a favorable environment for fish and plankton. In fact, a study [*McGauhey et al.*, 1970] for the Lake Tahoe Area Council concluded the following. First, the lake has a limited but high yield of benthic biota of the low-oxygen-tolerant types because of limited DO in the summer; second, the lake had developed a varied plankton population by July 1969, indicative of high productivity; and, third, a major finding was that by simple impoundment the reclaimed waste water quality was changed from being untenable to fish and certain algae to being of good productivity, limited of course by available nutrients.

OPERATIONAL PROBLEMS

Even with this advanced degree of treatment maintaining control of water quality influent to Indian Creek Reservoir and thereby maintaining a level of limited productivity within the lake, a serious problem has arisen. As was indicated in the preceding discussion, sufficient levels of DO could not be maintained at all depths to support the desirable biota throughout the lake. This problem manifested itself first during winter operation and complete ice cover, when stocked trout could not survive because of a lack of DO. Two factors contributing to this DO deficit would be the relatively low DO in the reclaimed waste water (1–2 ppm) and the relatively low chemical oxygen demand (COD) that would exert itself over a long detention time in the lake.

TABLE 5. Dissolved Oxygen Profiles for Indian Creek Reservoir

June 11, 1969		August 1, 1969		September 16, 1969	
Depth, meters	DO, mg/l	Depth, meters	DO, mg/l	Depth, meters	DO, mg/l
surface	7	surface	8	surface	6
1.5				5	6
		16	5		
				20	6
		23	2		
8	2				
		28	1		
		45	1	45	5

SOLUTION

The South Lake Tahoe Public Utilities District investigated, requested a system design, purchased, and, on January 5, 1970, installed an Air-Aqua controlled aeration system in the reservoir. A plan of the reservoir and the aeration system is shown in Figure 2. Using the mechanism of diffused aeration, the system distributes low-pressure air over the reservoir bottom to circulate artificially and oxygenate the water at all depths. The system includes oilless air compressors and specially perforated preweighted diffuser tubing. Needless to say, the equipment was installed by cutting holes in the ice.

RESULTS

The primary objective of the aeration system was to prevent winter kill of trout stocked in the lake by the California Department of Fish and Game. The following timetable [*Tharratt*, 1970],

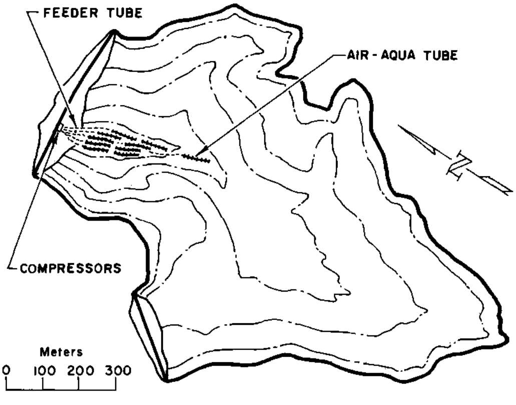


Fig. 2. Aeration system for Indian Creek Reservoir.

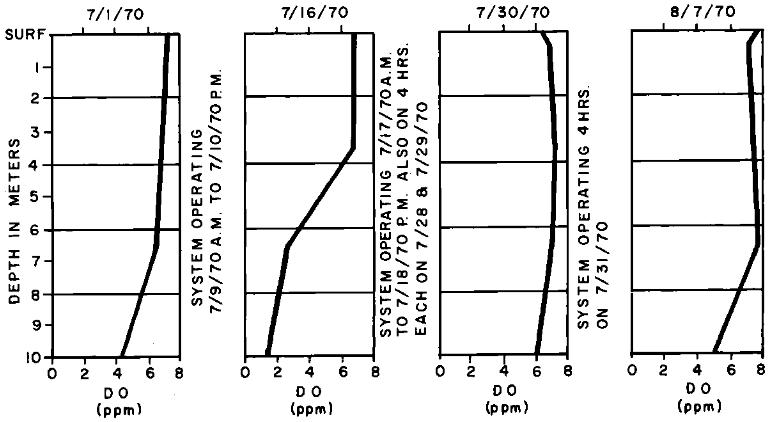


Fig. 3. Some DO profiles for the summer of 1970 in Indian Creek Reservoir.

provided by the California Department of Fish and Game, indicates the success achieved.

In May 1968, live cage tests in the reservoir with rainbow trout fingerlings were unsuccessful. All fish were dead within hours. In June 1968, additional tests with rainbow trout at the plant and in the reservoir were still unsuccessful. In September 1968, live cage tests in the reservoir with rainbow trout fingerlings were successful. All fish survived up to 2 weeks when the tests were terminated. In October 1968, experimental plants of 2080 7- to 10-cm rainbow trout fingerlings were made. Some delayed mortality was observed over the next week. From December 1968 to February 1969 there was heavy snow and an ice cover. In March 1969, gill net sampling did not take any fish, and no fish were observed in the lake. No fish had survived. In September 1969, additional live cage tests were successful. Fish were held in live cages from June through September. In August 1969, experimental plants of 8000 rainbow and rainbow-cutthroat hybrid fingerlings were made. The lake was frozen over during the latter part of December 1969. On January 5, 1970, the Air-Aqua system was placed in operation. The lake was completely ice free in about 2 weeks. The DO levels were at saturation with no thermal stratification. In March 1970, rainbow trout 20–30 cm long were successfully gillnetted. The trout season opened on May 2, 1970. The creel census results for May 2–3 were: boat anglers, 191; shore anglers, 729; total anglers, 920; angler hours, 3382; catch per angler hour, 0.37; and total fish caught, 1251. The rainbow trout averaged 32 cm long and 0.6 kg. The rainbow-cutthroat hybrids averaged 23 cm long and 0.17 kg. The estimated harvest for the opening weekend was about 11 kg/ha. The total visitors from May through November in 1970 were 7000–10,000 visitor days on the basis of a car counter and U.S. Forest Service use counts.

Additional benefit was derived from the system during the summer months. Just prior to March 1970 the power generator and compressors supplying air to the lake were stolen. Replacement compressors and generator were purchased and reinstalled in early 1970. The DO profiles presented in Figure 3 show the effects of intermittent operation of the system. June–August represents the period of maximum stability or stratification in a lake or reservoir. As was shown previously in the text, DO concentrations dropped to ≤2 ppm below a depth of 6 meters during June and August of 1969. As is shown in Figure 3, the DO concentration reached a measured low of 1.5 ppm at 10 meters depth on July 16, 1970. Intermittent operation of the aeration system increased the DO level well above the critical 4 ppm required by trout to live and thrive. These DO levels will also support and maintain the entire desirable biota of the lake.

CONCLUSIONS

Indian Creek Reservoir, a man-made lake, is a definite success in the waste water reclamation field. Maximum usage of impounded water in the form of agricultural irrigation and in-reservoir water contact sports, including boating, swimming, and fishing, is being achieved. Water quality control, a necessity to assure these uses, is being maintained on the influent reclaimed waste water by one of the world's most advanced waste treatment plants and in the lake itself by a controlled aeration system for circulation and oxygenation. Indian Creek Reservoir is indeed a product of 'fail-safe' imaginative technology.

Acknowledgments. The author greatly appreciates the assistance and information provided by Mr. Russell Culp, General Manager of the South Lake Tahoe Public Utilities District, by Mr. Robert C. Tharratt, Associated Fisheries Biologist with the California Department of Fish and Game in Sacramento, and Doctor P. H. McGauhey of the University of California, Richmond Field Station.

REFERENCES

McGauhey, P. H., et al., Eutrophication of surface waters—Indian Creek Reservoir, Lake Tahoe Area Counc., Calif., May 1970.

Tharratt, R. C., Miscellaneous data and background material on the California Department of Fish and Game's trout stocking program at Indian Creek Reservoir, Calif. Dep. of Fish and Game, Sacramento, Aug.-Oct. 1970.

Gas Supersaturation Problem in the Columbia River

PETER B. BOYER

Water Quality Section, North Pacific Division
U.S. Army Corps of Engineers, Portland, Oregon 97209

The gradual development of power, navigation, and flood control projects on the Columbia and Snake rivers has culminated in a series of stair-stepped dams with relatively slow-moving waters between them. Although this development has produced many benefits to the region, it has also produced an unanticipated serious problem: gas bubble disease in fish, resulting from exposure to the gas-supersaturated environment attributed to the operation of the spillway–stilling basin features of projects. This paper is prepared primarily to alert the design engineers and project operators to possible adverse effects of hydraulic structures having potential for entraining air and dissolving its constituents in amounts exceeding their normal saturation values. It also describes the U.S. Army Corps of Engineers efforts to alleviate the seriousness of the problem through structural and regulation modifications at the projects and through research.

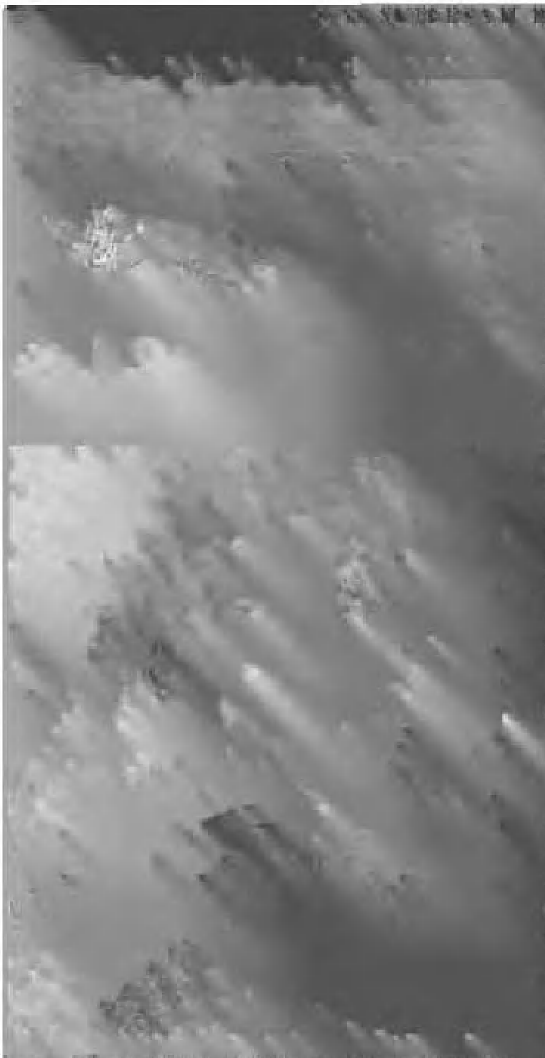
CAUSE AND EFFECT OF GAS SUPERSATURATION

Gas bubble disease has been known to exist for many years in fish hatcheries with water supplies from groundwater containing higher than normal dissolved nitrogen. It was not, however, until the spring of 1968 that the biologists and engineers also recognized gas bubble disease as a significant cause of fish mortality in a river under certain hydraulic conditions. Since then the U.S. Army Corps of Engineers, cooperatively with the federal and state fisheries agencies, has accumulated overwhelming evidence that the source of the dissolved nitrogen excess in the Columbia River is the entrained air introduced by the action of the spillway–stilling basin. Under hydrostatic pressure a part of this air is driven into solution before it has the opportunity to rise to the surface and escape into the atmosphere. Since the solubility of a gas is temperature-pressure dependent, one would find nitrogen-supersaturated waters also in stratified lakes, in deep pools at the bases of waterfalls, and at the junction of a warm stream and a colder one. Fortunately, these streams are generally shallow and turbulent, conditions conducive to rapid equilibration with the atmospheric pressure. In the stratified lake the dangerously supersaturated layer is at a considerable distance from the surface, it occurs in the fall when that layer warms, and it is of short duration.

Of course, the engineers knew that air would be entrained in amounts depending on the geometry of the spillway–stilling basin and the magnitude of spill. Its constituents would go into solution mostly in the stilling basin in concentrations exceeding the normal saturation values. But no one suspected that the velocity of the water, its circulation, and its turbulence in the run-of-river reservoirs on the Columbia and Snake would not be sufficient to purge the water of excess dissolved nitrogen completely between dams and equilibrate the partial gas pressures in the water with those in the air at the surface.

The constituents of the entrained air are: nitrogen and argon (79%), oxygen (20%), and other gases (1%). Biologists tell us that it is the dissolved nitrogen that causes gas bubble disease, because nitrogen is in greater abundance, is inert, and plays no role in the metabolic processes of the fish. In contrast, excess dissolved oxygen, in amounts occurring in the Columbia and Snake, is mostly metabolized, and other excess dissolved gases are in amounts too small to affect the fish. Thus the problem is referred to as 'the nitrogen supersaturation problem.' Actually, it is the magnitude of the difference between the sum of all partial gas pressures in the fish and the immediate environment of the fish that causes damage.

Fish will not suffer from gas bubble disease in supersaturated levels occurring in the Columbia



RESEARCH

On becoming aware of the nitrogen problem in the Columbia River, the U.S. Army Corps of Engineers immediately embarked on an aggressive and expensive research and development program and exerted leadership in marshaling the coordination of all interagency efforts to alleviate the seriousness of the problem. Together with federal and state fishery scientists the corps has prepared a list of research needs and priorities under two major categories: (1) engineering research leading to an improved understanding of the relation of causative factors to gas supersaturation and providing a solid background for operational and structural modifications in the interest of reduced nitrogen supersaturation levels without significant mechanical damage to fish and (2) biological research leading to an assessment of the adverse effects of nitrogen supersaturation levels on fish of various sizes and species and to an assessment of the effects of exposure time, swim depth, and temperature in combination with levels of such water quality indication as dissolved oxygen, carbon dioxide, turbidity, and *p*H.

One of the long-range engineering research objectives of the corps is the prediction of the dissolved nitrogen levels in the lower Columbia and Snake under different reservoir system regulations and geometries of the spillway-stilling basin. Predetermined nitrogen supersaturation levels are useful not only to engineers who prepare advanced regulation schedules but also to the engineer who designs release facilities, hopefully, with an eye on the dissolved gas supersaturation hazards. The ultimate aim of the corps research effort is to establish design and operational criteria for nitrogen supersaturation control at levels acceptable to fish or at levels that will meet the federal and state nitrogen stan-

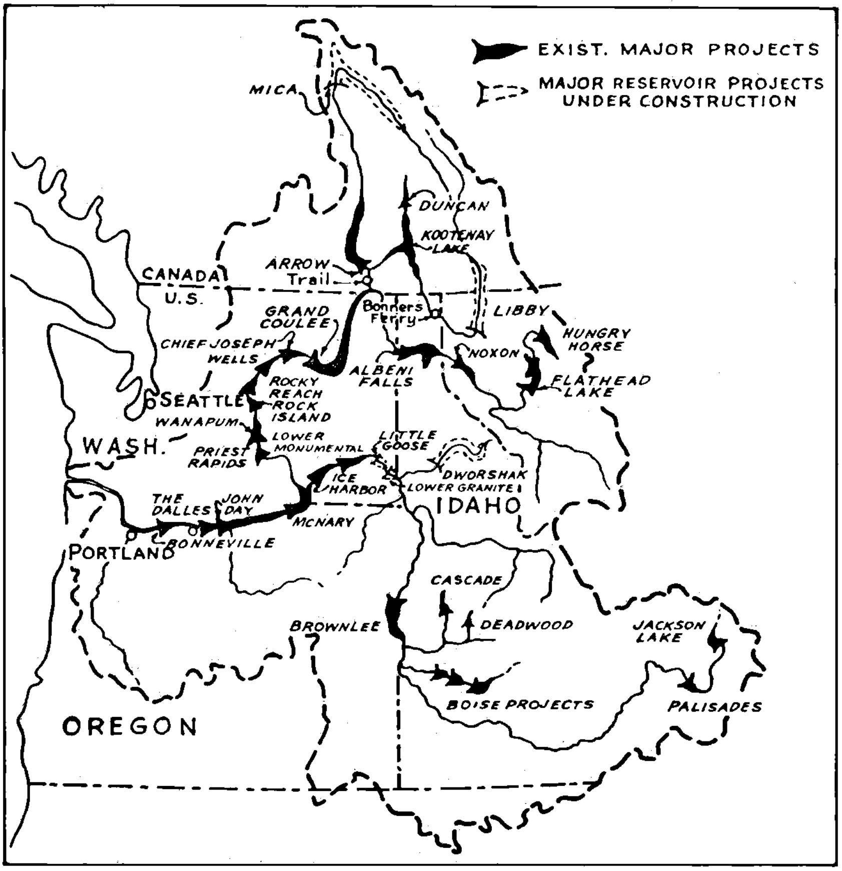


Fig. 2. Columbia River basin developments.

dards being established now. To this end, available nitrogen and related data are being evaluated for adequacy and guidance in preparing a valid economic nitrogen-monitoring program.

The corps has recently developed, under contract, a mathematical model and its computer program for simulating the dissolved nitrogen balance in the lower Columbia and Snake reservoirs. Properly calibrated, the model should predict the dissolved nitrogen levels at dams and in reservoirs. Essentially, the calibration consists of determining from measured data the best overall air entrainment coefficients unique to the hydraulic characteristics of each spillway–stilling basin and the degasification coefficients unique to the character of the flow in each pool or in the stream below a dam. Progress in model testing has been slow because the required field sampling and laboratory analysis of water samples for dissolved elemental nitrogen is slow, cumbersome, and expensive. Moreover, relatively few are qualified to take representative water samples and analyze them for dissolved nitrogen. But we are not discouraged. We aim to make the model operational by linking it to the daily reservoir system regulation 'master' model. The master model will then be capable of distributing the forecasted flows through turbines and spillways in the interest of reduced nitrogen supersaturation levels consistent with congressionally authorized project purposes.

REMEDIAL MEASURES

As a result of the concerted coordinated efforts of concerned federal and state agencies we now know when, where, why, how, and in what amounts the nitrogen supersaturation occurs and affects the fish in the lower Columbia and Snake rivers. But we do not know yet which of the many alternative possible solutions considered will be most reasonable and effective. Some have suggested 'blowing up' a few dams selectively to provide natural river circulation and a degasification opportunity! We do not have to resort to this unorthodox remedy. Since the turbine flows do not contribute to nitrogen supersaturation, the immediate solution approach points to increased upstream storage, modified regulation, and structural devices that will reduce spill, shift power loads, and prevent spillway discharges from submerging deep into the stilling basins. The corps is therefore proceeding with the following more orthodox studies and remedial actions.

1. As a temporary and partial measure, collect and transport a substantial number of seaward-migrating fingerlings overland from Little Goose Dam on the Snake River to below Bonneville Dam on the Columbia River to prevent a long exposure to the most hazardous nitrogen-supersaturated section of the reservoir system.
2. Provide more storage space, even at some risk of power losses.
3. Shift the power load to (and pass as much excess water as possible through) turbines at projects where spillways contribute the most to nitrogen production.
4. Pass the turbine capacity through slotted bulkheads in skeleton bays where the turbines are not yet installed provided mechanical damage to fish is not encountered. Provide such bulkheads also at generating turbine intakes where it is feasible.
5. Attach flow deflectors to selected spillway bays to prevent the deep submergence of the spillway water and air.

SUMMARY

The nitrogen supersaturation, which causes gas bubble disease in fish, is the most serious water quality problem in the Northwest. It is attributed to the operation of reservoirs on the Columbia and Snake rivers. During the April–July high-water season, power requirements are low; the excess flow must be passed over the spillways. The plunging water carries with it a large volume of air deep into the stilling basin. Here, under hydrostatic pressure and continuous spill conditions, water can hold dissolved nitrogen and oxygen in excess of its normal saturation value. Having lost its original turbulence and shallow depth to stair-stepped run-of-river reservoirs and a deep navigation channel, the river is no longer able to completely throw off the excess dissolved nitrogen. As a result the gas-supersaturated condition persists for 90 days everywhere in the Columbia River from Canada all the way to the Pacific Ocean. The problem is particularly serious because the Columbia River salmon is a valuable natural resource and the nitrogen supersaturation season coincides with the major fish migration season.

Cognizant of the seriousness of the problem

and concerned with the adverse effects of project operations, the U.S. Army Corps of Engineers has taken positive action toward both mitigation of the problem at existing projects and prevention at future projects. The corps is in continuous contact with other power producers in the region and is cooperating with the fishery scientists in the collection of quantitative and qualitative information on levels of nitrogen supersaturation, its effects on controlled samples of fish, its relation to hydraulic characteristics of the spillway–stilling basin feature, and its control through reservoir regulation and structural modifications and research.

Summary: Resettlement

THAYER SCUDDER

Division of Humanities and Social Sciences, California Institute of Technology
Pasadena, California 91109

Resettlement, both from the point of view of the local people and from that of the government, has probably been the least satisfactory process associated with the creation of man-made lakes. I do not mean to imply that dam construction has failed as a mechanism for incorporating rural and often isolated populations into the type of economic, social, and political development desired by national planners. Quite to the contrary, once a decision has been made to construct a dam, contacts between the local people and the outside world increase rapidly and significantly. Inevitably, the construction of access roads and the arrival of a large though temporary labor force accelerate change in certain areas of local behavior [*Scudder*, 1969]. Roads, for example, bring new ideas and behavioral patterns into the lake basin, and they also facilitate the incorporation of the local people into the national economy by functioning as feeder roads for commercial crops, including fish from the reservoir itself.

In the Pacific Northwest of the United States, *Walker* [1970] points out how dams have accelerated the assimilation and acculturation of even the local Amerindians, and *Fahim* [1970] emphasizes the extent to which relocation in connection with the Aswan High Dam has facilitated the political integration of the previously isolated Nubians into Egyptian society, although it has also reinforced their cultural identity. From the planners' point of view, such integration would usually be considered a major benefit accruing from the dam, although the situation is more complex as seen by the local people.

A major problem with relocation in connection with major dams is the lack of published research dealing with both the execution and the evaluation of specific resettlement programs. I am aware, for example, of no published material dealing with Latin America (aside from Mexico) or with India. Nor am I aware of any detailed evaluation of the resettlement of over 12,000 families in connection with Tennessee Valley Authority (TVA) dams in the United States. Though some research has been completed in Thailand and Turkey, little of this has yet been published. By far the most work has been done in Africa, especially in connection with four major projects. These are Lake Kariba (hereafter called Kariba) in Zambia and Southern Rhodesia (where over 50,000 people were relocated), Volta Lake (Volta) in Ghana (where approximately 80,000 people were moved), Lake Nasser (Aswan) in Egypt and the Sudan (where 100,000 people were moved), and Kainji Lake (Kainji) in Nigeria (where 42,000 people were moved). However, even in these places, no benefit-cost analyses of relocation have been completed, in part because of the difficulty in quantifying some of the variables involved and in part because we still have much to learn about the impact of relocation on people as individuals and as members of sociocultural systems.

NATURE OF RELOCATION

Population relocation in connection with man-made lakes can be categorized in terms of a number of distinguishing features. First, relocation is compulsory, the local people having no option but to move or be moved. Although certain individuals may welcome resettlement, usually the majority resent being forced to move. This resentment in itself is apt to foster antigovernment attitudes, which make planned development more complicated. Since the people did not ask to be dislocated, they may expect the government or the relocation authority to take over the major responsibility for their rehabilitation. If government does 'too little,' it may be severely criticized; if it does 'too much,' a dependence relationship can develop, as it did at Volta.

Because resettlement is compulsory, everyone must be moved, not just the progressive, who might move on their own initiative anyhow, but also the conservative, the young and the old. Though the situation obviously varies from population to population and within a given population, resettlement involves stress during the initial transition period. This transition period starts when the first rumors begin to circulate about the possibility of inundation. It ends when the relocatees regain their former self-sufficiency and work out a satisfactory relationship with their new environment and its previous inhabitants (hereafter called the hosts). Though for some the transition period terminates only with death, the large majority tend to adapt to their new surroundings within 2–10 years following their physical removal.

Compulsory resettlement is characterized by multidimensional stress, which can be broken down into physiological, psychological, and sociocultural components for analytical purposes. Although statistics are lacking, there is some evidence that, in spite of improved medical facilities, morbidity and mortality rates go up during the transition period. I suspect that an interplay of factors is involved, including, for example, higher population densities in new settlements, contact with new diseases or disease strains, and psychological and sociocultural stress. The elderly appear to be particularly susceptible to psychological stress, although this result has been better documented for urban renewal in the United States than for other types of resettlement.

Sociocultural stress can be inferred from a number of regularities associated with resettlement. One relates to a loss of confidence in local leaders and to a crisis of cultural identity. If local leaders agree to resettlement, their legitimacy tends to be rejected by the people. If they oppose relocation, their impotence is plain when resettlement proceeds according to schedule. A crisis in cultural identity is precipitated by the people's realization that their actions, institutions, and values are totally incapable of protecting their homeland.

Another regularity that would appear to increase sociocultural stress immediately following relocation is a temporary reduction in the complexity of behavioral patterns and hence a simplification of the relocatees' sociocultural system. Some activities that formerly gave pleasure and provided security are not transferred because they are tied to the old habitat or are irrelevant in the new. At Kariba, agricultural and other neighborhood rituals would be an example, and in the resettlement areas below Aswan the Egyptian Nubians dropped their Nile rituals when they relocated in a desert area several kilometers inland from the river. Other activities are not transferred for fear of alienating the hosts or provoking their disdain. This was especially the case among the 6000 people who were relocated below the Kariba Dam in an unfamiliar area with a bad reputation and among a people with a different heritage speaking a different language. As strangers the relocatees felt an insecurity that was increased when the hosts warned them to truncate their complex funeral ceremonial, since this, they were told, would alienate the spirits of the land. So the stress of not being able to cope with death in their customary way was added to all the other stresses that accompany resettlement.

Fortunately, the long-term capacity of people to adapt to new and even hostile conditions is little short of marvelous. On the basis of research carried out by *Colson* [1971] and myself in connection with Kariba resettlement, I hypothesize that people learn to cope primarily by using old behavioral patterns and old premises in new ways. In other words, they change only so much as is necessary to continue doing under new conditions what they previously valued. At Kariba, for example, a preexisting pattern was used by a number of those relocated below the dam to establish institutionalized relationships with the hosts. Once these relationships were formulated, they were used by the more influential and innovative relocatees to gain at least temporary access to some of the better host land. Though supposedly the relationships were based on reciprocity (the relocatees helping the hosts with plowing, food, and occasionally cash), in the long run I suspect this mechanism will serve the numerically dominant relocatees effectively as a means for establishing claim to more land in an area where land shortage is already a major constraint on agricultural development.

Another example of incremental coping relates to how the 6000 downriver relocatees adapted themselves to their new physical and biotic environment. At first, during a period of numerous deaths and associated fear, the people claimed that the land was 'bad' in a way that made it very difficult to take positive action. This state of affairs lasted for several years, but then a new type of spirit medium arose who claimed that it was not the land that was bad but people in it. These people caused barrenness and a wide range of potentially fatal illnesses and conditions, all of which could be cured by the medium. Although the concept of spirit medium was fundamental to the belief system, the actual spirit involved was a new one associated with the new area. Since the medium was indeed effective in achieving cures, his 'innovation,' which was based on an existing set of premises and on the old role of spirit medium, served as a very effective mechanism in helping the people adapt to and feel at home in their new habitat. Even the minority of Kariba relocatees who sought new occupations, like fishing, after relocation tended to use their increased income in traditional ways, although some individuals also used fishing as a stepping-stone to other occupations, which tended to remove them from the demands and influence of their relatives and neighbors.

These examples illustrate the type of coping mechanisms used to bring the transition period to an end. The emphasis is on continuity rather than on change and on the familiar rather than on the new. I am aware of no cases associated with resettlement of more radical social change from within, what anthropologists call revitalization movements. Involving one or more communities as opposed to separate individuals, these are 'deliberate, organized conscious attempts by some or all of the members of a society to construct for themselves a more satisfying culture.' In their search for new identities 'a people can successfully accomplish sweeping changes in culture in a very short time' [*Wallace*, 1967, pp. 448–449]. It may well be that the stress of relocation is sufficient to inhibit rapid revolutionary change; that is, the coping mechanisms used are incremental means whereby a traumatized population attempts to restore its sense of well-being gradually rather than a radical departure from the past. I am not completely convinced of this point (in fact, there are too few long-term studies to date to justify generalizing it), but the theory deserves testing simply because its validation would indicate that radically new systems of land use and radically new behavioral patterns and premises should not be introduced by planners during the transition period. Rather they should concentrate on reducing the duration of this period to the absolute minimum by helping the people to get back on their feet at the earliest possible moment.

> The broad intention or policy should be to move the people to new village sites, in such a way that their identity, self respect and initiative are not lost. The plan should be so worked out that once evacuated to new sites the people can complete their houses and recommence working as soon as possible. If feasible the changes involved should facilitate development, either agricultural or industrial, at a later date.
>
> *Butcher* [1971, p. 6]

PLANNING AND EXECUTION OF RESETTLEMENT

In their papers, both *Sikka* [this volume] and *Takes* [this volume] refer to a number of variables that need to be taken into consideration in connection with the planning and execution of resettlement. A more systematic checklist is given by *Brokensha and Scudder* [1968]. Also based primarily on the African experience is a resettlement manual by *Butcher* [1971].

I wish to stress in this review a number of topics that have received insufficient attention to date. These concern (1) resettlement timing and finance, (2) the nature of resettlement schemes as a complex of agencies and interest groups with quite different organizations and views as to what types of life styles are desirable, (3) the planning and realization of new systems of land use and occupations for relocatees, and (4) relationships between relocatees and hosts.

It is necessary to distinguish two very broad types of resettlement policy. The first type, discussed by *Eidem* [this volume], is characterized in the United States, where relocation authorities generally consider the individual household or farm as the unit under consideration. Though towns are moved as physical units, only rarely do the responsible agencies attempt to ascertain which rural residents would like to move as a community. Nor are they concerned with hardships that befall families and individuals who move out of the area on their own initiative. Rather the function of the relocation authority is to help those families and individuals who remain behind to find new homes. The emphasis is on housing as opposed to community, new job opportunities, or systems of land use.

Although the approach to resettlement in the United States may be the most suitable for people characterized by a relatively high level of education and job skills and by high individual and family mobility, it is not suitable for the elderly, community-oriented minorities, and populations of rural poor. Yet in the United States it is just these categories that tend to be disproportionately represented in reservoir areas. A number of major projects have flooded out the heartland of Indian reservations, and up to 50% of the population relocated in connection with TVA dams were sharecroppers. As for the elderly, *Eidem*'s [this volume] paper on the Perry Lake project in Kansas shows that they composed a larger segment of the population there than in neighboring urban areas. As for Perry Lake farmers who were required to relocate, Eidem notes that their farming skills were not so easily transferred as other skills since they were partially tied to knowledge of a particular piece of land and, in a broader sense, to knowledge of an area and its climate. In addition, when a sizable population of old people and farmers are all looking for land as close as possible to their former homes, prices are apt to rise, and hardships are apt to occur. Under these conditions, compensation may be inadequate, and additional types of assistance may be warranted.

By contrast, in Africa, resettlement is being viewed increasingly as a type of settlement scheme in which government planners attempt to relocate communities as communities, primarily because most lake basin residents want to be resettled with kin and neighbors. They still have a strong sense of community, and relationships within such communities are usually underlain by strong ties of kinship. Additionally, African governments view relocation today as an opportunity for implementing planned change within a broad program of national development. The projects associated with the Volta, Aswan High, Kainji, and Kossou (Ivory Coast) dams all illustrate this point.

The rest of this review concentrates on the resettlement of communities as opposed to that of individual families, not just because there is a published literature on African resettlement but also because the African experience is more appropriate for developing areas.

Resettlement Timing and Finance

Planning for resettlement is seldom initiated at an early enough stage. The same applies to setting up a suitable organization to administer the resettlement program. At Kariba, surveys to identify potential resettlement areas were not initiated until after the 1955 decision was made to build the dam.

> In Ghana the 1956 Report of the Preparatory Commission dealt with the 'Effects of Inundation' in considerable detail. Soil suitability and other surveys, however, were not oriented toward the type of intensive settlement and agriculture which the Ghanaian Government subsequently decided to implement among those relocated. Though the Kaiser reappraisal of the Volta River Project was published in 1959 and preparatory works were initiated during 1961 with the main civil contract finalized that August, the head of the Resettlement Unit, with supporting staff, was not recruited until May 1962. As for the relevant soil suitability and social surveys, they were not initiated until after the commencement of dam construction. In Egypt, the general situation was similar. Preparatory works at Aswan were completed in 1955 with the first Russian loan negotiated in late 1958. The Social Survey which involved forty social workers over a 30-day period was not carried out until 1960, delaying the formulation of comprehensive plans almost until 1962.
>
> *Scudder* [1966, p. 100]

Similar delays occurred in connection with Kossou. Though preliminary works at the damsite had begun by 1968 and construction on the dam itself began in February 1969, the agency responsible for relocation was not established until the following July.

Under such circumstances, there is insufficient time to plan and execute resettlement properly. Rather the move prior to flooding becomes a crash tension-laden program to move people physically into new environments, which will not be capable of supporting them on even a subsistence basis for years to come. Part of the problem arises from the tendency of governments to oversimplify the complexities associated with resettlement. Although those working at the damsite are frequently on or ahead of schedule, the resettlement agency is apt to fall farther and farther behind in its program. At the last moment it may have to call on outside assistance, perhaps from the armed services, to help out.

Another aspect of the problem concerns the incomplete integration of the resettlement and rehabilitation of lake basin inhabitants into the overall project design at an early enough date. Indeed, in some projects, as *Takes* [this volume] points out, integration never really occurs. For example, at Nam Pong in Thailand, relocation became the responsibility of a single department of one ministry, and at Kariba the Federal Power Board was only interested in the economic generation and transmission of power. The lake basin residents were not seen as a resource whose development could benefit themselves and their country but as an expensive nuisance.

It is important to emphasize the word 'expensive.' Not only is relocation complex, but it is also costly in terms of finance, personnel, equipment, and time. In my experience with the major African reservoirs, final cash costs tend to be 2–3 times the original estimates! To date, costs vary from approximately $200 per capita at Kariba, where relocation had no major impact on the housing and agriculture of the relocatees, to 10 times that amount at Aswan, where both the Egyptian and Sudanese governments attempted to transform Nubian society radically by resettling the people in modern towns supported by an irrigation economy. Where more intensive dry farming is stressed along with improved housing and a widened range of service facilities, as it was at Kainji and Volta, final costs have varied in Africa between $500 and $1000 per capita. Relocation of 50,000 people at $1000 per capita comes to $50 million, which rarely will be <20% of the combined cost of dam and power station construction. This cost, along with the human costs that accompany the transition period, is hard to justify when the relocatees, like those at Volta, have still to reestablish their former productivity 9 years after resettlement.

The logical corrective is to broaden the preinvestment feasibility surveys to include whatever ecological, agricultural, fisheries, medical, and social surveys are necessary to plan and implement productive resettlement properly. With the major exception of the report of the preparatory commission in Ghana, the scope of feasibility surveys, not only those done by national and private agencies but also those done by international agencies, has historically been too narrow. The World Bank's evaluation, for example, of lake basin fisheries and agriculture in connection with Kainji virtually ignored local agricultural and fishing practices in spite of the fact that indigenous irrigation (which is rare in tropical Africa) and a small commercial fisheries existed in the area.

Though the rate of change is still too slow, the situation is gradually changing. Governments are more apt to request international expertise in connection with resettlement and lake basin development, and international agencies are slowly broadening their studies to include resettlement and lake basin development. Concerning the financing of these studies, the additional costs involved are small when they are compared to the benefits that can accrue to both the lake basin population and the countries involved. Big dams in Africa have been the largest single projects in the national development plans to date. Because their implications are national rather than local, the development associated with these projects should be viewed as a large-scale pilot effort to develop more productive environments for rural residents, including the relocatees. (Both *Afriyie* [this volume] and *Takes* [this volume] make this point.)

Resettlement Schemes as Systems

Increasingly, social scientists study the complex of interrelationships between settler communities and development agencies as part of a single system [*Chambers*, 1969]. When this approach is applied to relocation, it is important to understand not just the behavior, premises, attitudes, and expectations of the relocatees and hosts but also those of the agencies that have a major responsibility for relocation and lake basin development. Depending on government policy, these agencies may consist of a dominant organization, like the Ivorian Bandama River Authority, or a number of government ministries whose separate activities may or may not be effectively coordinated. In either case, contracts will also be negotiated with various other agencies, including private and international organizations.

All these bureaucracies should be viewed as separate social and cultural systems. As *Foster* [1969, p. 96] pointed out, 'A bureaucracy in its structural and dynamic aspects is strikingly like a "natural" community such as a tribe or peasant village. It is a real society with a real culture.' Furthermore, 'bureaucratic "cultures" are similar to other cultures in that they are based on explicit and implicit premises to which their members subscribe and which they take for granted' [*Foster*, 1969, p. 97]. One of these premises is what I call 'the development from above syndrome,' that is, the tendency for development agencies to impose on settlers plans that have been worked out within the agency with a minimal understanding of the settler culture or cultures and minimal settler input. A benevolent paternalism is part of this syndrome, along with the expectation that settlers should be grateful for what government is attempting to do for them. There are also certain premises among professional groups within development agencies that at times seem almost immutable. Agriculturalists, according to *Foster* [1969, p. 104], 'believe that the highest possible yield per unit of land must be achieved, with the fewest possible farm hands,' whereas I have found fisheries experts more interested in productivity than in the number and type of fishermen involved. Although such attitudes make sense in some situations, they create difficulties in overcrowded relocation areas, where people need a new livelihood. Then it is more sensible to have several thousand fishermen, for example, catching 90% of the annual lake potential than to have a somewhat more efficient enterprise based on one-fourth that number.

Granted the development from above syndrome, it is very difficult to work 'with' as opposed to 'dictate to' settlers. (Certainly, part of the high failure rate among settlement schemes around the world can be attributed to the fundamentally different premises held by project personnel and settlers, and part can be attributed to essentially one-way communication, project personnel dictating to settlers whose behavior they only partially understand.) Even where development administrators are willing to facilitate self-reliance among settlers by helping them help themselves, poor communication can cause misunderstandings that undermine development. *Fahim* [1970, p. 12] analyzes just such a situation among Nubian relocatees at Kom Ombo north of Aswan.

> Besides the language barrier, the administrators' attitudes and efforts are often misinterpreted. This is clearly exhibited in Nubian resentment, for example, toward agricultural extension service agents, who are viewed as ignorant supervisors on matters Nubians assume to know better. Government-initiated suggestions or regulations are often taken as orders and are strongly resented by the Nubians.

Furthermore, 'Administrators report that any misunderstanding between an administrator and a settler usually becomes the concern of the latter's tribe . . .; the entire group will then antagonize the administrator' [*Fahim*, 1970, p. 12].

Not only must improved two-way communications be established between developers and settlers, but also conflicting behavioral patterns and goals must be understood to the extent necessary for avoiding conflicts that will jeopardize development. Thus more use should be made of organizational and operations research and of skilled social scientists and administrators, whose job it is to study the capacity of development agencies to do the job that they are committed to, to point out conflicting behavioral patterns and premises within these agencies, to study settler communities, and to interpret and clarify conflicts between individuals within an agency, between agencies, and between agencies and settler communities. Also at least some local settlers should be more involved in planning than they have been in the past, and more emphasis should be placed on facilitating development by encouraging and assisting local initiative and innovation.

New Systems of Production Associated with Relocation

Afriyie [this volume], *Sikka* [this volume], and *Takes* [this volume] all emphasize the need for project authorities to take responsibility for developing new economic opportunities for relocated farmers. Sikka and Takes stress the need for new opportunities for landless laborers, tenants, artisans, and others, and Takes urges assistance for those who wish to use relocation as a chance to change their occupations. I strongly support these points.

While resettlement has been one of the least satisfactory aspects associated with reservoir creation, the development of viable economic systems to support relocated communities has been one of the least satisfactory aspects of relocation. The slowness with which new systems of land use, and especially agriculture, have come into being has been a cause of major disappointment within developing areas. (In the United States, very little emphasis has been placed on the loss of livelihood in connection with both reservoir relocation and urban renewal. Though compensation is provided for lands and structures lost, for moving expenses to new homes, and sometimes for finding new homes, there is a general assumption that people will be able to find jobs and to purchase equivalent land and homes on their own initiative. Though this appears to be true for the large majority in any industrial society, the assumption is probably not warranted for certain categories of people. These include the elderly, certain minority groups, and relatively uneducated and unskilled low income groups.) There are two principal reasons for this situation. One, as *Takes* [this volume] points out, is simply because proper rehabilitation measures have not been adequately built into project planning. The other relates to a wide range of other difficulties. Since many of these are commented on by *Sikka* [this volume] and *Afriyie* [this volume], I plan only to supplement their comments here.

Agriculture. In dealing with reservoir relocation in Madhya Pradesh, Sikka comments on the Gandhi Sagar project, where approximately 52,000 people were relocated. He emphasizes the extent to which people, in his experience, are tied to the land or to particular occupations. Though he stresses the need for providing equivalent land, he does not comment specifically on the quality of the new land. Here the land policy seems similar to that used in Thailand for approximately 30,000 people relocated in connection with the Nam Pong tributary dam. The upland forest lands provided by the government were inferior in quality to the inundated lowland rice fields of the relocatees.

A major problem associated with relocation of peasants and tribesmen is the increasing scarcity of equivalent agricultural land. Governments respond to this situation in one of three ways. The first is to shift people to less fertile upland soils, examples being Kariba, Kainji, Nam Pong, and Chittagong (Bangladesh). The second is to provide smaller plots of roughly equivalent land, as was done at Volta and Kossou. The third is to reclaim desert or other unoccupied lands, examples being Kom Ombo and Khashm el Girba. All three approaches require intensification for satisfactory long-term results. Even where planning is excellent, agricultural intensification is an incredibly complex process, especially with relocation projects, since one must deal with total communities rather than with a number of carefully selected settlers. Furthermore, these are communities that are under stress as a result of relocation and that are apt to resent further government 'meddling' in their lives.

The Kariba experience is a good illustration of this point. Even though the land was known to be insufficient to support the people in many of the resettlement areas on the basis of their traditional system of agriculture, less emphasis was placed on the intensification of agriculture than on other local opportunities. Today, 15 years after flooding began, $<1\%$ of the farmers have intensified their agriculture through such measures as crop rotation and the application of soil additives in the form of either animal or green manure or chemical fertilizers. Furthermore, no lasting conservation measures have been established. Since land is limited and most communities have already cleared the better areas, a continuation of the same practices will inevitably lead to decreasing yields per hectare through land degradation. Already, severe hunger periods have reappeared in certain resettlement areas, and the erosion of upper catchment areas and riverbanks in the middle and lower reaches of the Zambezi tributary system is accelerating. (Although the middle Zambezi Valley has long been a famine area, it was not unreasonable to expect relocation to serve as a mechanism for correcting this adverse situation.)

In reappraising the situation after independence, the new Zambian government at first seriously considered the re-relocation of at least 6000 people. In part because the relocatees did not wish to move again and in part because of other factors, the Ministry of Rural Development is now pushing a program of agricultural intensification based both on smallholder irrigation and on dry farming of select cash crops. Although this new strategy is well conceived, the hour is late. If more than a small minority of farmers are to be reached, far more emphasis will have to be placed on extension, timely provision of small loans, and the timely provision through proper outlets of a wide range of agricultural requisites.

At Kariba, considerable research had been carried out that was directly relevant to the agricultural development of the lake basin area. However, it was not extended to the people in an acceptable fashion at the time of relocation. Rather the local people were left largely to their own devices. Although this approach reduced the transition period, it also produced adverse long-range effects. The resettlement at Kom Ombo represents a polar opposite. There the government wished to use relocation as an opportunity to increase productivity greatly through intensive irrigation. Although planning and execution were good, the complexity of the development program lengthened the transition period, so that 6 years after relocation settlers were still dependent on the government for food relief and other types of assistance.

Where government planning and execution in connection with agricultural intensification are poor, it may be many years before the relocatees get back to their original subsistence economy. This situation occurred at Volta Lake, where World Food Program assistance was still needed 7 years after relocation. For a complex of reasons, some of which *Afriyie* [this volume] outlines, viable farming systems have not been achieved in any of the new Volta settlements for a majority of the residents. As a result a significant number of the new core houses remain empty, their occupants having either moved to fish camps or left the lake basin entirely to seek land or job opportunities elsewhere. Such a situation is obviously in no one's interests. To consider other alternatives, a socioeconomic survey was carried out in 1968. With the information provided a new policy was formulated. This will 'lay emphasis on improved subsistence agriculture with each entitled settler and host-farmer being allocated a 3-acre plot to be cleared by hand.' Food for work will be provided by the World Food Program. Though the new program was designed to correct past mistakes, it is plagued by new uncertainties, of which Afriyie is well aware. These include the provision of an effective extension system and the use of techniques by the farmer that will maintain soil fertility.

To sum up, the record to date in connection with agricultural development for relocatees is poor. To correct this situation, the logical alternative is to integrate planning for relocation into early project design, including agricultural and socioeconomic surveys in the original preinvestment or feasibility surveys. Also, sufficient funds for resettlement agriculture should be included in the project estimates, including funds for the legal acquisition of land for both resettlement villages and farms [*Butcher*, 1971, p. 7]. Land preparation and extension work should begin prior to relocation. Wherever it is possible, small pilot projects should be implemented as soon as (if not before) the decision is made to proceed with preparatory works at the damsite. Their purpose would be to test the viability of proposed land use systems in the field and to serve as demonstrations to local farmers both before and after relocation. Special attention should be given to the development of what I call 'compromise systems,' which are systems that are acceptable both to national planners and to the local settlers.

Use of the lakeshore margin. Where relocation involves thousands of people, more attention needs to be paid to various uses of the lakeshore margin. Because of land scarcity and existing land rights it is seldom possible to resettle lake basin residents below the dam, where they can benefit from gravity flow irrigation. As a result they are often shifted to lower potential soils in the hills and valleys surrounding the new lake. Left untouched are the thousands of hectares of annually flooded land in the drawdown area. There are at least two reasons why this land is left untouched. One is an attempt by the government to protect the reservoir from siltation and pollution by prohibiting settlement along the reservoir margin. Except for small reservoirs near urban centers, I doubt that this policy makes much sense either ecologically or economically. More serious is the irregular nature of the drawdown, which is directly tied to inflow, local rainfall, and outflow at the dam in connection with power and downstream needs. Not only does the drop in lake level begin at a different time each year, but any farmer who cultivates the emerging land has no way of knowing how fast the water will drop or whether it will begin to rise and flood his fields before his crops are harvested. At Lake Kariba, where the drawdown uncovers hundreds of thousands of hectares of cultivable land in some years, only a scattering of farmers dare plant this area. The risks are simply too great, including the periodic discouragement of having excellent crops flooded when the reservoir begins to rise.

Though I am not aware of any relevant benefit-cost analyses, I suspect that, where drawdown agriculture could provide land for thousands of farmers and vegetables and other crops for local consumption and export, it would be socially and economically profitable to integrate it into national and regional planning. This integration would of course require regularizing the drawdown in such a way as to guarantee a water-free period sufficient to cultivate select crops. This regulation could have potentially negative implications for power generation and downstream flow, which would have to be assessed carefully. Perhaps the costs would exceed the benefits accruing from use of the drawdown area. A priori, we do not know, hence the need to build more complex models that can evaluate this additional possibility. Adverse implications for power generation might be offset through the development of national and international grids, although benefits and costs would have to be assessed carefully.

Not only would it be necessary to regularize the drawdown, but reliable information would also have to be relayed to the farmer as to when, where, and what he could plant. Since a well-organized extension service is already a prerequisite for any major relocation project, drawdown agriculture would be included in the responsibilities of the extension staff.

The potential of the drawdown area is not just restricted to food and cash crop production. The area is also available for livestock. Since drawdown is apt to begin during the latter part of the dry season, the lakeshore margin and the drawdown area provide a potential source of dry-season grazing for cattle and small stock. Water, obviously, is also abundant at a time when drought often creates serious problems for inland stock. In the evaluation of this option for the local people the planting of fodder crops in the drawdown area should also be considered as a possibility.

Another possibility concerns fish ponding in the drawdown area. Finally, small pumping schemes should be considered in connection with the irrigation of suitable areas immediately inland from the high-water margin. This possibility is receiving serious consideration at Lake Kariba, and experimentation is about to start at Volta Lake as a result of Obeng's pioneering efforts in her own garden. Though these efforts follow relocation by more than 5 years (in fact, 10 years at Lake Kariba), at Kossou the Ivorian government is considering pump irrigation in carefully selected lake basin locales as part of its preinundation planning.

Fisheries. A major exception to the slow development of new systems of production has been the rapid emergence of reservoir fisheries. Regardless of government policy, small-scale commercial fishermen have quickly pioneered the use of new reservoirs. Examples are worldwide. In the United States, *Walker* [1970] refers to the development of gill net fisheries among Amerindians, who have begun to use gill nets on the reservoirs of the Pacific Northwest. In Africa, over 2000 local Tonga were fishing Lake Kariba at the time that the lake reached its upper margin 4 years after the dam was sealed. Even more spectacular was the situation at Volta Lake, where *Lawson* [1966, p. 11] reports estimates of 10,000 fishermen and 4000 canoes within 2 years of initial impoundment. By 1970 an estimated 20,000 fishermen with over 12,000 canoes were catching an estimated 60,000 metric tons of fish per year. Approximately 1000 fishermen are present on Thailand's Nam Pong Reservoir in spite of an attempt by the government to discourage settlement along the lakeshore margin.

The emergence of small-scale peasant fisheries in connection with tropical reservoirs is an excellent example of the rapidity with which rural residents will respond to certain types of new opportunities. On the basis of past experience we can predict with a high degree of probability that lake fisheries present government with an excellent opportunity to facilitate development. If we can agree that the local population should share in the benefits of the dam, government assistance is most needed where the lake basin residents have little to no background in commercial fishing. This situation occurred at Lake Kariba, the policy of the then Northern Rhodesian government still serving as one of the best models for other African reservoirs. Realizing the lack of local skills, the provincial administration closed the lake during a 5-year period to all outsiders. During that time a major attempt was made to train the local Tonga as gill net fishermen at a Fisheries Training Center opened in 1962. Through the efforts of the provincial administration, nets, boats, and outboards were provided at an early date, and a revolving fund was established for the purchase of equipment. The local district council was encouraged to assist by financing a ferry service to call at outlying fish camps and by stationing fish orderlies in the major camps. The council also benefited financially, since it collected a tax on fish exported by traders. As a result of these activities the better local fishermen were able to compete successfully when the lake was opened to other fishermen in 1964.

Irrespective of who the fishermen are, reservoir fisheries, along with processing, trading, and other service activities, provide not only an important source of protein in protein-deficient tropical countries but also a significant number of new jobs, far more, for example, than those provided by the major industrial users of project power. Furthermore, Zambian evidence indicates that the development of new fisheries is correlated with at least a temporary drop in the proportion of labor migrants leaving the area for urban and other external employment. Because of the rising rates of urban unemployment in tropical cities, more attention should be paid to the development of reservoir fisheries, emphasis being placed not just on fish landings but also on providing opportunities for the largest number of people and on taking pressure off the limited lands available for agriculture.

Other job opportunities. Though most rural residents in tropical Africa are farmers with secure access to land under traditional systems of tenure, the same is not true elsewhere. Partly for this reason, *Sikka* [this volume] and *Takes* [this volume] are rightly concerned about the loss of livelihood suffered by landless laborers, tenants, artisans, traders, and others. A similar concern occurred at Aswan in connection with the owners and crew of the sailing craft that served otherwise isolated riverine communities prior to inundation. Artisans and traders are frequently integrated into the social and economic organization of specific communities, an organization that may be altered fundamentally by relocation. Furthermore, since governments in developing areas usually use relocation as a mechanism to create larger settlements, small-scale specialists may find themselves at a competitive disadvantage once they move from villages to towns. Landless laborers and tenants may well find themselves unemployed after the move, especially during the transition period, when farmers have not yet received or prepared all their land.

To the best of my knowledge, no resettlement authority has developed a satisfactory policy to cope with this broad problem. Pointing out that compensation and access to improved service facilities are not sufficient, *Sikka* [this volume] notes a number of ways in which alternate opportunities could be provided, although he does not tell us the extent to which these have been incorporated in existing projects. One of his points brings up the very complex question of integrating relocation with construction townships. In spite of the timing problems, it should be possible to coordinate the construction of large dams and the relocation of large numbers of people in such a way that construction townships are able to turn to other viable activities once construction is completed without a permanent loss in population.

Relationship between new systems of production, housing, and social services. In recent African projects, too much emphasis has been placed on housing, and too little has been placed on the economic basis for supporting elaborate new communities. If I had to rank these factors, both of which are obviously important, I would place viable land and water use systems first and housing last. As for improved social services they are really the easiest aspect of resettlement to achieve. In all the cases with which I am familiar, new schools are used and appreciated. Indeed, where new productive systems are not sufficient to support the entire relocated community, I suspect that many settlers who have moved elsewhere will send their children back to the improved schools associated with the resettlement projects. Then the dominant groups in costly new communities will be the elderly and children.

Improved medical facilities, feeder roads, markets, and other facilities are also appreciated and used. Ironically, the least effective service to date has been the water supply [*Scudder,* 1973].

Relationships between Settlers and Hosts

Too little attention has been paid to the relationships between relocatees and prior inhabitants, or hosts, in relocation areas. These relationships are apt to be strained for a number of reasons, of which the most important is increased pressure on limited land. At Kariba, for example, land conflict was a problem 12 years after relocation in the Lusitu resettlement area below the dam. Relationships between approximately 10,000 relocatees and hosts were strained because the relocatees (who were numerically superior) were expanding their fields into the territory of the hosts, who continued to maintain ritual authority over the land involved. At Volta, problems of land tenure and ritual authority were also severe, to the extent that the Volta River Authority had to purchase land and redistribute it 4 years after resettlement. I suspect that similar problems will arise in the years ahead at Kossou and other resettlement projects simply because of the increasing scarcity of suitable land. To cope with this problem, at the very minimum the resettlement agency should obtain, prior to relocation, the legal authority to intercede in land disputes that threaten development. Sometimes adjudication of disputes may suffice, but at other times it may be necessary for government to not only acquire and then redistribute the land in question but even arrange for the transfer of ritual authority over the land.

Another source of tension between settlers and hosts arises when the settlers are provided with new housing and improved social and economic services that are not available to the earlier inhabitants. The proper approach here is to involve the hosts in the development planned for the relocatees, even though this involvement will increase cash and staff requirements. It is too much to expect the hosts, especially if they are losing some of their land,

> to understand that government assistance is being provided as compensation for being uprooted and removed and hence is exclusive to those undergoing relocation. At the very minimum new services such as schools, medical facilities, and training centers should be equally accessible to both old and new residents. Where agricultural change is involved, and the development of fisheries, again it is important to include the prior inhabitants. To do otherwise is to risk trouble which could have serious consequences.
>
> *Scudder,* [1966, p. 25]

EVALUATION

A report by the *National Academy of Sciences–National Research Council Committee on Water* [1966, p. 15] states that 'no major water project in the United States has been studied with sufficient care and precision to determine its full effects on the systems of water, soil, plants and human activity that it has altered.' The worldwide need for research is especially important in connection with compulsory relocation. We just do not know enough about the impact of resettlement on people and about how to offset adverse implications and capitalize on beneficial ones. At the same time, there are no adequate benefit-cost analyses of various relocation strategies, let alone of whole river basin projects. A fundamental reason for broadening the feasibility studies to include ecological, agricultural, fisheries, medical, and social surveys is that such surveys can also serve as a base line for subsequent evaluation.

Two types of evaluative research are needed. The first would consist of a limited number of systematic long-term studies. Their purpose would be to monitor projects carefully selected to represent the entire range of resettlement strategies. Though they would obviously have practical implications, their principal justification would be theoretical: to help us better understand how people react to the compulsory resettlement and to the various types of development associated with relocation. They would also be designed to provide benefit-cost analyses at different points in time.

The second type of evaluative study would be built into each major relocation project in the form of periodic short-term surveys. Though these studies would also have theoretical implications, their main function would be practical: to identify problems and bottlenecks as they arise and to provide updated information for formulating policy to remove them.

SUMMARY

The planned resettlement of entire communities is an incredibly complex process, far more complex than most relocation agencies realize at the beginning of their activities. This process is dynamic and can be divided into two major periods. The first is a transition period, during which most people are usually worse off than they were before. They suffer stress and must rely on outside assistance for 2 or more years. The major role of government at this time should be to help the people get back on their feet at the earliest possible time. The second period begins when a majority of the relocatees are once again self-sufficient.

Community resettlement is a type of settlement scheme, and the failure rate of settlement schemes is discouragingly high on a worldwide basis. Planners do not yet have the knowledge to execute a successful settlement scheme in the same way that engineers can build a successful dam. This lack of knowledge is especially true of the forced resettlement of large numbers of people. Yet, because relocation in connection with dams is compulsory, governments have a responsibility to help the evacuees benefit from these projects along with other citizens. Where community ties are loose and there is considerable family and individual mobility, the best resettlement strategy, granted our present knowledge, may be to facilitate attempts by individual household heads and family members to start a new life elsewhere. In other words, the unit for resettlement and rehabilitation would be viewed as the individual and the household rather than as the community. The stress would be on helping these people purchase equivalent or better lands and reestablish old occupations or new ones throughout the nation rather than in a specially planned new community.

Though the proportion of relatively self-contained and mobile households is obviously higher in an industrial nation than in developing countries, developing countries should not automatically assume that all lake basin residents wish to be relocated together. One of the principal purposes of timely social surveys should be to find out as accurately as possible just what people's skills and intentions are so that plans can be formulated to help them realize these intentions as individuals, families, and communities. At Nam Pong in Thailand, for example, <50% of the people opted to settle in the planned community that was being prepared for them. Among the majority, some took to lake fishing in spite of attempts by government agencies to discourage settlement around the lake margin. Others moved to northern Thailand to purchase roughly equivalent land there. Others presumably moved to the cities, and the rest commuted between their homes in the government settlement and other locales for both seasonal labor and the cultivation of small, rented or purchased plots. By helping relocatees to move as individuals and families to the city, to get into new occupations like fishing and certain types of skilled labor, or to purchase new lands in either pioneer and established areas, government not only facilitates national development by enabling innovative citizens to help themselves but also saves money and lowers the risk that a costly settlement scheme will fail economically or be only partially occupied.

Some people, even in industrialized countries, will not only need greater assistance but will also wish to be relocated as a community. I suspect that this statement applies, for example, to Amerindian and certain other minority communities in the United States. It certainly applies to the majority in contemporary tropical Africa. Under these circumstances, government really has no choice but to plan new communities and suitable economic systems for this majority. Though this task is far more complicated and far more susceptible to failure, case studies have already charted the major pitfalls along the way and led to a number of positive approaches based on past experience. At the same time the number of people involved can be reduced by facilitating individual and family migration wherever it is possible.

Acknowledgments. The contents of this paper have been greatly influenced by research carried out by Elizabeth Colson and myself in the Lake Kariba basin. This research has been sponsored by the Rhodes-Livingstone Institute (now the Institute for Social Research of the University of Zambia), the Social Science Research Council, the American Council of Learned Societies, the Food and Agriculture Organization of the United Nations, the University of California (Berkeley), the California Institute of Technology, and the National Science Foundation. I wish to thank my colleague Elizabeth Colson for reading and commenting upon an earlier draft. Though I take individual responsibility for this paper's contents, we have worked together so closely over the past 17 years that it is no longer possible to know with whom certain ideas originated.

REFERENCES

Afriyie, E. K., Resettlement agriculture: An experiment in innovation, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Brokensha, D., and T. Scudder, Resettlement, in *Dams in Africa,* edited by N. Rubin and W. M. Warren, chap. 3, pp. 20–62, Frank Cass, London, 1968.

Butcher, D., *An Operational Manual for Resettlement: A Systematic Approach to the Resettlement Problem Created by Man-Made Lakes, With Special Reference to West Africa,* Food and Agriculture Organization, Rome, 1971.

Chambers, R., *Settlement Schemes in Tropical Africa,* Routledge and Kegan Paul, London, 1969.

Colson, E., *The Social Consequences of Resettlement, Kariba Stud.*, vol. 4, Manchester University Press, Manchester, Engl., 1971.

Eidem, J., Forced resettlement: Selected components of the migratory process, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Fahim, H. M., Cultural pluralism and the development of resettled Nubian communities, paper presented at the Society for Applied Anthropology Meeting, Boulder, Colo., 1970.

Foster, G. M., *Applied Anthropology,* Little, Brown, Boston, Mass., 1969.

Lawson, R. M., An interim economic appraisal of the Volta resettlement scheme–Ghana, *Tech. Rep. 13,* Volta Basin Res. Proj., Univ. of Ghana, Legon, 1966.

National Academy of Sciences–National Research Council Committee on Water, Alternatives in water management, *Publ. 1408,* Washington, D. C., 1966.

Scudder, T., Man-made lakes and population resettlement in Africa, in *Man-Made Lakes,* edited by R. H. Lowe-McConnell, pp. 99–108, Academic, London, 1966.

Scudder, T., Relocation, agricultural intensification, and anthropological research, in *The Anthropology of Development in Sub-Saharan Africa, Monogr. Soc.*

Appl. Anthropol., vol. 10, edited by D. Brokensha and M. Pearsall, pp. 31-39, Society for Applied Anthropology, Lexington, Ky., 1969.

Scudder, T., Man-made lakes and human health: Resettlement, in *Man-Made Lakes and Human Health*, edited by N. F. Stanley and M. P. Alpers, Academic, London, in press, 1973.

Sikka, D. R., Guidelines for resettlement and rehabilitation of uprooted agricultural population in river valley projects, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Takes, C. A. P., Resettlement of reservoir inhabitants, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Walker, D. E., Jr., Politico-economic effects of Columbia River dams on Indians of the North West, paper presented at the American Anthropology Association Meeting, San Diego, Calif., 1970.

Wallace, A. F. C., Revitalization movements in development, in *The Challenge of Development*, edited by R. J. Ward, pp. 448–454, Aldine, Chicago, Ill., 1967.

Resettlement of People from Dam Reservoir Areas

CHARLES A. P. TAKES

International Institute for Land Reclamation and Improvement
Wageningen, The Netherlands

Hundreds of dams have been constructed all over the world. They were built to generate power, control floods, supply irrigation water, and improve navigation. Thus the people living in the areas affected by such projects usually benefit greatly from these works. There is one category, however, that instead of benefiting often suffers from the projects, namely, the inhabitants of the reservoir areas that are inundated as a result of the dam construction.

It is true that in some recent big dam projects in Africa much thought went into the rehabilitation of these people, but in a great many other projects, particularly small ones, this aspect has been either unsatisfactorily dealt with or even completely neglected. Apart from publications on the 'big four' dam projects in Africa (Aswan, Lake Kariba, Volta Lake, and Kainji Lake), hardly any literature exists on the problems of rehabilitating reservoir inhabitants. Thanks to authors like *Brokensha* [1963, 1968], *Scudder* [1965, 1966], *Colson* [1967, 1964], *Fernea and Kennedy* [1966], and *Chambers* [1969, 1970], much knowledge has become available about the way in which reservoir inhabitants from these four African projects were resettled.

It is not surprising that the big African projects devoted considerable attention to the problems of resettlement, since in these projects the large reservoirs that were formed necessitated the evacuation of tens of thousands of people; here the problems were obvious. However, even in smaller projects, where few people are compelled to leave their lands and homes, proper measures need to be taken for their rehabilitation. In the years to come, many more dam projects will be planned and executed, many of them located in the developing countries. It is essential that proper rehabilitation measures form an integral part of dam projects, for it should never be forgotten that, in the public interest, people are being ousted from their familiar surroundings by the very creation of the man-made lakes of the project.

MORAL AND PRACTICAL JUSTIFICATION OF REHABILITATION MEASURES

People who, for the benefit of the many, are compelled to leave a reservoir area are not merely losing their land and other immovable properties; they are being deprived of their means of living as well. Therefore it is the responsibility of the project authorities to ensure that the displaced people are not only provided with suitable compensation for their losses but also assisted in every possible way to obtain a new livelihood elsewhere.

In the past, resettlement efforts have often proceeded on the assumption of a moral responsibility of ensuring that people displaced by reservoir construction should be 'no worse off than before.' Apart from the difficulty of measuring what no worse off means, this concept is far too passive and lacking in dynamism. Instead resettlement and other readjustment measures should be regarded as a golden opportunity to let the displaced groups too benefit from the development that the dam project will bring. After all, the sole reason for their displacement is to enable other people in the larger surrounding area to profit from this development. There is no justification whatsoever for rehabilitating the evacuees in such a way that they are not guaranteed a fair and equal share of the benefits (Committee for Coordination of Investigations of the Lower Mekong Basin, unpublished report, 1968).

Summarizing, one might say that from a moral point of view the rehabilitation measures should comprise three components: (1) compensation for the loss of property, (2) provision of adequate new means of living, and (3) participation in the benefits brought about by the dam project.

Apart from the moral justification, there are arguments of a more practical nature that plead for full and early attention to the resettlement of reservoir inhabitants. Such arguments stem from the fact that these people are the first to be affected by the construction of the dam. Resettlement areas can serve as pilot projects into which a wide range of social and economic development measures can be introduced. These could cover new farming techniques and new crops or varieties, farmers' cooperatives, processing and marketing systems, farmers' organizations, village layout, housing, health, education, community development, and so on.

A further reason for giving full attention to the planning, financing, and execution of rehabilitation measures, one also stemming from the fact that the reservoir inhabitants are the first to be affected by the project, is that a satisfactory execution of readjustment measures will ensure favorable publicity for all subsequent project activities. Discontent among the reservoir inhabitants about the treatment that they have received is liable to arouse widespread public suspicion toward the project activities in general, and this may well prove highly detrimental to the acceptance of all the improvement measures made possible by the dam.

REHABILITATION, AN INTEGRAL PART OF A DAM PROJECT

The rehabilitation of persons displaced from reservoir areas is quite different from the rehabilitation of refugees and landless poor, for whom settlement programs have been carried out in many countries. Most of the reservoir inhabitants are farmers, like the other people in the river basin; often they are even somewhat more prosperous than the average because they are occupying low-lying relatively fertile lands. The need for their displacement is a direct consequence of the execution of the dam project, and their rehabilitation should therefore be considered an integral part of the whole project, although this has rarely been so in the past. Project budgets in developing countries normally cover only outlays for construction, which is financed for the greater part by donor countries and/or international agencies; outside experts and contractors are engaged to carry out feasibility studies and the planning and execution of the construction work. The usual assumption is that the rehabilitation measures can be left entirely in the hands of the government of the country in which the project is located. In practice, this procedure is not conducive to coordinated effort, and the usual result is that rehabilitation activities lag far behind the purely physical project implementation and sufficient funds and technical know-how are not made available for the satisfactory planning and execution of rehabilitation.

The reason for this fragmented approach lies largely in the extreme reluctance of project authorities, whose outlook is generally dominated by considerations of physical engineering, to 'inflate' their estimates with 'hidden' costs and thus show a less favorable cost-benefit ratio. They should realize from the beginning that the costs of rehabilitation are indispensable for the complete success of the project.

The mobilization of international expertise for the planning and execution of rehabilitation measures (just as is done for the physical aspects of dam projects) is strongly recommended. Mobilization of external financial resources is also recommended. There is a great need for simultaneous planning and budgeting of all project costs, including those of rehabilitation. To fail in this responsibility is to court serious and perhaps disastrous human consequences.

RESETTLEMENT AND OTHER READJUSTMENT MEASURES

Usually, reservoir areas in river basins will be inhabited mainly by farmers and their families; therefore their resettlement to other cultivable lands will be the most obvious way of providing them with adequate means of living. However, the needs of landless laborers, sharecroppers, artisans, and people with other occupations also have to be taken into account, the more so because their needs are less obvious. Further there is always a possibility that some of the people may prefer to switch to other professions. Experience has shown that in several projects, e.g., the Volta project in Ghana, the Kariba project in Zambia and Southern Rhodesia, and the Nam Pong project in Thailand, considerable numbers of displaced farmers took up commercial fishing for their livelihood, the creation of the new reservoir opening up good possibilities for this occupation. Others preferred to migrate to a town and become shopkeepers, taxi drivers, wage earners, and so forth. The authorities in charge of the rehabilitation should, as far as possible, take individual wishes into account and facilitate these changes when and where it is possible. The people who are entitled to receive cash compensation for the loss of means of production should be encouraged and assisted to use that money purely for productive purposes.

The selection of areas suitable for resettlement, the opening up and preparation of these lands, and all other activities aiming at the proper rehabilitation of people to be ousted from a reservoir area take time. Thus their planning should not wait until the construction of the dam has nearly been completed. Much human misery has been the result of a belated planning and execution of rehabilitation measures.

PLANNING AND EXECUTION OF RESETTLEMENT FROM RESERVOIR AREAS

There are many problems to be solved in planning and executing resettlement projects. It would be interesting to review the ways in which these problems have been tackled, satisfactorily or not, in the different countries where dam projects have led to the evacuation of people from man-made lakes. It would be impossible to attempt such a review within the context of this paper, but what can be done is to give a brief survey of the most important factors to be taken into account and to indicate some general principles for their handling. Four stages may be distinguished: preparation, transfer, development, and evaluation.

Preparation. The first step is to define the exact future maximum lake margins in order to find out how many and which people need to be evacuated. A census should then be taken for the purpose of registering the occupations of these people, their family structure, and the titles to and value of their lands, houses, fruit trees, and other immovable properties. To prevent squatters settling in the area with the intention of profiting from the compensation that will be paid to evacuees, it is advisable to make as early a start as possible with this census. There are other reasons too for starting early. Experience has shown that such a census is a time-consuming activity in which much delay is caused by such unexpected troubles as land disputes or the lack of exact data. Further it is recommended that full advantage be taken of the opportunity provided by the census to supply the people with as much information as possible on the dam project and the inevitable consequences that it will have for them. This is of the utmost importance; in fact, there are numerous examples indicating that people often cannot believe that they will be displaced and refuse to leave the area until it is inundated. Films and photographs of dam projects carried out elsewhere may help to convince them.

A socioeconomic survey might be combined with the census [*Morsink*, 1966]. For the planning of the resettlement area it is desirable to know as much as possible about the social and economic structure of the population to be resettled, their social organization, group life, habits, types of farming, tenure arrangements, and so on. Group leaders should be consulted in matters like the selection of resettlement sites and the physical layout of the resettlement area.

For all these inquiries and consultations with the people a multitudinous, well-organized, and qualified staff is needed. The organization of these activities will usually require a good deal of cooperation between different governmental agencies. Sufficient funds should be made available for the training and employment of the staff needed to carry out the survey and valuation and for the payment of compensation to reservoir inhabitants. If these preparatory works are not done properly, great difficulties may be expected in later stages. Technical and financial assistance from international agencies and donor countries will be as useful at this juncture as it is in the construction stage of the dam project, although it is usual nowadays to request such assistance only for construction.

As far as possible, compensation should be given in kind, e.g., by providing farmers with good new farmland that has been cleared, stumped, leveled, and ploughed in advance to enable them to continue their farming activities immediately after arrival in the resettlement area. Much confusion, delay, and annoyance can be prevented if the new holdings are carefully delimited and marked so that each family can easily find its precise destination.

In the selection of suitable resettlement sites the following factors should be taken into account: quality and irrigability of the soil, location and accessibility of the area, tenurial status of the lands, size of the sites (preferably one or a few large units, enabling resettlers to live together in groups), degree of existing inhabitation (preferably 'empty' areas to avoid the difficulty of adaptation between newcomers and resident population), availability of water for drinking and household purposes, health conditions (no infestation with malaria or other diseases), and availability of indigenous materials for village industries and household purposes. As a general rule, people ousted from a reservoir area do not like to be resettled far from their home area, but, if the alternative is 'bad land nearby or good land in a more distant place,' many people will certainly prefer the good land, particularly if they are resettled in groups with their relatives and friends, the stress of being uprooted from their familiar surroundings thus being diminished.

In the preparatory stage, early attention should also be given to proper planning of the resettlement areas. A basic requirement for this is a survey of the lands available and an investigation of their agricultural potential. It would be going too far to describe in detail what factors should be taken into account in determining the types and sizes of farms in resettlement areas. Suffice it to say that, following the principle that the ultimate objective of resettlement is an increase in productivity and a rise in the standard of living and social well-being of the people concerned, the farm sizes should be such as to enable these objectives to be met. Further it would be very useful to make an early start with experiments on different crops, leading to the design of cropping patterns that can be recommended to the settlers later on.

The next point, which is often forgotten in the planning of resettlement areas and which therefore should be stressed here, is that sufficient land should be kept in reserve for the purpose of both the future expansion of farms and the creation of new farms to prevent the uneconomic subdivision of holdings.

As far as housing is concerned, the provision of ready-built houses by the project authorities is an expensive solution, which, moreover, bears the inherent risk that the beneficiaries are given little motivation to keep the houses in good condition. More recommendable is a system where 'core' houses and a choice of designs for extension are supplied, the settler being responsible for their construction. It will be advisable for the project authorities to assist by supplying settlers with the building materials needed.

In practice, it will often be difficult to have all infrastructural facilities ready before the settlers arrive, but resettlement authorities should at least see that vital needs, such as water supply and roads, are immediately available for newcomers. Of urgent importance also are health and police services as well as schools, shops, or markets.

Before the layout of a resettlement area can be designed, a decision on whether the houses will be dispersed (every farmer living on his own plot) or concentrated in villages needs to be made. Both settlement patterns have their advantages and disadvantages. If existing patterns of settlement according to the traditions and customs of the people do not prevent it, an intermediate system can be recommended in which each family has a small home lot near the center of the village and a larger farm lot some distance away.

In general, community facilities and organizations can be better equipped and consequently will function better in large villages of 100–200 settler families than in small ones, but the main limiting factor to the size of a village is the distance from home to farm. A proper solution depending on the local conditions of transport should be found for each community.

The organization and administration of the resettlement activities should be established well in advance. A resettlement project is a typical example of an activity that needs an integrated approach. It contains a wide range of aspects, such as irrigation, agricultural extension, marketing, cooperatives, credit, health, education, and community development, which usually fall under the competence and responsibility of different governmental departments or agencies.

In principle, there are two ways of organizing the planning and implementation of the project: (1) by close cooperation of the various departments and agencies involved, e.g., by the creation of a committee consisting of representatives of all these organizations, this committee being responsible for the planning and smooth implementation of the project, and (2) by putting the project under the sole responsibility of a special resettlement authority equipped and competent to deal with all the different aspects involved.

Both systems have their drawbacks. As far as the first one is concerned, it has been experienced in many countries that the full and timely cooperation of all agencies concerned is very difficult to attain. In the second system it may be difficult to equip the authority with sufficient specialized staff and funds to handle all the different aspects of its many-sided tasks. It is not possible to recommend one of the systems for general application. The choice in each specific case will depend on the existing conditions, practices, and regulations.

Transfer. It is essential that the transfer of reservoir inhabitants to the resettlement area be planned carefully. First, the time of transfer should be chosen judiciously. Usually, the best time for moving to the new farm will be after the farmers have harvested their crops. They can then take the largest possible supply of foodstuffs with them and can start preparing the new land for the next farming season, if the new land has been readied in advance, as was recommended in the preceding section.

If, for economic or other reasons, no dwellings have been built in advance by the settlement authority, care should be taken that reasonable provisional shelter will be available for the newly arrived families.

The mode of transportation for settlers and their belongings will depend on the distance involved and the facilities available. In the Sudan, thousands of resettler families from the Aswan project were transported by special trains from Wadi Halfa to the Khashm el Girba resettlement area. Their personal effects and livestock were sent by freight trains [*von Blanckenburg*, 1969]. If the distance is short or there is no railway, buses or trucks should be used. With regard to the transport of the resettlers' belongings the authorities should not be too tightfisted in restricting the quantity of goods that can be taken along. For old people, in particular, such restrictions would only increase the trauma of leaving their homes and familiar surroundings.

Even if resettlers are transferred after they have harvested the crops of their old farm, there will still be a great need for other items of food on arrival in the new area. The best solution for the distribution of fruit and vegetables is for the resettlement authority to establish a communal farm long before the settlers arrive so that fresh fruit and vegetables will be available on their arrival. It is of equal importance that there are stocks of dried meat, dried fish, powdered milk, salt, sugar, and so on as well as firewood and kerosine for cooking. If farmers cannot bring their own staple foods, supplies of these should also be available. For the temporary supply of foodstuffs the World Food Program might be of assistance, as it has been already in a number of resettlement projects.

Development. Assistance to the resettler community should be continued for several years, particularly to help them organize a number of necessary institutions in the economic, social, and cultural fields, such as the distribution of irrigation water and the maintenance of the irrigation works on the field level; supply of seeds, seedlings, fertilizers, insecticides, and other agricultural inputs; processing and marketing of produce; provision of rural credit; training in handicrafts; and community centers, women's and youth groups, adult education classes, and centers for religious life. Village level workers of the agricultural extension and community development services can be very useful in all these fields of action; sufficient numbers of them should be trained in advance.

It must always be kept in mind, however, that the settlement should not remain an isolated community for long but should, as soon as possible, be incorporated into the existing governmental and organizational structure of the country. Thus locally created institutions, such as multipurpose cooperatives, farmers' associations, credit societies, and irrigation societies, should be absorbed as local branches of larger organizations working on the district, provincial, or national levels. Government assistance, e.g., agricultural extension, which is provided in a special way during the initial stages of the resettlement, should also be absorbed into the larger organization. As soon as farmers have adopted the new system and are able to manage the new institutions themselves, the special government assistance should cease.

Evaluation. As all aspects of resettlement should be directed toward development, it is of the utmost importance that progress be evaluated periodically. Such an evaluation should not merely aim at discovering what impact the project has on the economic position of the resettled population, as measured by the criterion of per capita income, but should include the achievements as well, such as the improvement of social institutions, the success of efforts to stimulate cooperation between different government agencies, the degree of adaptation of resettlers to the new environment and way of living, and the fusing of different population groups into a new community. In short, all the measures taken should be reviewed to determine whether they were practicable and what factors hampered their success. In this way, very useful lessons may be provided for the planning and execution of further resettlement projects.

Apart from this evaluation of a resettlement project as its implementation proceeds, a long-term evaluation of the socioeconomic impact of the project should be undertaken before it is finally integrated into the national systems. The socioeconomic survey undertaken prior to the transfer of the people to the new area will be indispensable for effective long-term evaluation.

It is desirable that both concurrent and long-term evaluation be undertaken by an impartial agency and not by the project administration itself. In fact, it could be one of the important functions of a land settlement agency at the national level. It might even be carried out by international evaluation teams, as was recommended by the Asia and Far East study tour on land settlement in 1958 [*U. N. and World Veterans Federation*, 1959].

REFERENCES

Brokensha, D., Volta resettlement and anthropological research, *Hum. Organ. Clearinghouse Bull., 22*, 286–290, 1963.

Brokensha, D., and T. Scudder, Resettlement, in *Dams in Africa*, edited by N. Rubin and W. M. Warren, chap. 3, pp. 20–62, Frank Cass, London, 1968.

Chambers, R., *Settlement Schemes in Tropical Africa*, International Library of Sociology and Social Reconstruction, London, 1969.

Chambers, R. (Ed.), *The Volta Resettlement Experience*, Pall Mall Press, London, 1970.

Colson, E., Social change and the Gwembe Tonga, *Rhodesia Livingstone J., 35*, 1–13, 1964.

Colson, E., *Social Organization of the Gwembe Tonga*, pp. 196–210, 218–227, University Press, Manchester, 1967.

Fernea, R. A., and J. G. Kennedy, Initial adaptations to resettlement, A new life for Egyptian Nubians, *Curr. Anthropol., 7*(3), 349–355, 1966.

Morsink, H., The community development approach to land settlement, *Publ. ST/SOA/63*, U. N., New York, 1966.

Scudder, T., The Cariba case: Man-made lakes and resource development in Africa, *Bull. At. Sci.*, 6–11, 1965.

Scudder, T., Man-made lakes and social change, *Eng. Sci.*, 18–22, March 1966.

U. N. and World Veterans Federation, Report of the Asia and the Far East study tour on land settlement, *ST/TAA/SER.C/37*, New York, 1959.

von Blanckenburg, P., and K. Hubert, The Khashm el Girba settlement scheme in Sudan, *Z. Ausländische Landwirt.*, 328–365, 1969.

Resettlement Agriculture: An Experiment in Innovation

E. K. AFRIYIE

Volta Lake Research Project, Akosombo, Ghana

In recent years, 'settlement' and 'resettlement' projects have been established throughout Africa for reasons as diverse as the nations are. Some started as land reforms to settle nomadic groups or to resettle refugees. Others started as a result of the erection of dams, which necessitated the resettlement of populations in the lake-fill area or the creation of agricultural resettlements based on mechanization to create new jobs. The purposes behind these schemes can be numerous; however, there is invariably one common idea underlying all of them: to provide a better way of life for those who are to be resettled based on an improved and mechanized system of agriculture.

The ultimate success or failure of resettlement schemes seems to hinge somewhat precariously on agriculture. But successful agriculture, although it may provide the economic base necessary for a fuller life, must always be viewed as only one of several facets of resettlement schemes. There is yet to be developed an all-embracing yardstick to measure the general improvement of resettlement schemes in their totality. The success or failure of a settlement scheme can only be argued from the aspect in which the researcher is interested. This paper draws heavily on the experience of the Volta River Resettlement Scheme. Also an attempt is made at drawing conclusions and generalizations that might apply broadly to resettlement agriculture elsewhere, particularly in Africa. However, no pretentions are made of defining what a settlement or resettlement scheme is, although I do agree with *Bridger*'s [1962] definition that resettlement schemes entail the transfer of population from one area to another on a planned basis with the objective of raising the standard of living.

AGRICULTURAL PHILOSOPHY

The discussion centers on the Volta settlements, which may have some similarities but do not necessarily apply to other schemes undertaken in Ghana [*Amarteifio et al.*, 1966]. The Volta resettlement scheme was one direct consequence of the damming of the Volta River at Akosombo. The resultant lake displaced about 80,000 inhabitants, who were eventually grouped and resettled in 52 different sites by the Volta River Authority. These settlements were expected to become economically viable communities and to achieve a standard of living that was higher than that before evacuation. The philosophy underlying the country's agricultural development program in the 1960's had been clearly documented in the *Seven-Year Plan for National Reconstruction and Development* [*Government of Ghana*, 1964], which was abandoned in February 1966. Ghana's plan was not different from that of many of the developing African states. In trying to discover what went wrong with the resettlement program (and why), we need to remind ourselves of this guiding philosophy. One of the basic props of the seven-year plan was that it provided '. . . the blueprint for the future progress and development of Ghana as a nation. It is a program of social, and economic development based on the use of science and technology to revolutionize our agriculture and industry . . . .' What was really needed was an 'agricultural revolution as a precondition for the industrial revolution' at which government policy aimed.

It had long been recognized that the Ghanaian farmer had a comparatively low productivity for a number of reasons: a too small farm acreage, a scarcity of water in some areas, a poor genetic stock of seeds and livestock, little improvement in husbandry practices, the inavailability of agricultural credit, the lack of easy access to markets, and, finally, the farmer's low level of nutrition and health. Searching for ways to ensure greater use of farmland and labor became one of the pressing tasks for agricultural research. Solutions were to be found in crop rotation, use of fertilizers, application of mechanical power, a program of water conservation and irrigation, provision for agricultural research, application of improved technology, provision of adequate marketing facilities, the establishment of fixed guaranteed and publicized prices, and a sound organization to undertake the purchase and distribution of farm products [*Government of Ghana*, 1964, chapter 4].

AGRICULTURAL EXPERIENCES OF THE VOLTA SETTLEMENTS

From the outset, government policy was that resettlement should be treated as an exercise in positive economic development on a regional basis, designed to transform the area and the lives of the people involved. Thus the people affected by resettlement would be introduced to new forms of farming, fishing, and industry, and the development of the resettlement area would be looked at as a whole and treated as a special undertaking within the overall national development plan [*Government of Ghana*, 1964, p. 210]. In addition to the treatment of resettlement as an attempt to get people established on a solid economic base, it was necessary to use the opportunities created by resettlement to initiate the agricultural innovations proposed under the seven-year plan, i.e., large-scale farming by modern methods and machinery, organization of farmers into cooperatives, and the establishment of public agricultural enterprises, such as the state farms and the agricultural wing of the Workers Brigade. The resettlement towns would be encouraged to organize into farming cooperatives to obtain access to machinery and modern techniques that otherwise might be beyond the resource of the individual farmer. The problem that the Volta settlements were bound to encounter in this situation was neither easy nor purely agricultural. The question was one not only of seeking ways of improving resettlement agriculture but also of grappling with the problems involved in adjusting to a new environment, the time involved in the completion of the original 'core-houses' allocated to the settlers, and finally the long delays experienced in some areas for delivery of farm machinery, which prevent settlers from farming immediately on arrival at their various sites [*Nicholas*, 1970, pp. 215, 234–235]. There were other problems involved, such as land acquisition, the availability of suitable farmland, and the hostile attitudes of some host tribes in the resettlement area.

Innovation in any direction involves a fundamental change in values and attitudes toward a new practice. Given the level of literacy, the availability of professional and technical staff, and the managerial and organizational experts as well as the resources at our disposal, one would have thought that the introduction of a completely different concept of farming would initially be concentrated on a vigorous extension program of experiments and demonstrations directly involving the farmers. Ironically, the extension unit of the Ministry of Agriculture was transferred to the state farms, the private farmer (including settlers) being deprived of the extension education that he needed vitally. The extension service was charged with the propagation of new farming methods.

A 1968 socioeconomic survey of the 52 Volta resettlement towns produced results, especially in the field of agriculture. The organization of the mechanized farms is so fraught with problems that it can hardly be said that the settlers have adopted any new farming methods (E. K. Afriyie and D. A. P. Butcher, unpublished report, 1969). In this respect, both settlers and government have been the losers. Records of past and existing resettlement schemes in developing countries have been discouraging; not only have they given rise to many problems, but outright failures and collapse have been common [*Chambers*, 1969]. The danger involved in starting projects but failing to see them through is that negative reactions build up among the people being helped. The apathy and lack of confidence thus generated becomes doubly hard to counteract later. The final proof that an innovation has been accepted is when local people use it as their own without the prodding of the innovator.

Questions related to the stages of adoption and the characteristics of adopters are well documented elsewhere. The more complex the new idea introduced, the longer the adoption process is; on the other hand, the higher the level of complexity in keeping with existing accepted behavior patterns and attitudes, the more the individual is likely to accept the new idea quickly. It is argued that economic considerations are factors in the rate at which the new practice or idea is adopted. In Ghana it was quickly recognized that, although fertilizers and improved seeds were desirable for increased productivity, it was expensive to import them into the country.

Farm machinery and equipment were also expensive. Nonetheless the idea was pressed in the interest of national progress. The final outcome was that there were shortages and long delays in the delivery of farm machinery and inadequate maintenance and technical staff. Where machinery and staff were available, they operated inefficiently for lack of technical know-how and because of equipment breakdowns; seed and fertilizer supplies were erratic, inadequate, or unavailable. The Volta settlements took more than their share of the above problems with the result that some settlements never received the promised seeds, fertilizers, or farm machinery. Where they were received, the productivity and profitability of the whole mechanized program in the settlements has been questioned. Consequently, an overhaul of the program was recommended as justified by the findings of the 1968 socioeconomic survey (E. K. Afriyie and D. A. P. Butcher, unpublished report, 1969).

With the inception of the Land Clearing Project assisted by the World Food Program, there has been a basic change in the agricultural program in the settlements. The new program will lay emphasis on improved subsistence agriculture, each entitled settler and host farmer being allotted a 1.2-ha (3-acre) plot to be cleared by hand. But as old mistakes are corrected, new problems crop up. Still with us are the questions of economically viable farm size, maintenance of soil fertility and organic content, a suitable land tenure system, the scarcity of land, and an organization capable of administering an effective extension service in the settlements. All factors considered, the agricultural program points more to the vulnerability than to the viability of the development work now being undertaken in the settlements.

CONCLUSIONS AND RECOMMENDATIONS

The Volta experience demonstrates that resettlement agriculture does not automatically produce higher standards of living. At best, resettlement can provide only improved facilities and the opportunities necessary to enhance the living standards of the people. Instances in which some people would have to revert to lower standards because their socioeconomic conditions have not improved sufficiently to enable them to take advantage of the new conditions may be expected to occur. Others certainly will benefit from the move. Thus an integrated approach to the development of resettlement schemes needs to be taken into consideration. In this respect, equal importance should be placed on the housing requirements, the service facilities, and the agricultural system as the three basic aspects of a resettlement scheme.

Settlement schemes in Africa and elsewhere may be viewed not only as bold attempts in terms of agricultural innovation but also as a positive direction in rural development. To succeed, it is essential to have an integrated program embracing agricultural extension, the propagation of information by mass media, and the application of science and technology as well as social welfare and community development.

One major drawback in the resettlement program in Ghana was the inadequacy of research-validated statistical information about the country as a whole to enable the formulation of sound agricultural policies. In addition, the magnitude and novelty of mechanized farming was overwhelming for a people who were either still longing for their former ancestral homes or trying to make the best out of their new ones. The lack of trained personnel to research the economic as well as the noneconomic aspects of the adoption and use of agricultural technology was also significant. Research should be oriented toward the communication aspects of adoption with emphasis on the sources of information used, on factors related to the whole innovative process, and, finally, on the diffusion of innovation as a study of social and cultural change.

Resettlement agriculture is usually tied intimately with the national economy. Of course, no resettlement scheme can exist in a 'national vacuum.' Thus it is more imperative for much foresight and thought to be given to the complex problems of the desirability of structural changes in the economy, the pace of development, and the sheer magnitude of agricultural innovation as balanced against the available human and material resources. In broad terms the strategy should be to identify points of potential leverage in the socioeconomic system and to apply pressure simultaneously to these points. Such pressures should necessarily be toward modernization. Divided effort in developing what should be an integrated undertaking is more likely to lead to failure.

Last but not least are some often neglected or ill-considered issues that need to engage our special attention with regard to settlement schemes. They are (1) the nature of the organizational machinery in charge of resettlement administration, (2) the timing of resettlement, (3) the role and attitude of government toward those involved in resettlement, and (4) the influence of politics and ideology regarding national priorities, especially in the field of agriculture.

These issues have been raised only to draw attention to the fact that, although they may be taken for granted as being insignificant in a settlement scheme, they may later pose the biggest problems in the course of the project. Pondering over them, it is hoped, will give realism to an otherwise exaggerated expectation from an overambitious project.

REFERENCES

Amarteifio, G. W., D. A. P. Butcher, and D. Whitham, *Tema Manhean, A Study of Resettlement,* Ghana University Press, Accra, 1966.

Bridger, G. A., Planning land settlement schemes, *Agr. Econ. Bull. Afr. 1,* 21, 1962.

Chambers, R., *Settlement Schemes in Tropical Africa*, pp. 10–14, Routledge and Kegan Paul, London, 1969.

Government of Ghana, *Seven-Year Plan for National Reconstruction and Development.* 1963/1964–1969/1970, Government Printing Department, Accra, 1964.

Nicholas, M. S. O., Resettlement agriculture, in *The Volta Resettlement Experience*, edited by R. Chambers, Pall Mall Press, London, 1970.

Guidelines for Resettlement and Rehabilitation of Uprooted Agricultural Population in River Valley Projects

D. R. SIKKA

Major Multipurpose Projects, Madhya Pradesh Government, Raipur, India

Rehabilitation of persons whose lands and houses are inundated by man-made lakes is indeed a human problem, and thus it cannot be measured solely in monetary terms. In one of the major projects in our state, 228 villages were inundated, 3000 ha of private land and 36,800 ha of government land being involved and a population of about 52,000 being uprooted. About 9000 landholders and 5000 holders of other properties were affected. The sphere for consideration, assessment, and implementation under such circumstances is further enlarged and at times aggravated when some of the lands involved are very rich and fertile and a part of the agricultural strategy of the region. The insistence of law and authority for land acquisition is not enough. When the tiller of the land becomes landless, no amount of cash and kind compensation will satisfy his hunger for land.

The persons who are thus displaced have a right to rehabilitation. One method is to pay them cash compensation for the lands acquired compulsorily. Had ordinary goods been involved, the payment of cash compensation would have been fair enough provided it was properly assessed. However, the very existence of tillers of the soil may depend on the land, and, after it is sold, they may not be able to buy an alternative plot to earn a living for their families. Hence payment of cash compensation is only a partial relief. More often than not, the cash compensation would be squandered away on unproductive enterprises with the result that large numbers of people might become unemployed. Both compensation and rehabilitation need to be thought out at the same time so that fresh avenues of employment may be created for the displaced population.

There is also the problem of the resettlement of the landless class of people who depend on the landowners for their livelihood, such as the tenants, landless laborers, village artisans, and shopkeepers. They cannot claim any direct compensation under the land acquisition clauses, and the indirect loss suffered by them deserves to be looked into in more detail.

The next most important problem is the question of finding alternative shelter for the people who lose their homes. Again, payment of cash compensation for the loss of a house is only a partial solution; what they need is a new house to live in. The construction of new colonies to accommodate the persons likely to be displaced has to be given the highest priority in the construction schedule. Or as an alternative the project authorities should give them suitable plots of land, the designs, the construction materials, the encouragement to build their houses with their own efforts, and the help of matching cash grants.

Normally, the cultivators suffer from a sort of inertia, inasmuch as they want to change neither their profession nor their surroundings. They have local ties, which are hard to break. Each individual's needs have to be taken into consideration before deciding the place of his resettlement.

Sometimes, a change of vocation may be distasteful to the individual, and the only thing that could satisfy him would be land in the same surroundings. Then government land must be found in contiguous areas to resettle some of the displaced persons. The question is more serious in areas of high elevation, where the holdings are small and cultivable land is scarce. Even in the plains, there is difficulty in finding government land in contiguous areas. Where the cultivator seeks cash compensation, the following points should be kept in view: the class of land based on soil classification, the charges for clearance of land, the charges for plowing, and the cropping pattern and production.

Normally, land acquisition in India is carried out under the provisions of the Land Acquisition Act. Where only a part of a holding or survey number comes under inundation, the owner is given an option to surrender the remaining part. If it is an uneconomic holding, the tenant gets full area in exchange for his flooded land.

To give an approximate idea of an estimate of compensation worked out while resettlement operations in a major lake were being considered, the following details are given.

Item 1: Land

Irrigation land	1,200 ha
Cultivated land	20,800 ha
Fallow land	7,600 ha
Difference of jungle clearance charges for 8000 ha at (80 − 40) Rs40 each	
Bunding charges for approximately half the above area at Rs40 each	
Wire fencing charges for approximately 8000 ha at Rs30 each	

Item 2: Houses

Total number of houses	17,526
Permanent type	
Ground floor	9,394.304 m²
First floor	4,009.084 m²
Partial permanent type	
Ground floor	273,152.692 m²
First floor	29,877.460 m²
Temporary type	
Ground floor	183,878.928 m²
First floor	9,134.496 m²
Huts and cattle sheds	9,489.200 m²
Platforms, compound walls, and so on	

Compensation

Item 1	Rs11,210,000
Item 2	Rs23,600,000
Total items 1 and 2	Rs34,810,000
Add 15% extra for other miscellaneous items	Rs5,220,000
Total	Rs40,030,000 (US$5,200,000)

Some of the conflicting points arose when, for a flooded area of 30,000 ha, the area required for rehabilitation was estimated at about 24,000 ha and this area was selected within a radius of 48 km from the lake. Out of this, about 11,200 ha were already available to the government as wasteland, and no clearing was required. The remaining 11,800 ha were forest areas requiring clearing and improvements. Thus an intensive program of clearing forest growth also had to be implemented. In addition, the tractor organizations were offered considerable areas. Potable water supply to those areas was also considered.

CRITERIA FOR AMENITIES AND COMPENSATION

The following are some suggestions of the considerations to be taken into account in providing amenities and compensation:

1. Compensation should be paid for all lands according to the Land Acquisition Act procedures.
2. Land nearly equal to the land lost under flooding should be provided at a very nominal price. Because of the nonavailability of land equal in extent to the land inundated, the government may need to release forest land to be converted into agricultural land.
3. A suitable site for a village, including jungle clearing, leveling, and layout, should be selected and acquired.
4. Forest land should be cleared and bulldozed.
5. Free sites of suitable size for dwelling houses, manure pits, and so on should be provided by releasing lands for individual or collective colonies.
6. Internal roads and drainage works should be constructed for such colonies.
7. Wells for drinking water or tube wells should be provided.
8. A village community or recreation hall should be constructed.
9. A school building that is suitable for the size and educational requirements of the population should be provided.
10. Places of worship should be constructed.
11. An approach road should be provided to the new village and to old villages for residual populations.
12. If an irrigation tank or a village pond is not available, one should be provided for watering cattle.
13. Compensation should be paid for structures at present-day prices minus depreciation (the reduction being limited to 25–30%). Then the

person may dismantle the structure and convey it to the new site.

14. Free transport to the new settlement should be provided for men and materials.

15. Credit facilities for housing and land development should be arranged.

16. Facilities for development of rural industries should be provided.

17. Land for cultivation should be provided free of cost to tenants and agricultural labor, as opposed to owners. Although they are not legally entitled to any compensation, the government decided in some cases to provide a few acres of dry land to each tenant or agricultural laborer affected by the submersion. Similarly, the artisans are entitled to compensation only for their structures and not for the loss of their means of livelihood. For such persons, industrial areas are built up near the towns, and they are provided with free sites and other facilities, such as free transport, to enable them to settle themselves in the new surroundings.

18. Sometimes, displaced families are assigned land equal in extent to the lands acquired from them (subject to a 12-ha maximum) for agricultural purposes. Two hectares is free of cost, and the rest must be bought at its market value plus the forest-clearing costs.

19. A supply of important structural and building materials, such as steel sheets, steel bars, and so on, should be provided at controlled rates for the displaced house owners. The owners of the houses to be flooded are allowed to take whatever building materials that they require from their old houses for the construction of their new houses. The materials are transported to the new site free of cost.

20. Loans should be arranged up to a certain limit for each displaced family provided adequate security is forthcoming. The security to be furnished includes the land assigned by the government.

21. Facilities like markets, banks, hospitals, post offices, and electricity should be provided. Weekly markets are organized.

22. Communications should be provided. New roads connecting the new villages with existing main roads are planned and laid out.

23. Earth-moving equipment and survey parties for land-shaping and land-leveling operations should be rented.

24. Arrangements should be made for contour-bunding operations and soil conservation measures.

25. New village sites should be grouped and the land near each village should be allotted according to old village boundaries.

26. Shops should be allotted preferentially in the market areas of the project during construction.

27. Displaced persons should be given preference in employment during the construction and maintenance period of the project.

28. Instead of following old conventional methods, new crop patterns should be adopted to suit the agricultural strategy.

29. Fishing cooperative societies should be formed.

30. Power should be supplied at reduced rates.

31. Police stations and inspection bungalows should be provided.

In the project estimates for formation of these lakes, realistic and adequate financial provisions are necessary for the rehabilitation and resettlement of displaced persons. The dam height has to be based on the strategic requirements of irrigation and power, and it might not be possible to reduce the height from the point of view of reducing expenditure. The uprooting of the displaced people has to be seen as a sacrifice for the betterment of the society as a whole.

NATIONAL POLICY

In such circumstances a national policy should be laid down by enactment of suitable legislative measures for the following.

1. A master plan and a projection of long-term objectives and social needs should be prepared to determine and assess properly the minimum areas of inundation in the basin as a whole.

2. Advance action should be taken for rehabilitation and resettlement measures so that the displaced persons are not put to any hardships when the lake is ready to be filled.

3. The basic principle that displaced people should be ensured, by provision of facilities, amenities, or compensation, a much better standard of living and earning than that which they had before should be accepted, and adequate financial provisions should be made for that purpose in the cost estimates of the project.

4. Effective administrative machinery should

be constituted to achieve the objectives within 3 years of formation of the lake.

5. Limiting heights of various dams within the basin should be determined so as to involve minimum flooding, the benefit-cost ratio of the project and the revised anticipated ratios expected for the displaced areas before and after formation of the lakes being kept in view.

6. A sort of revolving fund should be established from the revenue of the scheme for the betterment of displaced persons for a certain period after completion of the project to be spent on their welfare until the targets are achieved.

7. Wastelands or forest lands should be designated for conversion to cultivable lands in the basin within a reasonable distance from the area of displacement, and irrigation and power facilities and, if necessary, demonstration farms should be provided as well.

8. Periodic agricultural and socioeconomic surveys should be undertaken for appraisal of the rate of development.

Forced Resettlement: Selected Components of the Migratory Process

JERRY EIDEM

Department of Geography, University of Kansas, Lawrence, Kansas 66044

Forced removal of large groups of people within free societies is relatively uncommon. It rarely occurs except when society wants a new facility that will abruptly transform an existing environment. The most notable results of transformation are reservoirs, airports, and highways. Forced migration from these areas is quite different from 'free' migration, a situation in which people have a choice in the decision to move.

This paper briefly describes the Perry Lake area of reservoir development in northeastern Kansas, identifies five characteristics that distinguish the forced resettlement of populations, and illustrates each characteristic with examples drawn from observations of forced migration in the Perry Lake area. Specifying significant migration differences should lead to a broader understanding of the unique nature of forced migration. Such an understanding is necessary to the establishment of comprehensive resettlement policies. In the following the terms 'forced removal,' 'forced resettlement,' and 'forced migration' are used interchangeably.

Perry Lake in northeastern Kansas is backed by a dam near the mouth of the Delaware River, a modest stream that enters the Kansas River between Topeka and Kansas City. The reservoir is dwarfed by the large main stem lakes of the Missouri basin. However, its size is typical of reservoirs developed in the Kansas River extension of the Missouri basin and reaches about 30 km upstream from the dam at flood pool level.

Like other reservoirs in northeastern Kansas, Perry Lake filled a valley formerly occupied by rural settlements. Of the approximately 800 people who lived in the project area, about half were farmers and their families, and about half lived in one of two small towns. The smaller, Ozawkie, provided only minimal services and in the course of reservoir development was completely removed. The larger, Valley Falls, remains a viable market center and was far enough upstream and upslope to be affected only by the relocation of a small residential section of the town. Agriculture in the valley was divided equally between full-time and part-time farmers. Full-time farms were generally larger and occupied most of the valley floor. Farms other than those of marginal value were primarily integrated upland-lowland operations, where cattle were pastured on the uplands and the lowlands were used for raising feed and cash crops.

Although it would be unrealistic to suggest that 800 migrants from the Perry Lake project represent a cross section of out-migrants from all areas of reservoir development, their resettlement exhibited specific characteristics with rather general application to the forced migration situation. First, Perry Lake migrants were of a decidedly rural character. Those not residents of farms lived either in rural nonfarm residences or in the towns of Ozawkie (an estimated 200 persons in 1960) and Valley Falls (1193 persons in 1960). Had the valley been occupied by a large urban settlement, the development of Perry Lake in its present location would never have been seriously considered. The costs of relocating large numbers of people together with extensive urban developments would be prohibitive under cost-benefit determinations. Barring the unusual, cost considerations mean that forced migrants have been and will continue to be primarily rural.

Second, with reservoir development essentially in rural areas it can be expected that farmers are part of the population, and, since the valley floor (usually the most intensively worked and highly productive area) is submerged, farmers lose not only their residences but also their major source of livelihood. At Perry Lake, agricultural economic units were, with few exceptions, destroyed, land acquisition causing four types of destruction: (1) total inundation, (2) the reduction of farm size below needed operational levels,

(3) the inundation of the lowland with the consequent severing of a necessary part of the lowland-upland operation (vertical severance), or (4) the splitting of a farm into segments separated by water (horizontal severance). Thus a distinguishing feature of forced resettlement is that it frequently involves not only loss of residence but also (because agriculture is involved) loss of livelihood.

Third, the free migrant, who in the course of his life moves from one place to another, may at some future time decide to return to the first place. For example, a son or daughter may return to live with parents, or an older couple may return from a retirement location to be among relatives and longtime friends. In such instances the return to place of origin is quite possible. But, in a reservoir project, relocation is essential. Some may resettle very close to their former locations, but the original site can never be reinhabited.

Fourth, forced migration differs from free migration in that it is essentially nonselective. All people, whatever their age, sex, occupation, length of residence, religion, or other characteristics, must be removed and resettled.

Finally, although most people in free societies may migrate when and if they desire, one restriction is that moving is frequently costly. Even a person with no dependents may find it extremely expensive to dislodge himself, pay moving costs, and reestablish himself at a new location. Further, there is small likelihood that he will move at all if he has little or no knowledge of the destination. If, then, he is to gain knowledge sufficient to motivate a move to a particular place, the move may be preceded by a search to provide reassurance that the destination is compatible with his needs. In free migration, both the searching and the moving costs are borne principally by the migrant. When people are forced to move because of government decree, society helps the displaced reestablish themselves. In reservoir projects like the Perry Lake development, funds are provided for purchasing the migrants' land and improvements, for reimbursing them for costs incurred in their search for suitable replacement sites, for paying the moving expenses, and for paying incidental costs at the destination, such as the fees charged for telephone reconnection. Free migration and this type of forced migration are in this respect totally different.

Thus there are at least five general characteristics that distinguish government-sponsored forced migration from the more common free migration: (1) rurality, the rural rather than urban nature of the source population, (2) livelihood transfer, residence shift plus a loss of occupation, (3) no return, the impossibility of return to the former location, (4) mass removal, total rather than selective migration, and (5) societal subsidy, the costs being borne by the public rather than by the migrant. Several tentative conclusions concerning their effects are drawn from the Perry Lake example, and generalizations are applied to other areas of resettlement.

RURALITY

The rural population of Perry Lake possessed characteristics distinct from those in nearby urbanized areas. Aside from occupation an important characteristic of these rural people was their age structure. Perry Lake migrants were older than their urban neighbors. In 1960, for example, 16% of the residents in the four townships directly affected by resettlement were 65 years of age or older. In nearby Topeka, <10% were over 65. In Kansas as a whole the median age for urban residents of both sexes was 28.8 years, whereas rural nonfarm and rural farm residents had median ages of 30.5 and 34.7 years. An older population with related characteristics, such as poor health, limited and fixed incomes, retirement status, and widowhood, suggests a group whose migratory behavior would be restricted unless external force became the stimulus. With this stimulus, minimum horizontal mobility might be expected, since migrants attempt to retain as much as possible of their former existence in their declining years. Partly because of the age structure associated with rurality, migration had a clustering effect. Among those people who had reached retirement age before their resettlement, for example, the mean distance moved was <16 km, a distance less than that for any other age group.

LIVELIHOOD TRANSFER

Few occupations compare with farming for horizontal stability, particularly when the farm is owner operated. Investments in land improvement, knowledge of local climate and soils, and established marketing channels tend to keep farmers immobile. Thus, because farming is a rural phenomenon, forced migration often selects an occupational group that is inherently fixed. Confronted with the prospect of resettlement, the farm owner-operator must consider not only a change of residence but also the challenge of reestablishing his source of livelihood with minimum disruption. At the Perry Lake project, most of the full-time farmers continued their farming operations, but the distances and directions that they moved point to a careful consideration of these factors. Of the 55 full-time farmers who lived on their farmsteads (10 of whom were nonowners), >25% resettled within 50 km from their original farm location. Further, this resettlement was directionally biased. Only four farmers moved in a southwesterly direction, probably because higher costs of land are associated with the urbanized Topeka area but also because the agricultural system (such as the Flint Hills grazing area to the southwest) differed too greatly from that with which they were most familiar. To the southeast, >50% of the search destinations named by farmers were 60 km or further from the point of origin. Yet, more than half of the resettlements to the southeast were <15 km from the original location. The concentration of resettlement to the northwest and somewhat less to the northeast indicates the farmers' preference for those areas that, compared with the southwestern and southeastern areas, differed less in physical respects from their homes. If the desire to maintain similar conditions were not involved in the relocation decision, we should expect no significant differences in directionality.

NO RETURN

The possibility of return to the point of origin was eliminated at Perry Lake. Research might profitably be aimed toward determining the extent of return to the immediate locale of a reservoir project from points further removed that were initially chosen for resettlement. Data on this type of 'near return' have not yet been gathered for the Perry Lake situation. Generalizations about near return can follow only after detailed study of this and other areas.

MASS REMOVAL

Mass removal placed all the residents in the Perry Lake project area in a mobile population. In addition to being essentially nonselective, mass removal sent all the migrants searching for new locations at about the same time. Thus an element of competition was undoubtedly created for favorable replacement homes and farms. There are recorded instances of people who, as unsuccessful competitors, left their homes at the latest possible moment without permanent destinations in mind.

When people migrate freely, they move individually or in small groups, and, when there is the possibility of exchange of population between places, the competition for space is lessened. Mass removal does inject noticeable competition that might be measured through a comparative analysis of land prices, housing rents, and construction costs. In any event the mass removal of population places the forced migrant in a special competitive category, a category not equally shared by the free migrant.

SOCIETAL SUBSIDY

Perry Lake migrants, who were free from personal searching and moving expenses, might have been expected to range widely to survey the maximum number of potential replacement sites within the permitted time limits and to select replacement sites without regard to moving costs. The dissatisfaction existing in free migration causes (when it is great enough) a person to move despite the personal costs incurred. This dissatisfaction does not seem to be found in forced migration. Since out-of-pocket costs are minor, we should expect to find people spending their time and the maximum amount of others' money to resettle with the greatest satisfaction regardless of the distances involved. However, most moves at Perry Lake were confined to the local area. Many migrants reported no search mileage for reimbursement. Self-performed moves, frequently with only personal vehicles, were far more common than commercial moves were. Thus the short moving distances involved are reflected. The absence of dissatisfaction as a motivating force is also seen by the fact that many who moved reestablished themselves near their former friends and relatives. The old town of Ozawkie has its counterpart, together with residents of the old town, in New Ozawkie <3 km away and within view of the former site. Whereas costs may prevent the initiation of migration or minimize distances moved among free migrants, factors other than costs apparently limit the distances moved by forced migrants. Some of these inhibiting factors have already been considered, including age, occupation, familiarity with the environment, and relatives and friends.

SUMMARY

In the forced resettlement situation, large numbers of people may not be involved, but the process is not selective, and the totality of the migrants' original environment is affected. Therefore present migration theory does not necessarily apply to these forced resettlement situations.

Since man-made lakes and other projects of similar scope will continue, it is important to consider the unique characteristics of this type of migration in order to understand the problems adequately and to apply relevant migration principles to relocating total sets of people.

Summary: Planning and Development of Marginal Agriculture, Watersheds, and Rural Water

D. R. SIKKA

Major Multipurpose Projects, Madhya Pradesh Government, Raipur, India

MARGINAL AGRICULTURAL ASPECTS

In reservoirs, large areas of land and properties come under submergence as soon as the construction of a dam is completed. It is therefore necessary that the requirements of land for these man-made lakes be carefully and properly assessed so that the owners are not subjected to hardships and unnecessary losses. In a predominantly agricultural country, where the economy of the people in the villages is entirely dependent on cultivation, the population growth rate is high, the pressure on cultivated land is increasing, and, consequently, the size of landholdings diminishes year by year, further serious thinking must be done before the areas to be acquired by the state are finalized. Any ill-planned acquisition or submergence of rich forest growths and mineral deposits would be a considerable loss to the exchequer. The case becomes further complicated when there is a chain of systems and irrigated areas are sometimes submerged along with their sources.

STAGE APPROACH AND FIXATION OF ACQUISITION LEVEL

The stage approach is therefore called for; i.e., the classification and distribution of lands must be in two parts, first, those lands that would be permanently submerged below the full tank level of the reservoir and, second, those that would be subjected to submergence or flood effects for certain periods. As is known, the wave action in a lake is dependent on fetch, wind velocity, depth of water, and other factors during the various seasons in a year. Thus these factors will also have to be taken into consideration and averaged for their impact when the areas of influence subject to flooding are being derived.

The question arises how best to provide for acquisition and suitable compensation for the lands in the permanent category and for the temporary acquisitions. Should compensation be provided by partial or full payment, and should the use of the land be authorized to the original owners or to others? We must first determine whether cultivation over such lands would not add to our problems by augmenting erosion and flow of sediments in the lake. The level and the demarcated areas up to which land should be acquired in the foreshore therefore call for much consideration in two contingencies: when the full reservoir level and maximum water level are the same and when these are different. This level would also vary materially owing to uncontrolled spillway crests and controlled crests.

If we acquire the land up to the computed maximum water level, a lot of unnecessary and costly work is initiated and thus may cause resentment to all concerned. It would therefore be pertinent to take into consideration the frequency of the design flood and then to strike at a reasonably safe recurrence interval, say 15–20 years, on the presumption that a little submersion once in this interval would not involve intolerable losses. Thus, to be suitably economic and efficient between full reservoir level (FRL) and maximum water level (MWL), we have a new level for the lake project, the maximum acquisition level (MAL). Where FRL and MWL are the same, the MAL will be FRL plus a certain part of the maximum wave heights.

MASTER PLAN

A master plan or a phased program for acquisitions in a basin must indicate the probable location of dams to be constructed and lands to be acquired under the two categories so that the landowners are able to prepare themselves mentally in advance for the proposed ultimate acquisition of their lands. Then forest or wasteland areas that would not be coming under submergence could be allocated or demarcated, and steps necessary to improve the fertility of these lands for agricultural purposes could be planned in advance to synchronize with the completion of lakes. The original landowners are always very keen to come back and take charge of these lands for cultivation. Intensive irrigation systems, being planned by the construction of numerous lakes, call not only for a unified approach but also for criteria as to what should be the gap or distance between the cultivated lands in the commanded area of a lake and the cultivated area in foreshore lands in the interest of soil conservation and sediment control.

ALLOTMENT AND USE

The allotment procedure, the method of releasing lands, the period of cultivation, and so on can at times be complicated and will need to be detailed by the administration with a view to making the best use of available lands.

As we have experienced on works in our state, sometimes after formation of the lake and lowering of its lands the area considered fit for cultivation does not work out to more than 60–70% of the land, and the rest consists of rough topography and other uncultivated lands that existed before. Then on what basis shall these marginal lands be allotted to the cultivators, original or new, particularly in view of the fact that their original field boundaries are disturbed or changed by erosion and silting cycles in the filling and changing of the lake levels in its operation stage? Also, on what rate structure should these lands be re-leased: the irrigated water rate system, its multiple, or land revenue rates? Should they be re-leased on an ad hoc basis or auctioned every year to the highest bidder? Sometimes the soil re-leased is very fertile, and so the use rate should perhaps be equal to the irrigated water rate or to a certain number of times the original land revenue rate. At other times the land that opens up perhaps cannot produce successfully because the soil, having been submerged for a number of years, does not have enough germinating power. All these factors have to be considered carefully in arriving at a correct and rational basis for enforcement.

A solution suggested in one project in our state was for the state to acquire these lands permanently, demarcate them in suitable blocks, and then auction them each year to the highest bidder, preference being given to the original landowners in case of equal bidding. Then the introduction of modern agricultural strategy, including short-duration and high-yield varieties and suitable cropping plans, could be pursued in the interest of the cultivator's economy as well as silt control. Another suggestion for the use of such lands by the old cultivators is that they should be charged the maximum rate of land tax or revenue that existed prior to the acquisition of their land and that the lands between FRL and MAL should be given only to them for cultivation, even though they might have moved to other villages.

Poor communication because of fluctuating water levels of the lake is a problem for agricultural requirements and proper living in these lands. A planning model in one project called for construction of a good road along the periphery of the MWL and branch or feeder roads spreading out as needed to the MAL so that people could have access to these marginal lands. These roads would at times be expensive, but the expense could be justified in very rich agricultural tracts with a high density of population, the cost-betterment ratio being kept in mind. Since a number of such lakes, large and small, have been and are being constructed, it would now be worthwhile to compute the factors concerning ratios and/or coefficients to plan investment programs for the future. The water requirements of the proposed high-yield crops could also be suitably designed, possibly by pumping water from the main lake or by constructing shallow tube wells in areas where the water table would have improved. 'Farming principles for MAL to MWL' would have to be formulated in close consultation with the irrigation, revenue, agriculture, and forest departments. The need for a proper agricultural-socioeconomic survey cannot be overemphasized as a means to provide guidelines for reallocation problems.

MAXIMIZATION OF NET FARM INCOME

When intensive agricultural operations are being planned on marginal lands and the commanded areas of man-made lakes, it is necessary to take into account the basic considerations of the region. These include the resources of the farmer, comprising land, family workers, livestock, implements, and capital; technical improvements in the sphere of agriculture; changing physical and economic situations indicating the availability of irrigation, transport, processing, marketing, and storage facilities; agricultural prices, farm wages, and prices of production goods; and the wants and preferences of the farmer, his technical and managerial ability, and the sizes of his landholdings. If we are to be consistent with the long-term maintenance of soil productivity, we have to aim at maximizing 'net' farm income either on the original foreshore land or by its supplementation with outside lands. This maximization will not be possible unless adequate means and organization are available for proper evaluation, each resource being put to most efficient use with well-defined norms for ascertaining cost and return relationship.

When we intend full development under such programs, lessons must be learned from case studies of similar ventures. The accepted criteria must clearly state all inputs on one side and the combination of farm enterprises and output of each enterprise on the other and must enunciate clearly the work period and the final implementation of plans. On that plan will depend the phasing of construction and development of water resources (both upstream and downstream) in an integrated manner. Development and optimum use of marginal lands cannot, however, be done in seclusion. They must also be part of a well-designed watershed program and multibenefit agricultural operations.

SMALL WATERSHED PROGRAMS

Haas [this volume] has indicated the important and effective role of small watershed programs in the United States as tools for economic development in flood-ridden areas. Watershed projects are not single-structure or reservoir proposals but consist of land treatment measures and the application of conservation practices, including contour farming, grass waterways, terracing, diversions, drainage channels, and several others, to reduce soil losses for maximum long-term use of each hectare of land. Reduction of flood damage is of primary importance. A single watershed project, planned on an interdisciplinary approach, may have several man-made lakes.

Let me indicate certain basic considerations for a watershed management program for some of our river valleys. Erosion from rural and developing urban areas continues to wash away our lands and choke streams and reservoirs with sediment. The protection and management of watersheds to maintain and ensure the quantity and quality of water is an important and continuing task. Soil erosion with its resulting effects through sedimentation remains a challenging problem in agricultural and urban areas. Watershed protection and management measures are required to meet the needs for various objectives. The outstanding example is the improved and stabilized pattern of streamflow that allows for a minimum reserve for silt storage in reservoirs due to the reduction of sediment yields and consequently reduces the height of dams, reduces the submergence upstream, or gives better use of the otherwise locked up capacity. Sometimes, in water scarcity areas, watershed management is likely to augment water supplies by enhancing the natural recharge of groundwater or by releases of postmonsoon flow.

Most population growth is expected to occur in the suburban areas of cities and towns in this state. If this growth is rapid, at times it may cause many sedimentation problems or other problems related to erosion, transport, and deposition. When the needs of such places in the catchment areas of reservoirs are being planned and programed, this aspect needs special attention.

Forecasting runoffs in a watershed for efficient operation of release systems in reservoirs is of far-reaching importance in getting maximum public utility benefits of irrigation, hydropower, municipal uses, and so on. Adequate organization will be needed for observation and analysis in our watershed programs. The problems will have to be examined when a watershed has several smaller watersheds that are different in respect to climate, elevation, and so on and that feed into several reservoirs. Adequate weather forecasting, along with rain gage and discharge stations and flood-warning devices for the operation and control of these reservoirs, is a must.

Also of importance are conservation measures, such as the classification of catchment areas into subcatchments and then the identification of forest lands, croplands, pastures, wastelands, village roads, water bodies, and so on. The data collected so far for certain reservoirs reveal that the rate of sedimentation (sometimes 900, 1500, or even 3600 $m^3/259$ ha of catchment area) has been greater than had been anticipated at the time of preparation of project reports. Even live storage capacity has been encroached on by silt deposition, the useful quantity of water thus being adversely affected. The planning and execution of soil conservation measures is done better on a watershed basis. It will necessitate steps like the contour bunding of agricultural lands, tree planting, pasture development, stream bank protection, silt retention or check dams, the creation of compact blocks needing afforestation, restrictions and controls on indiscriminate cutting of forests, efficient disposal of surplus water by terracing excessive slopes, and ensuring interstate coordination in these essential measures.

FARM PONDS

Hawley [this volume] has highlighted construction of over 2 million artificial ponds, pits, reservoirs, and earthen tanks covering over 862,000 ha of farmland surface in the United States. Their construction has been a part of the conservation activities of the U.S. Department of Agriculture with the objects of erosion control, emergency water supply under drought conditions, stock watering resulting in rotational grazing and consequently soil protection, irrigation, increased recreation facilities, and fish and wildlife development.

In India we had and have thousands of such small soil conservation, drinking water supply, and microirrigation or submerged cultivation works. These tanks, anicuts, and diversion weirs exist in almost all regions in this country where rain-fed storage structures, use of the postmonsoon flow, or diversion of the flows during the monsoon might be advantageous.

Several tank works for irrigation and water supply purposes have existed in India since circa 300 B.C. According to ancient writers the digging of a tank was regarded as the greatest of the seven meritorious acts of a man that was calculated to provide water.

In Madhya Pradesh, thousands of small tanks, diversion weirs, or regulators, constructed in the past and being taken up at present, are used for erosion control, minor irrigation, tank bed cultivation, drinking water, use of postmonsoon flow for 'rabi' crops (wheat crop period), and diversion of river flow for monsoon crops (rice crop period). There are small minor or microminor works meant to irrigate not more than about 1000 ha, the majority irrigating up to 200 ha. Suitable criteria are fixed for their planning and investment on the basis of cost per hectare, the ratio of irrigated area to submerged area being considered. They are financed by state funds executed by the Irrigation Department, and water is supplied on a charge basis. These works involve construction of small earthen tanks with wasteweirs, sluices, and channels or small concrete or masonry regulators and weirs. Careful and economic planning of cheaper designs is needed, particularly in respect to their surplus arrangements and canal structures, to cause minimum damages and acquisitions in spill channels. Provision must be maintained for desilting or raising, as may be necessary. These small works or farm ponds are suitable for execution in view of the lesser initial investments involved, the quickness of construction and benefits, and the creation of job potential for thousands of semiskilled and unskilled laborers. These do not involve problems of large-scale acquisitions, submergences, and resettlement.

FISHING AND WILDLIFE

Great scope and huge potential exist for the development of fish culture in our man-made lakes, large or small, all over the world. Revenues can be increased considerably, along with assured supplies for the welfare of the community. Apart from their normal potentialities as riverine fisheries, the construction of dams and formation of reservoirs further extend the scope of development, reservoir fisheries having in comparison a better magnitude of output. Experience in our state has shown that the program of development depends essentially on adequate and timely assessment of key items, like a fishery survey of the reservoir, the mode of fishing, and the various facilities for storage and marketing.

Likewise, as soon as an impoundment is programed, it has to be phased for advance action for the safety of the wildlife in the adjoining forests. Sanctuaries, reserved blocks, or suitable areas prohibited from game and shooting may be needed. If there are no adjoining forests beyond FRL, afforestations may have to be programed on the enlarged foreshore to create conditions similar to the natural glamour lost in the lakes. Nature's wildlife needs to be an integral part, living and moving around these man-made lakes, which have in fact added more charm to the original landscape. All possible steps to preserve especially the rare species should be launched by allocation of adequate organization and funds. Since recreation and tourism are becoming an international practice, it is desirable to suggest that international norms should be communicated for the preservation of the wildlife in our reservoirs.

The concept of integrated soil and water planning must be accepted as an important criterion for planning, construction, and development of these man-made lakes.

REFERENCES

Haas, J. W., Small watershed program: Its status and effects, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Hawley, A. J., Farm ponds in the United States: A new resource for farmers, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Small Watershed Program: Its Status and Effects

JOSEPH W. HAAS

Watersheds, Soil Conservation Service, U.S. Department of Agriculture
Washington, D. C. 20250

This paper provides a brief summary of the 'Small Watershed Program' administered by the Soil Conservation Service of the U.S. Department of Agriculture under the authority of the Watershed Protection and Flood Prevention Act [*U.S. Congress*, 1954]. It includes a short discussion of programs leading up to the act, accomplishments to date, and some of the results of projects installed. Then a detailed description is given of a particular project, Brush Creek watershed, West Virginia, and its impact on a rural community.

The first authorization for the Department of Agriculture to become involved in flood control programs was contained in the 1936 Flood Control Act [*U.S. Congress*, 1936]. That act delegated responsibility to both the Secretary of War and the Secretary of Agriculture to carry on a national program of flood control. It specifically included authority for the U.S. Department of Agriculture, under the direction of the Secretary of Agriculture, to conduct investigations and apply measures for runoff and water flow retardation and soil erosion prevention on specified watersheds. The act constituted the upstream complement to investigations and improvements of rivers and other waterways for flood control and allied purposes carried out under the supervision of the U.S. Army Corps of Engineers.

Flood control work was suspended during World War II and did not resume until 1946. Authority for additional work was contained in the 1944 Flood Control Act [*U.S. Congress*, 1944]. Under this act the Soil Conservation Service was authorized to apply special treatment for flood protection on 11 watersheds, encompassing nearly 12,835,600 ha (32 million acres) in 12 states.

Over the years it became evident that a new approach was needed to make flood prevention and watershed protection available to local organizations in upstream areas through a program separate and apart from major river improvements. A pilot demonstration program was authorized for 62 small watersheds as part of the Agricultural Appropriation Act for fiscal year 1954 [*U.S. Congress*, 1953]. The success of the approach was evident, and in August 1954 the Watershed Protection and Flood Prevention Act [*U.S. Congress*, 1954] was enacted.

The basic act was primarily for the treatment of upland areas to reduce erosion and sediment damages and for the installation of floodwater-retarding dams to afford flood protection. Since the initial law was enacted, it has been amended several times to broaden its scope to permit the management of water for other purposes. Municipal and industrial water supply storage, improvement of habitat for fish and wildlife, recreation developments, irrigation and drainage, water quality control, and other purposes may now be included. The program is now truly multiple purpose and permits full development of water resources in upstream watersheds.

To avoid duplication of authorities given to other agencies, the act contains certain limitations. Watershed project areas may not exceed 101,215 ha (250,000 acres), total water storage in any one structure may not exceed 30,837,500 m^3 (25,000 ac ft), and flood prevention storage may not exceed 15,418,750 m^3 (12,500 ac ft).

In general, the federal government is authorized to pay all construction costs allocated to flood prevention and up to 50% of the construction costs allocated to irrigation, drainage, public recreation, fish and wildlife development, and municipal and industrial water supply.

Watershed projects are unique in that they are not federal undertakings but are planned and installed by local sponsoring organizations that have identified a water resource problem and have taken steps to correct it. The Secretary of Agriculture is authorized to assist such organizations by conducting investigations and surveys, preparing plans and estimates for engineering evaluation, obtaining the cooperation and assistance of other federal agencies, and generally coördinating the plan development. Sponsoring agencies remain completely involved throughout the planning process; they guide the development and make decisions about what alternatives will be selected to meet their project objectives. During the formulation, Soil Conservation Service planning specialists urge sponsors to consider all resource needs and to develop plans that are broader in scope than those that might be suggested by special interest groups. The various technical disciplines in the Soil Conservation Service are called on; outside agencies are consulted, and experts in every field are used to assure that the plan developed is, in fact, comprehensive and based on an interdisciplinary approach to planning. Increased emphasis is being given to the identification of all the environmental impacts of these projects.

As of July 1, 1970, 1001 watershed projects had been approved for installation. Construction is completed on 291 of these, and 433 others are under way. Preconstruction services are being provided on 219 more. An inventory of potential projects shows a national need for 8925 such projects, indicating there is much yet to be done. Applications for assistance have been received on 2885. In addition to the 1001 projects approved for construction, 368 others are currently being planned.

Watershed projects are not single structure or reservoir proposals. Rather they consist of a variety of measures to be installed within a project area. The first increment considered is always 'land treatment,' the application of conservation practices on cropland or other areas. This is in keeping with the basic mission of the Soil Conservation Service: to reduce soil losses to an amount that will permit the long-term use of each hectare of land within its capability. Land treatment measures include contour farming, grass waterways, terraces, diversions, drainage channels, establishment of vegetation, and over 100 others. Such practices reduce sediment yields, improve the infiltration capacity of the soil, and slow the runoff of excess water to reduce flood peaks.

In combination with land treatment, various structural works of improvement are analyzed, the problems and needs of the area and the priorities established by the local sponsors being considered. Generally, the reduction of flood damage is of primary importance. To reduce flood damage, floodwater-retarding dams are proposed first, since they can be designed to include water storage for other purposes, helping to create multiple-purpose projects. Channel improvement is sometimes needed where enough floodwater storage is not available or dams are not feasible. But, since channel improvement can be more disruptive to the natural environment than dams, it is recommended only after other combinations fail to provide adequate protection. Thus a single watershed project may include several man-made lakes and many other measures to create a development responsive to the stated needs and conducive to environmental protection.

At the time that this paper was prepared, statistics had been compiled through June 30, 1969, for all watershed work plans approved for installation. In the 937 plans approved by that date the total estimated installation cost of land treatment and structural measures was $1.8 billion, over $774 million being for the construction of small reservoirs. When these measures are installed, they will prevent flood damages of over $56 million annually and will provide recreation benefits exceeding $15 million annually, agricultural water management benefits of over $16 million annually, and other miscellaneous benefits to bring the total to nearly $120 million annually.

As of July 1, 1970, 2728 dams had been constructed under the watershed program. Of these, 2452 are single-purpose floodwater-retarding dams, 150 are multiple-purpose reservoirs, and 126 are debris basins. An additional 3232 floodwater-retarding dams are proposed for construction within approved projects. As a sidelight it is interesting to note that farm ponds installed in watershed projects under the land treatment program now total over 100,000.

We will now turn our attention to a discussion of a single project and the impact that it has had on a rural community.

BRUSH CREEK WATERSHED

To evaluate the community development benefits accruing from small watershed projects, the Soil Conservation Service entered into a contract with Spindletop Research, Lexington, Kentucky, to study in detail the effect of two watershed projects. One of these is the Mud River watershed in Kentucky. The other is Brush Creek watershed in West Virginia, which will be discussed here.

The Brush Creek watershed lies in Mercer County in southeastern West Virginia. The work plan includes six floodwater-retarding dams, four multiple-purpose dams, and about 10 km (6 miles) of channel improvement. The project is complete except for one multiple-purpose structure. The total installation costs are estimated to be $3.8 million with annual operating costs of $31,800.

The major linkage between the watershed project and the regional economy is the flood protection provided by the project in and around Princeton, West Virginia. Another important link is the water supply provided by three of the structures to Princeton, Bluefield, and nearby rural areas.

Prior to 1960, Mercer County had a trend of declining employment. An upturn in employment coincided with the flood retardation provided by the first watershed structures. Interviews were made of firms locating new plants or expanding existing ones to learn if their decisions were influenced by the watershed project. It was concluded that 545 manufacturing jobs now exist in Mercer County that would not be there without the project. If employment multipliers are applied, over 1300 new jobs are attributable to the project, which had yielded an increase of $20 million in wages and salaries by the date of the study. In total, more than $17 in community development benefits have been realized for every dollar of project cost.

In addition to the measurable development benefits, social changes that cannot be assigned monetary values at the present state of economic analysis have occurred in Princeton and Mercer County. For example, over 40,000 people are now or will be provided with plentiful, safe, clean water, whereas before the project the supply was often short or contaminated. A total of 8600 people have been provided with sanitary sewage disposal by the project, primarily by sewage lagoons. And the lakes and associated facilities are expected to attract 35,000 annual visitors for fishing, picnicking, boating, horseback riding, and other recreational opportunities.

In addition to investments in the manufacturing industry, public investments have been made to help stabilize the community. These include a new $4 million 206-bed hospital financed by local and federal funds. The hospital will be built on the protected floodplain and will use project water. It will employ over 200 people. Also a $2 million vocational school employing over 30 people has been constructed. Additional investments will soon be made in a new high school, grade school, and associated garages and maintenance buildings. Long-range plans call for a mental health center near the hospital.

In the view of many the natural rugged mountain beauty of the area has been improved by the addition of lakes on the landscape. This, along with the prevention of the ugliness that normally followed the annual flooding and thousands of hectares of conservation practices, has definitely improved the scenic quality of the community and surrounding area.

On the basis of Brush Creek watershed it appears that small watershed projects can be effective tools for economic development in regions where flood problems exist and water supply shortages are bottlenecks to economic growth. Certainly, the town of Princeton has been given new life, has reversed its downtrend in population, and can expect moderate growth in future years.

Sidelights to the Brush Creek story include the fact that the project was selected as 'Watershed of the Year' in 1969 by the National Watershed Congress. Also a movie, *Brush Creek Bounces Back*, has been produced to depict the highlights of the project, and, last but not least, Dr. Daniel Hale, whose leadership helped to make this project a reality, was recognized in 1970 by the National Watershed Congress as 'Watershed Man of the Year.'

REFERENCES

U.S. Congress, Flood control act, *Public Law 74-738*, 74th Congress, 2nd Session, June 22, 1936.

U.S. Congress, Flood control act, *Public Law 78-534*, 78th Congress, 2nd Session, Dec. 22, 1944.

U.S. Congress, Department of Agriculture appropriation act, *Public Law 83-156*, 83rd Congress, 1st Session, July 28, 1953.

U.S. Congress, Watershed protection and flood prevention act, *Public Law 83-566*, 83rd Congress, 2nd Session, Aug. 4, 1954.

Farm Ponds in the United States: A New Resource for Farmers

ARTHUR J. HAWLEY
Department of Geography, University of North Carolina
Chapel Hill, North Carolina 27514

Adding a new spatial component to a rural landholding in the United States usually means that the component will become a permanent part of the landholding. One recent widespread addition to the rural landscape has been the construction of over 2 million artificial ponds, pits, reservoirs, and earthen tanks. These man-made structures are found in all 50 states and cover over 5357 km² of former land surface. Hydrologists and limnologists have studied these water bodies, but no one has assessed their geographic significance. This paper presents the preliminary results of such an investigation.

DATA SOURCES

The technique of impounding water by excavating or by constructing an earthen dam has a long history. Although data on ponds built prior to 1936 in the United States do not exist, apparently there was little interest in pond construction. Since 1936, detailed statistics on pond construction have been published by the *U.S. Department of Agriculture* [1936–1973]. Since that date, pond construction has been a part of the Agricultural Conservation Program (ACP) of the U.S. Department of Agriculture (USDA), and the Soil Conservation Service (SCS), organized under the USDA in 1935, annually reports ponds for which it provides technical assistance. Unfortunately, accurate records are not kept by SCS officials at the local level on whether ponds are constructed at the sites surveyed [*Hawley*, 1963, pp. 11–12]. Artificial ponds, pits, reservoirs, and earthen tanks were enumerated in the 1954 and 1964 agricultural censuses [*Bureau of the Census*, 1954, 1964] and will be counted again in 1974. These census enumerations and ACP data provide relatively accurate information on the growth of this new water supply on farms in the United States.

POND NUMBERS AND LOCATION

The policies of the USDA have been instrumental in the introduction, growth, and persistence of ponds in the United States. Since 1936, pond construction has qualified for cost sharing under the ACP. The USDA has subsidized up to 50% of the cost of pond construction provided the pond functions as an erosion control, livestock, or irrigation reservoir.

The numbers of ponds built as a result of ACP cost sharing increased steadily from 4167 in 1936 to a record high of 124,815 in 1946. Since 1946 the number built each year in the 48 contiguous United States has averaged over 63,000. In 1954 the agricultural census [*Bureau of the Census*, 1954] enumerated 1,768,060 farm ponds in the United States, 74% of which had been constructed under the ACP. By the 1964 census [*Bureau of the Census*, 1964] the number of ponds had increased to 2,154,955, 87% of which had received ACP cost-sharing assistance. In 1954 one of five farms (19%) in the United States had a pond, whereas in 1964 one of four farms (26%) had an artificial pond, pit, reservoir, or earthen tank. Thus farmers have responded readily to the economic incentive of having the USDA pay part of the bill by constructing ponds on their landholdings.

When the SCS was organized under the USDA in 1935, it was given responsibility for implementing the adoption of soil and water conservation measures by farmers throughout the United States. However, the administrative structure selected for carrying out this program (local soil conservation districts) required authorization by the state legislatures. Not until 1945 had most of the states (45) given their approval. Two years later the SCS estimated that three fourths of all the farms in the country were included in soil conservation districts. In 1969, over 99% of the nation's farms and 97% of the farmland were included.

In pond construction the SCS serves both as an engineering service to provide free technical advice and assistance and as a propaganda voice for USDA policy. Ponds built with ACP funds must be approved by the SCS. Since SCS personnel will locate, design, and stake out a pond site at no cost to the landowner, most farmers who build ponds avail themselves of this service. It is of interest that two periods of intensive pond-building activity in the 48 states correspond remarkably well with the initial organizational activity of the SCS after World War II and the years following 1952, when the SCS emphasized heavily the use of durable conservation practices, one of which was pond construction. Moreover, this second period marks the widespread adoption of irrigation throughout the southeastern states from Arkansas and Louisiana eastward [*Hawley,* 1970]. The full story of the role of the USDA in pond construction has not yet been told.

Farm ponds were heavily concentrated in the lower Midwest in 1964. The six states with more than 100,000 ponds each (Texas, Missouri, Oklahoma, Kentucky, Kansas, and Tennessee) had more than half of all the ponds counted in that year. From 1965 to 1968 these six states had 38% of all the ponds built for erosion control, livestock, or irrigation (70,864 of 184,042) but only 7% of the ponds built for fish or wildlife (1659 of 22,971) under the ACP. These man-made reservoirs are becoming more widespread as other states begin intensive pond construction.

Areas with low pond densities correspond closely with well-known conditions in the physical environment: (1) glaciated topography in the upper Midwest, where natural lakes are plentiful, (2) rugged uplands and mountains with sparse rural populations in the Appalachians, the Adirondacks, New England, the Rockies, the Sierra Nevadas, and the Coast Ranges of the Far West, (3) low-lying coastal or floodplain areas in the Atlantic and Gulf coastal plains and the Mississippi alluvial valley, where surplus surface water is a problem, and (4) semiarid to arid climates in the Great Plains and Far West, where evaporation from small water bodies is extremely rapid. One should be cautious in interpreting these associations, however, to avoid inferring a cause-effect relationship. Nevertheless, common sense dictates that these are areas where small man-made water bodies are either unnecessary or impractical under present occupance patterns.

PLANNED POND USES AND EFFECTS

Water bodies constructed under the ACP must be used for erosion control, stock watering, irrigation, or (since 1965) fish and wildlife. However, these ponds are not exclusively devoted to one use, since stocking with game fish (provided by the U.S. Fish and Wildlife Service) is a nearly universal practice. Multiple uses characterize all but the smallest farm ponds in the United States [*Holz,* 1959]. This fact should be borne in mind during the following discussion.

Erosion control. Published data on ACP ponds built from 1946 through 1954 record the pond use for which cost sharing was provided. Over 28% of the 750,000 ponds constructed during this time period were designed for erosion control. However, declining emphasis on this aspect of conservation policy in the USDA is reflected in the precipitous drop in numbers of erosion control ponds built after 1950. From 1946 to 1950, over two fifths of all the ponds constructed were for this purpose, but by 1954 this had dropped to only 4%. Unfortunately, more recent data on pond construction do not provide this information on function. If we can surmise that ACP funds are allocated to implement conservation practices currently in favor with the USDA, pond construction for erosion control must be an insignificant part of recent ACP pond numbers.

Stock watering. During the period when erosion control was declining in importance (1950–1954), pond construction for livestock watering dominated this part of the ACP. From slightly over half of all the ponds built prior to 1950, livestock ponds increased to over 90% in 1954. They qualify as a soil conservation measure because farmers and ranchers can effectively employ rotational grazing with alternative water sources in the pastures. This reduces overgrazing and helps retain a sod cover to inhibit erosion.

One unforeseen development of this policy decision was the growth of the beef cattle industry in the South, and perhaps elsewhere as well. The number of cattle and calves on farms in the South has increased steadily from 13.5 million in 1950 to 19.5 million in 1969. Two and one-half million cattle were added during the 1950–1954 period alone. Accompanying this increase in numbers has been a growth in permanent pastureland and a marked decline in pastured woodland. These land use changes would have been difficult, if not impossible, without the farm pond water supply. Throughout the piedmont, especially, streams dry up periodically during dry summers, and wells are an uncertain water source. Low-cost ponds provide a dependable water supply and have enabled many farmers to convert a part of their landholdings to pasture.

Irrigation. Although only 2% of the ACP ponds built between 1946 and 1954 were for irrigation, 1954 had 2½ times as many irrigation ponds (3800) as any of the previous years. Did this increase continue or was this simply an isolated instance? The final answer lies in the files of the USDA in Washington, D. C. However, irrigated land in the 11 southeastern states has risen dramatically from 284,000 ha in 1939 to over 1,280,000 ha in 1964. The 1969 agricultural census [*Bureau of the Census*, 1969] shows a continued increase to nearly 1,400,000 ha. The pivotal period 1949–1954 was marked by the widespread adoption of irrigation throughout the South in areas not previously irrigated. With the exception of the established irrigated states of Florida, Louisiana, and Arkansas, irrigated land increased from 809 ha in 1944 to 8093 ha in 1949 and 112,909 ha in 1954 in the Southeast. It seems likely that farm ponds were instrumental in this increase. The special report on irrigation in humid areas in the 1954 agricultural census [*Bureau of the Census*, 1954] found irrigation ponds on 42% of all farms reporting irrigation during 1955 in this area of the United States (28 eastern states). Unfortunately, comparable information is not available for recent agricultural censuses.

Recreation, fish, and wildlife. Recreation and wildlife uses form the most recent cost-sharing functions for ponds under the ACP. Since 1965, over 11% of all ACP ponds have been built for these purposes. A new dimension has been added to the role of ponds in the farm production schedule, and many small or part-time farmers now can benefit from (and receive aid for) pond construction on their landholdings. Stocking these ponds with game fish (typically largemouth bass and bluegills) provides a full spectrum of water-related recreational activities.

UNPLANNED POND USES AND EFFECTS

As the man-made pond has become a ubiquitous phenomenon throughout the United States, it has assumed functions unforeseen by either the USDA or the farm landowner. Representative of these new uses, but not exhaustive, are: rural status symbol, public health hazard, emergency water supply, and commercial warmwater fisheries.

Rural status symbol. Landowners in rural areas are as status conscious and competitive as urban dwellers. Consequently, as ponds were built in an area, a social mystique developed around having the oldest, the largest, the clearest, or the best fishing pond in the neighborhood. Individuals installed earthen dams for ponds in locations and on soils where SCS officials informed them that they would not be successful. Without SCS approval, and therefore without USDA cost sharing, the incentive for pond construction must have come from noneconomic motives. No statistics have been gathered on this facet of pond building, but instances have been found in Georgia, North Carolina, Michigan, and Ohio. Multiple-pond ownership may be expected to increase in these areas in the future, just as multiple-automobile ownership has grown in urban areas. In both cases the symbol provides a highly visible record of achievement.

Public health hazard. With the increase in area of standing water throughout the country the danger of fatal accidents by drowning has risen. Moreover, beyond this immediate danger lies a more subtle but equally important hazard. Malaria and other diseases borne by water-based vectors are indigenous to the southeastern United States. Drainage of swamps, spraying, and other public health measures have significantly reduced the incidence of these diseases, but the introduction of the farm pond could reverse this trend. Properly designed and maintained ponds pose no problem, but unfortunately the existence of shallow-water pond areas with emergent weeds and brush is not unusual. How serious this problem is has yet to be investigated.

Emergency water supply. The existence of man-made farm ponds proved extremely beneficial to both farmers and urban dwellers in piedmont North Carolina in 1968. During that summer the state endured one of the most severe droughts in its history. Municipal water supplies for many towns in the piedmont reached the critical point, and drinking water had to be brought in by tank truck in some localities. Farmers who had ponds could provide irrigation water to their high-value crops, and in several instances they sold their pond water to the local town. This water was pumped into the municipal water supply system and enabled several cities and towns to hold out until the rains came. As pond numbers continue to increase in North Carolina, this potential emergency water supply also increases, and the margin of safety for both towns and farmers is widened.

Commercial warmwater fisheries. Continued reductions in crop allotments for the primary cash crops in the United States have forced farmers to seek alternative sources of income. One possibility being explored is the production of catfish in farm ponds for sale to individuals, restaurants, and retail grocery stores [*Wilborn,* 1970]. Income possibilities from this form of pond use are substantial. The Louisiana Soil Conservation Service estimates an average annual net return to land and management of over $593.00/ha. The initial development of this type of catfish farming began in 1951 on 113 ha in eastern Arkansas. However, marketing problems and lack of technical experience probably would have doomed this early experiment to failure without the assistance of the federal government. In March 1958, Public Law 85-342 [*U.S. Congress*, 1958] was passed to provide funds for research to develop a successful fish-farming industry in conjunction with the production of rice. More recently, the federal government has allocated nearly $750,000 for research designed to support the growth of commercial warmwater fisheries throughout the Southeast. Thus once again the federal government is subsidizing the development and use of rural man-made reservoirs. If this research is successful, the farm pond seems likely to become an even more important component of the farm production system in the South than it already is.

RESEARCH DIRECTIONS

Artificial ponds, pits, tanks, and reservoirs become permanent parts of the rural landscape once they are constructed. Even those that fail to hold water typically are not removed but rather are left in the hope that siltation will eventually seal the leak. This permanent nature and their growing numbers imply that their impact will increase rather than diminish in the future. What are some of the areas in which research on farm ponds could profitably be undertaken?

First and foremost is the role of the federal government in the introduction and growth of these water bodies. The geographer, especially, is interested in the spatial variations in program emphasis, funding, and research and the impact that these variations have on pond distributions throughout the United States. Second, research also needs to be undertaken on how closely farm pond uses coincide with the functions specified under ACP cost-sharing arrangements. Indeed we have only sketchy evidence of pond functions within individual landholdings much less over broader areas.

Third, has the farm pond had any effect on the microclimate of those areas in which it is concentrated or on the hydrology of the watersheds? Does the existence of ponds in the densities present in the lower Midwest have any effect at all on the physical environment?

Lastly, of particular interest to me is the role that this rural water reservoir plays in the adoption of irrigation and the shift in land use throughout the South from cropland to pasture. Obviously, farm ponds are only one of a complex matrix of factors causing this shift, but how important have ponds been? Indications are that they were pivotal in the spread of beef cattle operations, but did they influence anything else? Research in these and other areas will shed light on one of the most widespread and recent, but unknown, components of the rural landscape in the United States.

REFERENCES

Bureau of the Census, *Census of Agriculture*, U.S. Government Printing Office, Washington, D. C., 1954.

Bureau of the Census, *Census of Agriculture*, U.S. Government Printing Office, Washington, D. C., 1964.

Bureau of the Census, *Census of Agriculture*, U.S. Government Printing Office, Washington, D. C., 1969.

Hawley, A. J., Impact of farm ponds on the morphology of land-holdings in Elbert County, Georgia, M.A. thesis, Univ. of Ga., Athens, 1963.

Hawley, A. J., Irrigation adoption patterns in the South, 1939-1964, paper presented at the 25th Annual Meeting, Southeast. Div. Ass. of Amer. Geogr., Columbia, S. C., Nov. 23-24, 1970.

Holz, R. K., The distribution and use of man-made ponds in Jackson County, Illinois, M.A. thesis, S. Ill. Univ., Carbondale, 1959.

U.S. Congress, Fish, Research for rice areas, *Public Law 85-342,* 85th Congress, 2nd Session, March 15, 1958.

U.S. Department of Agriculture, *Agricultural Statistics*, U.S Government Printing Office, Washington, D. C., 1936-1973.

Wilborn, E., To succeed in catfish farming, *Progr. Farmer, 85*(4), 16B, 1970.

Man-Made Lakes and Wildlife Values

JAMES B. TREFETHEN

Wildlife Management Institute, Washington, D. C. 20005

There is a mounting ground swell of public interest in wildlife riding beneath the breakers of current environmental concern in the United States. The old-line wildlife conservation movement was made up primarily of organized sportsmen and nature enthusiasts who could count on a rather narrow base of public support. Today, in this age of environmental militancy, when you hoist the banner of wildlife conservation, recruits come running from all directions.

Some of the newcomers are poorly informed and highly emotional, and a few march off on their own quixotic side campaigns whose success would damage rather than enhance the wildlife conservation movement. These people, however, represent the conspicuous part of an iceberg of more objective public concern that can be crystallized as the foundation for constructive natural resource programs. But the broad public concern and interest in wildlife resources do exist and have become forces to reckon with by anyone concerned with natural resource management.

Not many years ago it was possible to plan and construct a single-purpose dam and reservoir (whether for flood control, irrigation, or water supply) and to justify it solely on economic grounds. Little concern had to be given to natural esthetics or the effects of the projects on fish, wildlife, and other renewable resources. Unless a proposed project would have impinged on a national park or an important historical site or threatened to destroy some well-publicized endangered species, local economic considerations usually outweighed any natural values threatened with displacement.

With our present broad-based public concern for natural values it has become hazardous for engineers to ignore or minimize the impacts of their works on the natural scene, including wildlife and wildlife habitat. In the United States the National Environmental Policy Act of 1969 [*U.S. Congress*, 1969] makes mandatory a review of the projected impact on the existing ecosystems of any proposed federally financed or licensed water project. The existence of this law is one evidence of the public concern that I have mentioned. The U.S. Army Corps of Engineers, in keeping with the spirit of the law, last year appointed an Environmental Advisory Board made up of conservationists highly qualified to advise on wildlife problems.

This step is to be applauded and could be profitably emulated by all other agencies and authorities concerned with water management. The engineer who plans a project without full environmental consideration today can stir up a hornet's nest. Although it involved a navigation canal rather than a reservoir, the fate of the Cross-Florida Barge Canal is a recent case in point. So are the fates of the Everglades Jetport and the supersonic transport plane. For good or for bad, public concern over the potential effects on the environment was the counterweight that threw the scales in favor of the opponents of the supersonic transport plane.

I point to examples of this kind not to downgrade or criticize engineers and engineering projects but merely to focus attention on the changing temper of the times. The public today is thoroughly aroused over environmental problems. It behooves all of us concerned with natural resources to take these new attitudes into consideration. Major engineering projects based solely on local values cannot stand alone. Future projects that involve environmental change, including the disturbance of wildlife habitat, are going to be subjected increasingly to critical public review.

Few, if any, engineering achievements have a greater impact on the environment of an area than the construction of a man-made lake. Even a comparatively small one drowns out miles of stream and inundates hundreds of acres of farmland, fields, brushland, and forest. On larger man-made lakes the destruction of preimpoundment natural values (whether wildlife, timber, or trout stream) extends over hundreds of square miles. Fortunately, however, by working in concert with wildlife authorities, the hydrologic engineer has an opportunity not given to those in other branches of his profession to create public wildlife values as great or greater than those that his works displace. Depending on the productivity of the reservoir site before impoundment, the nature of the local wildlife population, and the size, design, and management of the reservoir, a man-made lake can be destructive or beneficial to wildlife.

In desert regions, where intermittent streams are dry for long periods of time and springs or seeps are few and widely spaced, a man-made lake can open up hundreds of square miles of previously uninhabitable range to deer, antelope, and other wildlife. It can also become an important oasis for waterfowl and shorebirds.

In more humid areas, where water is not the limiting factor, the effects of reservoir construction, at least temporarily, are almost totally negative. When a man-made lake is filling, the displacement or elimination of the existing wildlife population on the immediate site is inevitable.

Practically every reservoir obliterates part of a natural stream. In some instances it may eliminate all free-flowing streams in an entire watershed. Natural floodplains are among the most productive wildlife lands.

NATURAL HABITAT

Except where overgrazing or other abuses occur, the banks and floodplains of streams almost invariably support a lusher and more diversified vegetative cover than that of the bordering uplands. On the prairies and in desert areas, banks and floodplains nurture the only true trees. In extensively wooded regions the larger streams provide breaks in the forest canopy, which permit the development of low shrubs and fruit-bearing trees that are intolerant of shade. Thickets of alder, willow, poplar, and other hydrophytic trees provide browse for deer and other large browsing mammals close to a reliable water supply. There is an abundance of insect life to satisfy the needs of songbirds and the insectivorous mammals, reptiles, and amphibians. Riffles and shoals provide fishing spots for wading birds, raccoons, and otters. The backwaters of coves support reeds and rushes, which are vital nesting sites for waterfowl and many species of songbirds.

Because they are less vulnerable to logging, river bottomlands and stream border swamps usually contain more mature and overmature trees than the adjoining uplands do. Oaks and other mast-producing trees provide essential food for a variety of wildlife. Southern hardwood bottomlands that are naturally flooded in winter support some of the largest concentrations of mallards, pintails, and wood ducks found anywhere in the United States.

Natural cavities in dead and dying trees or those opened by pileated woodpeckers and enlarged by decay provide homes for wood ducks, squirrels, raccoons, and chickadees. Eagles and ospreys prefer tall snag trees as roosts and nesting sites wherever they are available.

Each stream valley forms an ecosystem that is unique in some ways from every other stream valley because of variations in the local microclimate, geology, topography, and land and water use. Not every stream valley is as productive as that just generalized. But whatever wildlife habitat is present in the lake site before impoundment is eliminated by construction and flooding. Often, it can be replaced only by deliberate and conscious habitat restoration programs.

In some large municipal water supply reservoirs that I have seen, sanitation has required the removal of most of the vegetation and top soil and the riprapping of the banks. In such situations the near-total disruption of the ecology occurs even before the floodgates are closed. Where construction activity is confined to the immediate vicinity of the damsite, the process is more gradual but equally inevitable as the flowing streams are replaced by the rising waters of the lake.

In addition to the effects behind the dam, construction activity may change the ecology of a stream for many miles downstream through the generation of silt and the elevation of water temperatures. The relentless rise of the man-made flood as a reservoir fills threatens many forms of wildlife with death. During the spring, when the filling of a newly constructed reservoir is most rapid, at least in temperate zones, nearly all species of wildlife produce all the young that they will be able to produce throughout the year. As nests and burrows are flooded, any eggs or young caught behind the rising water are almost certain to die. Even aquatic species like the muskrat and the beaver are subject to such losses.

The adults of most terrestrial species are able to keep pace with the rising water level and escape to adjoining cover. But biologists have long known that animals moving into a range that is fully stocked rarely survive for long in competition with resident animals of the same species. And usually the cover into which the displaced creatures are forced is inferior to that that they have vacated.

Birds, mammals, and reptiles incapable of flight or swimming for sustained distances often become trapped as hills become dwindling islands that eventually disappear. Rescue operations can never be more than partially successful.

Even though it may not affect them directly, a man-made lake of substantial size can influence populations many miles from its shores. Many species of the larger mammals (caribou, elk, and mule deer in North America and a variety of African and Asiatic ungulates) are essentially migratory. Some winter a hundred and more miles from their summer ranges. Although some, like the caribou, are excellent swimmers, any large man-made lake may create a physical barrier that few, if any, can cross. The route around the lake may be so long that the traditional and essential migration pattern is broken. In the western United States and Canada the floors of canyons, which often are among the choicest reservoir sites, are frequently the winter terminals of the big-game migration routes.

Thus, insofar as the wildlife is concerned, as the water levels begin to stabilize, the new ecosystem created by the reservoir starts with a clean slate.

NEW HABITAT

Once a man-made lake is filled and is relatively stabilized, it may create a new habitat that can be more valuable to a wider range of species than that that existed on its site before, especially when some consideration for wildlife values is worked into its design. Artificial impoundments, after all, are major tools of the wildlife manager. In the absence of natural lakes or marshes, impoundments usually form the core around which the typical national wildlife refuge in the United States is formed.

The impoundment designed for wildlife usually has values superior to those of the natural lake because its water level can be manipulated to meet specific seasonal needs. It is a common practice on many refuges to lower the water levels in spring or early summer. This change permits the natural or artificial cultivation of smartweeds, sedges, millet, or other wildlife foods on the exposed flats and shores. When the area is reflooded in late summer, it contains an abundance of seeds and leafy vegetation for the autumn and winter needs of waterfowl, muskrats, and moose.

Water level manipulation also offers one of the most effective and least expensive methods of controlling cattails, canes, and other littoral plants whose overly rank growth can crowd out more valuable food species.

Water level manipulation for the specific benefit of wildlife is practical only on wildlife refuges and management areas. But on many reservoirs designed for other purposes, such as irrigation and water supply, a similar pattern of drawdown and reflooding takes place. The peak demand for irrigation water and water used domestically usually comes during the height of the plant-growing season in late spring and early summer. Autumn rains replenish the waters and reflood the beds of any shoreline plants that may have developed during the summer.

Whether this pattern will benefit wildlife depends on the design of the reservoir and its topography and bottom soils. On many exposed shorelands, plant development is hindered when soils dry out quickly and excessively.

I am no engineer, but I assume that the ideal water storage reservoir (whether for power, irrigation, or potable water) would be designed for maximum volume and minimum surface area to reduce loss through evaporation. Some reservoirs in the canyon gorges of Utah may approach this ideal with their sheer rock walls, great depths, and narrow widths. Reservoirs of this kind have little wildlife value.

The ideal wildlife lake is almost the opposite of the irrigation engineer's ideal: shallow with gently sloping shores, small low islands, and an abundance of vegetation both in the water and on the shores. Islands are choice nesting sites for Canada geese, terns, and many species of ducks. Dead timber, whether standing or floating, is usually an asset rather than a liability in a wildlife impoundment.

Fortunately, at least from the wildlife viewpoint, the engineer rarely attains anything approaching water tank efficiency in the design of a reservoir. Most man-made lakes contain secluded coves, islands, shoals, and other features that characterize a good wildlife area. It is in such areas that engineers and officials charged with the administration of reservoirs have an opportunity to replenish lost wildlife for public benefit. State and federal wildlife agencies stand ready with funds and expert advice to assist in such programs.

ZONING AND REGULATION

If an area on a man-made lake has inherent wildlife values, much can be done to enhance it through zoning and the regulation of human use. Most forms of wildlife can tolerate a considerable amount of human intrusion into their habitat. But, if an aquatic area is to realize its full wildlife potential, most uses must be regulated, and a few must be excluded. High-speed motorboating and water skiing, popular and legitimate forms of recreation on many man-made lakes, can create so much disturbance as to render an otherwise valuable wildlife area almost useless. Many mammals and birds, especially those with nests or young, have a low tolerance for extraneous noise and motion. Constant disturbance, particularly by aquatic recreationists, is one of several factors in the decline of the southern bald eagle, which usually nests near water.

Less frenetic types of recreation may be quite compatible with wildlife values. Fishing, canoeing, sailboating, and even powerboating with low-power or throttled down motors cause minimal disturbance as long as the concentration of use does not become too high. Hunting is a legitimate use of surplus game in the autumn and early winter and is easily regulated, as local conditions warrant, through the use of access permits, waterfowl blind spacing, and similar regulations. Hunting also is useful in keeping deer herds and other ungulate herds from growing so large that they damage protective watershed vegetation.

The wildlife values of many of the natural lakes in this country have become degraded through unrestricted shoreline development to a degree that would be tolerated on few modern man-made lakes. Some New England lakes that I am familiar with are hemmed in by shoulder to shoulder cottages, and their waters are contaminated by sewage.

The protection and management of the shores and watersheds of a lake are even more important to wildlife than the protection and management of the open water. Some water birds rest in open areas far from shore, but practically all feed in the shallows, and all nest either on land or in emergent vegetation close to shore. Even the Canada goose, usually considered an aquatic species, derives much of its winter food by feeding in fields.

Most artificial lakes of any substantial size constructed in recent years are managed by agencies or authorities with sweeping regulatory powers over the use of the water and a surrounding belt of watershed lands ranging from a few hundred yards to many miles in width. Like regulated timber management, wildlife habitat development on such protected lands is fully compatible with the operation of the reservoir. Even without deliberate planning and management, the shorelines and watersheds of many man-made lakes, through natural plant succession, develop food and cover as good or better for more species than those of the stream bank complex that has been replaced (and there often is more of both).

When state and federal wildlife specialists work with the engineers and the controlling authority of a man-made lake, the benefits can be compounded. Frequently (even apart from esthetic and recreational values), the benefits are reciprocal. In the western states, there are 22 national wildlife refuges totaling 127,260 ha maintained by the Bureau of Sport Fisheries and Wildlife and 49 wildlife management areas administered by state wildlife agencies, all operating on lands acquired or withdrawn by the Bureau of Reclamation. Most of these refuges are vital links in the chains of protected waterfowl habitat that join the northern breeding grounds and the wintering areas in the South. Their upland areas are havens for pronghorn antelope, bighorn sheep, prairie chickens, and endangered species. Many of those with independent water structures in addition to being wildlife refuges also serve as silt traps on the streams that feed the main reservoirs.

Wheeler and Kentucky Woodlands national wildlife refuges, developed as part of the Tennessee Valley Authority lake system, support one of the largest wintering concentrations of Canada geese in the Southeast. Nearly a quarter of a million ducks now gather each winter in the

Tennessee Valley, an area nearly barren of waterfowl before 1930. The restoration of the deer herd of the region has been equally spectacular. Prior to 1936 and at least as far back as the turn of the century, deer have been about as common there as polar bears. Today, thanks to a cooperative program involving the state wildlife agencies and the Tennessee Valley Authority, there are no fewer than 150,000 white-tailed deer. Quail, wild turkeys, squirrels, and other wildlife are far more abundant than they were in the early 1900's.

The accomplishment in this valley is an outstanding example of what can be achieved when engineers, foresters, land planners, and wildlife agencies work together to achieve public values that extend a step beyond the purely materialistic. Not all administrators of man-made lakes can work on so grand a scale. But it is an example that more could profitably follow in this day of environmental concern.

To protect water quality, the investments of individuals, and public values on man-made or natural lakes, shoreland zoning under state or federal authority is a prime necessity. If local wildlife values are to attain their full potential, zoning is the fundamental step toward sound wildlife management.

REFERENCE

U.S. Congress, National environmental policy act of 1969, *Public Law 91-190,* 91st Congress, 1st Session, 1969.

Summary: Health Aspects of Man-Made Lakes

A. W. A. BROWN AND J. O. DEOM

World Health Organization, Geneva, Switzerland

Man-made lakes are formed as a result of engineering works constructed for a variety of purposes, such as hydropower generation, flood control, improvement of navigation, irrigation, recreation, and fish culture, that can all be combined in a single project. Each of these objectives confers benefits that are assessable. These benefits, however, will not necessarily accrue to the people in the immediate vicinity of the lake.

The formation of a new lake inevitably produces a number of local environmental changes, some favorable to the local inhabitants, some harmful. For instance, in an arid pastoral area the accessibility of water may improve agriculture and animal husbandry and provide a protein addition to the diet from fisheries. On the other hand, these advantages may be offset or outweighed by overgrazing and erosion, by the overstretching of local administrative and other facilities (e.g., schools, health units, and communications) due to an influx of population from elsewhere, and by the introduction of new diseases or the aggravation of existing diseases in the area.

The first man-made lakes to demand serious consideration in a public health context were those constructed some 40 years ago in the Tennessee Valley of the southern United States, and there the concern was that the transmission of malaria would be aggravated. For the same reason the government of India introduced a requirement 25 years ago that all dam construction and new irrigation systems be cleared first with the Health Ministry. In the last 10 years the public health aspects associated with man-made lakes have come into sharp focus with the construction in Africa of vast impoundments, such as Lake Kariba, Kainji Lake, Lake Nasser, and Volta Lake, all of which are now colonized by snail intermediate hosts of the causative organism of schistosomiasis. The raising of the water level of Lake Victoria (70,000 km^2) by the Jinja Dam and the consequent small fluctuations in lake level have created new foci of schistosomiasis.

With other large dams about to be completed in Africa, such as the Kossou Dam in the Ivory Coast, the Cabora Bassa Dam in Mozambique, and the Tafilalet Dam in Morocco, not to mention those in Asia, it is necessary to learn from the lessons of the past what the future may hold. Since most impoundments constructed primarily for power are employed to supply different-sized irrigation systems, we have to consider the health hazards associated with irrigation water as well as with the impoundment of the lake itself, the spillways, and the river below the dam. At the dam on the Dez River in southwestern Iran, close to a focus of urinary schistosomiasis, efforts are being made to keep the irrigation system below the impoundment free from schisotosomes. In tropical areas outside Africa the developments planned for the Mekong Valley in southeast Asia and the San Francisco Valley in northeastern Brazil will entail health hazards from snail-transmitted and insect-transmitted diseases in both the impoundments and the associated irrigation systems. Just as the type of crops and their cultivation largely decide the receptivity of irrigation systems to the breeding of vectors and intermediate hosts, so does the type of vegetation growing along the shorelines and in the water decide the health hazards of the man-made lakes.

PLANT ECOLOGY OF MAN-MADE LAKES

Once the impoundment has been completed, the succession of plant growth colonizing the shorelines, and at times even the body of the lake, will influence the incidence and development of vector-borne diseases. Most of the early man-made lakes were located in temperate zones, often in uninhabited highlands, where their steep shorelines precluded colonization by plants. Moreover, there are many large natural lakes in the tropics that, apart from plants in shallow margins, are devoid of vegetation. It was therefore hardly expected that man-made lakes in tropical areas would be seriously invaded by aquatic vegetation and still less that the vegetation would result in such an increase in population with the attending public health problems.

In tropical lakes, two floating plants have caused considerable trouble, namely, the water hyacinth *Eichhornia crassipes* and the water fern *Salvinia auriculata,* both of South America, where they are apparently of little importance. *Pistia stratiotes,* the water lettuce, may also be an important invader. Large mats of floating vegetation may move over the surface of the lake, navigation channels being blocked and deoxygenated conditions inimical to fish being created. If such masses of sudd-type vegetation are subsequently removed from the shoreline, they are often replaced by submerged plants, such as *Ceratophyllum demersum,* which may harbor the snail intermediate hosts of schistosomiasis.

Salvinia auriculata was present for some years in the Zambezi River, and an explosive development of it occurred in Lake Kariba when the lake began to fill following clearing and burning off. Mats of the weed harbor the snail intermediate hosts of human schistosomes and may transport them to different locations; i.e., the mats of weed are foci of schistosome transmission. The area now occupied by the plant in Lake Kariba appears to be receding, although the plant still covers 6% of the total lake surface (about 320 km^2). *Eichhornia* has not been seen on Lake Kariba.

All man-made lake projects in tropical areas are faced with the problem of what to do about the natural vegetation along the shoreline of the flooded area. In some places, such as Lake Kariba, extensive clearing was carried out before inundation, and this proved very expensive; in others, such as Volta Lake, little clearing was attempted. The Brokopondo impoundment in Surinam offers an extreme example, since it is essentially a drowned rain forest because no clearing was done at all; the acid waters of the Surinam River, which feeds it, were apparently unfavorable for the development of snails.

Eichhornia and *Salvinia,* both of which have caused much trouble in other parts of Africa, seem to be absent from Volta Lake. Many new vegetation types have developed, including a floating sudd-type vegetation in the creeks feeding the Volta below the damsite, *Vossia cuspidata* being one of the components. The thick mats of *Pistia stratiotes* observed in the Afram area of Volta Lake do not persist, but the *Vossia* sudd, usually associated with submerged weeds, such as *Ceratophyllum, Utricularia,* and *Polygonum,* is more enduring. Whereas *Pistia* appears to be seasonal in growth, mats of the common sedge *Scirpus cubensis* build up in the quieter bays and periodically break off into the lake with their snail fauna. For the most part, Volta Lake escaped the initial explosive weed growth phase that occurred at Lake Kariba, but both *Pistia* and *Ceratophyllum* show a marked seasonal variation in quantity, reaching their maximum development following the rainy season, *Ceratophyllum* apparently forming extensive underwater meadows during optimal conditions.

Kainji Lake occupies what was previously wooded savanna, and only partial clearing was undertaken before inundation. Along the margins of the lake and immediately inland from the swamps are abundant growths of the sturdy grass *Jardinea congolensis,* and floating mats of uprooted swamp plants and floating aquatic plants are present.

Lake Nasser offers an extreme example in that virtually no vegetation existed before inundation and the lake is now bordered by sandy beaches and rock outcrops covered with algae. Nonetheless, these inhospitable substrates support a sizable snail fauna infected with schistosomes. Higher up the Nile the impoundment above the Jebel Aulia Dam has become heavily overgrown with *Eichhornia crassipes.*

Obviously, the decision to clear trees and other vegetation from areas that will form the bed of a man-made lake, whether reached for navigational, fishery, or public health reasons, calls for the inclusion of cost-benefit assessments in the initial planning for any project.

Ecological changes will be felt not only in the lake itself but also downstream, where they may affect the health of the river dwellers. Excessive weed or algal growth, for instance, may spread downstream. Action taken in the lake for the biological, chemical, or mechanical control of such weeds will result in dead vegetation in the river below, which may well be the source of the water supplies of riverine communities.

Not only will the vegetation of the man-made lake promote the breeding of schistosome-bearing snails and malaria mosquitoes, but it could also encourage the development of the filariasis vectors in the genus *Taeniorhynchus* (now placed as the subgenus *Ochlerotatus* of the genus *Aedes*). The organic detritus from vegetation settling to the bottom of the impoundment often produces plagues of chironomid midges, which constitute a real threat to those allergic to them. This detritus may also result in dense populations of clams and mussels, which are known to be concentrators of harmful chemicals and which can damage pumps and turbines if they are carried downstream.

SCHISTOSOMIASIS PROBLEM IN MAN-MADE LAKES

Schistosomiasis is essentially a 'water-based' disease, since it is dependent on an aquatic organism, namely, the snail intermediate host, for a part of its transmission cycle. This serious debilitating disease affects over 200 million people. The prevalence of the infection is nearly always enhanced by the impoundment of water in man-made lakes and by the irrigation systems frequently associated with them. Irrigation systems have long been known as areas of schistosomiasis insofar as they increase the availability of water and consequent human contact with it; it is now becoming apparent that the man-made lakes themselves produce similar deleterious effects.

It is important to emphasize that the definitive host, man, is responsible for the dissemination of schistosomiasis by contaminating the aquatic environment, where he in turn becomes infected. The snail is only a passive intermediate host. Therefore, for the epidemiology and control of schistosomiasis, consideration must necessarily be given to the ecology of the human as well as to that of the snail hosts.

Where schistosomiasis is prevalent, a man-made lake is likely to present a considerable hazard for lake users, including the increasing numbers of fishermen and lakeside settlers who may come from schistosomiasis-free regions. It may also seriously jeopardize the health of the resettled population displaced by the impoundment. In Lake Kariba, transmission of both urinary and intestinal schistosomiasis has been demonstrated in limited foci, where the respective snail intermediate hosts *Bulinus (Physopsis) africanus* and *Biomphalaria pfeifferi* are associated with mats of the water fern *Salvinia auriculata*. In 1968, a decade after completion of the dam, the prevalence of *Schistosoma mansoni* was observed to be 16% among all age groups, whereas that of *S. haematobium* among children reached a mean of 69%. It is therefore vitally important that the presently focal transmission of schistosomiasis be contained.

In the vast Volta drainage area some 20 years ago the prevalence of schistosomiasis was low, the aquatic ecological conditions being generally unfavorable for the snail intermediate hosts. It was, however, predicted that on the west side of the future lake a number of areas might become ideal breeding grounds for *Bulinus* and *Biomphalaria* snails. In 1967–1968 a sharp rise in the transmission of *S. haematobium* occurred in lakeside communities because of enormous densities of *Bulinus truncatus rohlfsi*, developing principally in association with the weed *Ceratophyllum*. Specimens of *B. (Physopsis) globosus* have been found only recently in one location on the lake, although this species is the most numerous and widely distributed intermediate host of *S. haematobium* throughout west Africa, including Ghana. *Biomphalaria pfeifferi* has not been collected from Volta Lake, but it is expected that the species may be found, particularly in the northern part of the lake. Although one authority has stated that the prevalence rates of *S. haematobium* will drop in conjunction with an observed decline in the number of bulinid snails in certain places, a recent limited survey indicated that transmission of the parasite by *B. truncatus rohlfsi* is focally intense and may become more widespread with the possible development of even more favorable aquatic vegetation for snails, such as that that would be afforded by *Potamogeton* or *Nymphaea*, both of which occur in Ghana. This apparent conflict of opinion regarding transmission may only be a reflection of the seasonal fluctuation in snail densities and concomitant infections and certainly underlines the need for careful longitudinal epidemiologic studies in the area as a whole.

In Kainji Lake, the snail intermediate hosts of both *S. haematobium* and *S. mansoni* are now in evidence, and transmission of the parasites in settled areas is taking place, the mean prevalence rates of the two schistosome infections in 1970 being 31 and 1.8%. These observations, made 2 years after closure of the dam, also established that the snails were still confined to scattered foci.

In Lake Nasser, transmission of *S. haematobium* takes place around the entire perimeter as a consequence of the large colonies of *B. truncatus* present on algae-covered rock surfaces. No species of *Biomphalaria* have been found in the lake. An inevitable increase in transmission of *S. haematobium* and perhaps *S. mansoni* is predictable in relation to the development of irrigated areas supplied from the lake.

Available evidence from the major man-made impoundments in Africa therefore clearly indicates that transmission of schistosomiasis is taking place in the main body of every lake as well as in the existing irrigation works. Despite the attempts to provide alternative water supplies in some resettlement villages, contamination of the environment through domestic, occupational, and recreational contacts by the new settlement and resettlement populations has resulted in new and increased transmission patterns in Africa.

Thus the containment and abatement of schistosomiasis calls for management of the impounded water by means of shoreline sanitation, education of the human population to improve its habits in disposing wastes and excreta, and sanitary engineering to minimize the contacts between man and lake water. These measures are particularly important in view of the impossibility of applying molluscicides over an entire lake to control the snail populations chemically.

INSECT-BORNE DISEASES

The ancient impoundment and irrigation system of Anuradhapura in Ceylon is a classic example of an engineering marvel that proved somewhat less than a marvel in health terms; one third of the population was wiped out by man-made malaria. In more recent times, devastating epidemics of malaria have been recorded following construction of the Sukkur Barrage in Pakistan and the Mettur Dam in India. The danger of outbreaks of malaria as a result of dam construction was realized by the Tennessee Valley Authority in the 1930's and was circumvented by shoreline sanitation, periodic water drawdowns, and insecticide application. Russian and Romanian health authorities paid particular attention to malaria abatement in their newly constructed reservoirs and irrigation systems. The increased amount of land devoted to rice cultivation in irrigated areas has in the past given rise to epidemic malaria in the southern United States and has contributed to the spread of malaria in Portugal, Greece, Venezuela, and California. The recent introduction of irrigation water into the Kano plain in northwestern Kenya has raised the population of *Anopheles gambiae* by 70 times. Two clear-cut examples of malaria outbreaks directly ascribed to dams and irrigation systems come from Tanzania, namely, a *funestus*-transmitted epidemic originating from a weed-grown impoundment on a tea estate near Amani in 1957 and a *gambiae*-transmitted epidemic in a 5000-ha area of irrigated sugar cane south of Moshi in 1951. A new irrigated area can be especially vulnerable, as witnessed by the buildup of malaria in the Gezira irrigation scheme, Sudan, between 1925 and 1935 as a result of the influx of farmers from malarious areas as far away as Nigeria. Conversely, there are numerous examples of nonimmune immigrants falling victim to malaria as soon as they entered a malarious region.

The great new African man-made lakes have not shown any patent malaria resurgence, but the water-filled hoofprints between the high-water marks and the low-water marks on Lake Nasser are perfect breeding places for *A. gambiae* should it succeed again in extending its range northward from the Sudan and repeat the malaria outbreak of 30 years ago, when the mortality rate in Abu Simbel rose from 2 per 1000 per month in 1941 to 34 per 1000 per month in 1942. Moreover, the new irrigation systems would greatly multiply the numbers of the existing vector *A. pharoensis*. The lush aquatic vegetation along the shores of Volta Lake could produce large populations of *A. funestus*, although unusually high numbers of larvivorous fish have been observed in the northern part of the lake.

The transmission of arbovirus diseases is associated mainly with the irrigation areas linked to the dams. Most thoroughly studied is the transmission of western encephalitis by the mosquito *Culex tarsalis*, which breeds in the outflows at the ends of the irrigation systems in the United States, particularly in California and the Rocky Mountain states. A related problem is created by *Culex tritaeniorhynchus*, the vector of Japanese encephalitis (JE) in eastern Asia, where breeding is particularly associated with irrigated rice cultivation. The development of dams in the Mekong Valley could exacerbate the situation. *C. tritaeniorhynchus* also extends across Africa as far west as Senegal, but JE has not been identified there. Another African species that could multiply in irrigation systems and impoundments is *Aedes caballus,* the vector of Rift Valley fever. The two important arboviruses transmitted by the domestic mosquito *Aëdes aegypti,* namely, yellow fever and dengue with its hemorrhagic form DHF, would not be expected to increase with the man-made lakes and irrigation systems. In reality, however, opportunities for the breeding of their vectors may increase, since the experience in resettlement villages is often that the pumping systems for piped water supply go out of order and large quantities of substitute water are stored in the houses.

Onchocerciasis in Africa is mostly transmitted by *Simulium damnosum,* whose larvae breed in the rapid sections of streams and rivers. The effect of impoundments is beneficial insofar as they drown out the breeding places for several kilometers above the dam. Although breeding may subsequently take place on the spillways and below the dam, the larvae may be artificially flushed away by opening the sluice gates, or insecticide may be administered to the outflow from the dam itself. A thorough program of *Simulium* control was necessary during the construction of the Volta and Kainji dams.

In tsetse-infested areas, there is a continuing danger of recrudescence of trypanosomiasis, since the extensive shorelines of the impoundments will constitute harborages for tsetse wherever they become lined with high vegetation, as they have in the Kossou and Kariba impoundments. There is evidence of decimation of cattle having been caused by bovine trypanosomiasis in the Lake Kariba area between 1962 and 1966. The contact of tsetse with man will be increased owing to the attractiveness of fishing boats and other lake shipping for these vectors.

RESETTLEMENT OF POPULATIONS DISPLACED BY THE MAN-MADE LAKE

In contrast to the dams constructed in uninhabited terrain in northern countries, large impoundments now being constructed in Africa and elsewhere in the tropics inundate territory occupied by sizable populations. Although the area around the River Niger that is now Kainji Lake had a population density of <10 people/km^2, the total impoundment of 1500 km^2 required the displacement of about 42,000 persons. The formation of Volta Lake, inundating some 9000 km^2, displaced a population of 80,000 persons, all of whom had to be resettled. The number of Egyptians and Sudanese demanding resettlement because of the impoundment of Lake Nasser amounted to 120,000.

If sufficient land is available, resettlement may be possible quite close to the shores of the new man-made lake, as it was at Lake Kariba, Volta Lake, and Kainji Lake. If land is scarce, the displaced population may have to be transferred to a new area at a distance of hundreds of kilometers, where they may have to face environmental hazards never experienced previously. The population to be uprooted and relocated is sometimes the bulk of an agricultural district, as it was in the Bandama Valley in the Ivory Coast, or even an entire large community, as it was at Wadi Halfa, Egypt. The Wadi Halfa community was moved 480 km to Khashm-el-Girba, near the Atbara River, where their staple diet was to be different and they were liable to meet with malaria, onchocerciasis, kala azar, and other serious anthropod-borne diseases for the first time. The road from Kossou to the resettlement area at San Pedro in the Ivory Coast runs through a sleeping sickness area, and the tsetse fly is present around San Pedro itself, another example of the hazards that must be foreseen and counteracted.

All experience hitherto gained emphasizes the formidable nature of any resettlement project, particularly in the respect of allocating and delineating land and of preparing the community physically and psychologically for their transfer. At Lake Kariba a considerable part of the valley community refused to move and suffered from famine as a direct result. At Kainji Lake, though resettlement was on the whole successful and atraumatic, there was delay in allocating land and paying compensation to the inhabitants of the most heavily populated sector, who were already suffering from the disruption of the onion farming that was their principal source of livelihood. On Volta Lake, resettlement was accomplished in a relatively smooth manner through prolonged and devoted work by the team concerned with it; nevertheless, it is doubtful whether the reallocated land will be sufficient for the future needs of the resettled population.

Specific health hazards are inevitable in the resettlement process, since the population densities increase in the reception zones and previously isolated communities are intermingled. Both of these factors are notorious for favoring the transmission of any communicable disease in an area where it previously existed at a low endemic level. The intermingling of nonimmunes with infected persons constitutes an explosive mixture, as is already well known in malariology; this statement could also apply to diseases such as poliomyelitis and water-borne, arthropod-borne, and soil-transmitted infections in general.

The health adviser in a resettlement project has a clear enough role. He must insist that communications, water, and environmental sanitation are basic essentials, even if these existed only in a rudimentary form beforehand. He must also stress the importance of intensifying the effective routine preventive measures now available for nearly all the common mass diseases of man, from malaria to tuberculosis and poliomyelitis, and of undertaking such action in combination with health education. His work should provide a basis for the health institution responsible for covering all the population affected by the dam.

UNSUPERVISED RESETTLEMENT OF THE LAKESHORE

As the great impoundments of Africa near completion, their shorelines become populated to a greater or lesser extent not so much by the original farmers as by immigrant fishermen. Numerous camps and settlements growing up along the shore are characterized by a lack of sanitary facilities and clean water supply. Here, rather than in the original construction workers, we can look for the source that infects a man-made lake with schistosomes. Even on the shores of Lake Nasser in the desert and Lake Kariba in the midst of game plains, unsupervised immigrant populations exist in sufficient numbers to contaminate the lakes. The situation on Volta Lake and Kainji Lake has been more thoroughly documented and can be described in detail.

In Volta Lake the 'biological explosion' that followed its formation involved first the aquatic weeds, then the fish, and then the snails, which transmit urinary schistosomiasis. The newly created rich fishing grounds attracted approximately 20,000 fishermen and their families, who settled themselves in over 1000 villages along the 6000 kilometers of lakeshore, usually without piped water supplies. The majority of these immigrants came from the Volta delta, a region with a high endemicity of urinary schistosomiasis. The 'seeding' of the lake by the infected urine of the fisherfolk led to a spread of urinary schistosomiasis among the families of the resettled farmers. It was found that 90% of the children in three resettlement villages situated within 1 km of the lake had become infected by 1968, and these villages were supplied with piped water. Among the immigrant fisherfolk themselves the intensity of transmission had evidently increased in certain areas of the lake, where the prevalence rates of infection surpassed the endemic level normally found in their original home in the Volta delta.

On the other hand, in Kainji Lake, which has a complete turnover of the water content annually and in which water stratification has only occurred once since 1968 (and then only for a month or two), weed formation has not been a problem along the 350 km shoreline. By late 1970, there were more than 300 fishing villages or camps of varying sizes on the lakeshores. Preliminary surveys in 1970 revealed the presence of infected *Biomphalaria pfeifferi* at Rofia-Jinjima, where the one and only lakeside road meets the water. At Shagunu and Amboshidi the lakeshore is not suitable for snails, except possibly in nearby creeks. In the main onion-farming area of Yelwa, both *S. haematobium* and *S. mansoni* infections were present, *S. haematobium* being much more common. No new infections were found among the former inhabitants of the riverside town of Bussa in their new home at New Bussa, 16 km from the lake and served by piped water. Neither were any new infections found at some smaller villages resettled at some distance from the lake.

HEALTH PROTECTION AND DAM CONSTRUCTION

Intrinsically, dam construction labor forces do not differ from those assembled for any other large public work. A dam construction labor force usually counts 7000–10,000 unskilled laborers drawn from the country in which the work takes place. The prospect of employment attracts a much greater number of persons, often from considerable distances. In recent years the policy of dam constructors has been to provide labor forces with good housing in pleasant towns with many amenities and thus to encourage them to bring their families. This development is most desirable and results in greater stability of the labor force, better nutrition (with wives doing the cooking), and less venereal disease. However, it does imply that the total population in the construction town will rise to over 20,000. These people, and the derelicts who fail to get work or become unfit, inevitably bring with them all the endemic diseases of the country and create an area of high population density in which potential for communicable disease is high.

Furthermore, since the construction work takes place close to water, the possibilities of transmission of water-related diseases increase to include intestinal infections everywhere, malaria and other arthropod-borne diseases almost everywhere, schistosomiasis in many tropical areas, and trypanosomiasis and onchocerciasis in Africa. Standards of environmental hygiene in construction towns may be high, but the problem of sanitation on the working site is difficult. Two particular hazards are thus created, namely, the spread of endemic and epidemic diseases in the labor force and its dependents and the introduction of diseases into an area previously free of them.

In contrast to the serious outbreaks of malaria and yellow fever among workers constructing the dams and lock systems of the Panama Canal, there has been no subsequent record of any serious outbreaks of communicable diseases during the construction of any major dam. On construction sites in Africa, such as Kainji Lake, Volta Lake, and Inga, the workers have been protected from the particular hazard of onchocerciasis by means of insecticide applications against the *Simulium* blackflies breeding in the river. At present, evidence that new endemic disease hazards have been introduced by a dam labor force is lacking. However, schistosomiasis and hookworm have been known to spread to some extent in certain labor forces, though they did not constitute a serious problem, and thus there is the possibility that a permanent infection might be established. In view of this nagging uncertainty, it would be desirable for health consultants to visit dam projects while they are in the construction phase.

ENVIRONMENTAL HEALTH REQUIREMENTS

The population groups displaced as a result of the construction of man-made lakes differ widely in their culture, levels of prosperity, allegiance to authority, and material requirements, but certain characteristics are common to all. They need water to drink and for domestic purposes; they produce wastes, which, if they are not hygienically disposed of, will endanger the health of their families and neighbors as well as of themselves; they bring new forms of sickness into the area and are susceptible to unfamiliar health hazards on their arrival; they need to eat, which usually means the establishment of markets and a degree of food processing and transport; they must be housed and clothed; they have to care for their domestic animals; and they need to produce food and cash crops or else to secure other employment to keep themselves and their families.

Authority and organization are essential prerequisites for the establishment of orderly communities, and, although schools, police, and places of religious worship are among the first priorities, the most pressing need is the preservation of health. To attain this objective, disease must be prevented by the provision of a healthy environment, controlled by anticipating and removing hazards, cured by providing medical attention and health services, and forestalled in the future by the study of relevant problems and the anticipation of dangerous situations. The education of the population, and in particular of children, will in time enable them more and more to look after their own living conditions.

These needs can be foreseen, and planning for them can be ensured in advance. Populations will move spontaneously under the physical and economic pressures of the new lake; it is useless to try to stop them, even if it were desirable. If they move without suitable preparation on the part of the authorities, the outcome is predictable: a breakdown of law and order and the upspring of unplanned agglomerations, where insanitary housing encourages the outbreak of epidemics, the pollution of the lake, and the spread of diseases. However, the identification of basic needs at the planning stage gives the authority the opportunity and sufficient time to create conditions conducive to the health and prosperity of the incoming settlers. These conditions would include the following: well-built and intelligently planned villages, which need not be much more expensive than haphazard development; a system of local government and infrastructure services; a health system based on local personnel trained in anticipation of the need; provision of market and trading facilities; and possibly a tax structure to pay for the running of the settlement in the future.

As far as the physical requirements of settlements are concerned, the usual measures of rural development, conditioned appropriately by the presence of the lake, will be taken. The communities displaced by the filling of the lake will probably be farmers and herdsmen, who had been attracted to their old sites by the fertile valley floor of the flood basin. They will presumably want to continue in their traditional occupations and are likely to be resettled downstream, on newly irrigated land, or some distance from the edge of the water. On the other hand, the fishermen who migrate into the area will approach the water as closely as possible, and it is their wastes that will pollute the lake water, which they and their families will drink and in which they will bathe and wash their clothes in the normal course of events.

Unless haphazard settlement can be checked and the immigrant population can be housed in preplanned communities, it will never be possible to provide the necessary sanitation services. Water that is safe and convenient must be a first priority if water-borne epidemics are to be avoided. The new water level in the lake will eventually raise the groundwater level for some distance around, so that wells can be used where the geologic conditions are suitable, but, since this change will not occur before the lake is full, other means of supply will be needed in the interim for the early settlements.

Excreta disposal either on an individual, familial, or institutional basis will be necessary to prevent the grosser sources of lake pollution. Washing slabs may be constructed in the village to relieve women from the necessity of entering the lake water with the attendant hazard of contracting schistosomiasis; swimming facilities may similarly prevent children from contracting the infection, but all precautions should be taken so that these additional water points do not themselves become foci of transmission. Segregation of animal watering places from those for human consumption may be desirable. Solid refuse must be disposed of otherwise than by throwing it into the lake.

HEALTH SERVICES REQUIREMENTS

Whenever a special program of development in a specific field of activity, supported by specific technical tools and a special budget, is superimposed on a general development program, health problems implied in the foreseeable changes are also considered in a specific categoric way. This consideration is perfectly justified, since it is quite true that ecological changes may involve new health hazards requiring new services to cope with them. However, two other aspects are often neglected: (1) the health situation prevailing in the area before the inception of the program of development, which will condition to a certain extent the success of the program, and (2) the structure and level of development of the health services in the area concerned, especially of the basic health services.

So far the experience with man-made lake projects has usually been that, although the ecological and epidemiologic aspects have been taken into account in a more or less satisfactory manner, the implementation and development of a health service structure (to cope with present and prospective health hazards) have been regrettably underestimated or neglected. Moreover, when the responsibility for health along with other concerns of the project was placed under an ad hoc institution (the dam authority or valley authority), the normal authority (the health ministry) has sometimes relinquished its duties.

For these reasons a responsible health institution, preferably part of or closely related to the health ministry, should be established to deal with the area concerned as soon as a development project involving a man-made lake has been decided on. A public health administrator-planner, assisted by advisers in the environmental fields of epidemiology, ecology, biology, sanitation, and any others that are required, would make a comprehensive diagnosis of the situation and establish base lines, including a complete inventory of the existing health facilities. He would then make a prognosis, taking into consideration the predictable health hazards and the demographic factors, with regard to the population already settled in the area; the labor force, and eventually their families, brought in for the construction of the dam and allied works; the population displaced by the lake and demanding resettlement; and the immigrants attracted to settle along the new shoreline.

Long-term plans and short-term programs would then be elaborated accordingly for the development of comprehensive basic health services covering the new communities. Mental, social, and welfare services should be grafted on these to alleviate the emotional stress of migration and minimize the 'pathology of social adaptation.'

These plans and programs for the area concerned should fit into those already established at the national level. They would be incorporated in the national health plan, if there is any, or at least in the health priorities in the general socioeconomic development plan. The programs would be coordinated as closely as possible, preferably by a coordination unit, with the general health services and with specific programs, such as malaria eradication, smallpox eradication, and family planning, the ultimate objective being their integration. A joint demonstration zone could profitably be located in the area of the man-made lake project.

The health services thus created with the substantial support of the development program for the man-made lake area could act as a model and as a stimulus for the general development of health services in the rest of the country.

PLACE OF PUBLIC HEALTH IN MAN-MADE LAKE ADMINISTRATION

Experience with the new man-made lakes has shown that the allocation of authority for public health matters often fell short of being satisfactory, and the remedy evidently lies in proper planning at the inception of such projects. Health planning along broad lines should be done in the earliest stages, i.e., when the dam itself is being planned. Forecasts of the new population should be made so that the health service needs may be estimated and the pressure on the environment from grazing or fishing may be restrained accordingly. Sites for settlement should be chosen, and road accesses should be planned. The needs of the different categories of settlers should be ascertained, and the program of construction should be developed so that at least the nucleus of each settlement is ready to receive the firstcomers in each category. The cost of housing, water, latrines, and other construction works should be estimated, programed, and budgeted for by the dam authority.

The appropriate authorities and institutions must be set up at the same time. Whatever the system of local government in the country, it must be ready for implementation before the arrival of settlers. If a local population already exists in the area, the problem will be one of strengthening local institutions to assume the new responsibilities. If no local population exists, the problem is more difficult, since as a first step a new authority must be set up at the time that the new village itself is being established.

It is at this stage that coordination between the dam authority and the regular departments responsible for the welfare of the country will be especially important. The health authorities in particular are going to be concerned with construction as well as maintenance of environmental facilities; to what extent they delegate their responsibility to the local institutions will depend, among other considerations, on the availability of suitable personnel for training as doctors, engineers, and sanitarians and in other related disciplines. Training must start at the earliest possible moment if the staff are to be ready to take up their duties when the need arises.

Because new populations will be arriving from elsewhere, the enforcement of sanitary and other regulations will become inevitable. The better the initial planning, the less enforcement is likely to be needed. It is easier to attract settlers to an area provided with prebuilt amenities than to use force to stop them building haphazardly elsewhere. Education of the public in the practice of hygiene and the creation of a local sense of participation in the community are likely to be a more efficient means of instilling sanitary habits than enforcement, though a degree of compulsion may be necessary for the common good. However, sanitary surveillance is going to be needed for some time to a greater or lesser extent, and it is important that the staff be armed not only with the necessary training and experience to know what has to be done but also with the weight of public opinion reinforced by suitable legal powers to ensure that preventive measures are implemented for the benefit of all.

When an irrigation system is planned, and the crops from irrigated farming are counted as assets to be derived from the formation of the lake or construction of the dam, the maintenance of a healthy labor force to cultivate those crops is essential. Since endemic diseases, such as malaria or schistosomiasis, will logically be expected to increase the overhead costs by reducing the efficiency of farm labor, the necessary precautions against sickness from such diseases are proper charges on the project and may well prove to be profitable economically as well as desirable on humanitarian grounds.

Just as the benefits gained by the man-made lake may be foreseen and assessed, so may the remedial and precautionary measures necessary to counteract ill effects. Consequently, the principle should be accepted that those benefiting should assist those suffering; for instance, part of the revenue from electricity sold should be used to pay for health services and to provide environmental facilities in new settlements for populations displaced by flooding. In drawing up the budget of the project as a whole, one should include public health expenditure as a legitimate charge.

Therefore a single authority seems to be called for to ensure that debits and credits are accurately balanced, to receive revenue, and to be responsible for disbursements therefrom for all costs arising directly or indirectly from its generation. There are many ways in which man-made lakes can improve health and well-being if intelligent foresight is used in their planning, maintenance, and operation; neglect at any of these stages, however, may result in jeopardizing the health or the lives of those living near the lake to provide economic benefits for another section of the population. The onus for ensuring that this does not happen must rest clearly on a single body so that divided responsibility may not be used as an excuse for neglect.

ENVIRONMENTAL RESEARCH

In major projects it is increasingly the normal practice to devote a percent of the profits to research into improved methods and development of new techniques and equipment. If commerce and industry find this profitable, so will the dam authority. Setting up a continuous program in this field, not data collection or the recording of conditions but a search for simpler, cheaper, and more efficient ways of reducing disease and improving health, will prove a most rewarding investment in the long run. Well before the dam construction starts, pilot studies should be undertaken on the most appropriate forms of housing and sanitary installations with respect to the local way of life, local soil and climate, and maximum use of local materials and skills. Stress should be laid on simple solutions that later could be applied throughout the country.

For long-term health studies the new lake constitutes an ideal location, since the health problems characteristic of man-made lakes and associated irrigation systems only become apparent as they mature and as epidemiologic patterns develop. Just as is true of the plant successions that form the background of these patterns, a dynamic process characterizes infestations of insect vectors and snail intermediate hosts and the colonization of the new environment by man. Many of the ensuing health problems are directly related to man's activity and his pollution of the environment. In many of the existing impoundments, serious health hazards are already encountered, and potential ones are predicted. Unfortunately, the information available is scanty and may be representative of only a very small part of a given problem in time and place.

There is unquestionably an urgent need to obtain information by continuous study in order to observe changes that may occur in time and place and therefore to avoid the fluctuations and vagaries that arise from sporadic sampling, particularly where schistosomiasis is concerned. Point prevalence surveys offer valuable information, but regular assessments of the rate of infection, the so-called incidence, are more valuable in establishing relationships between the observed infection levels and the constantly changing conditions that give rise to them.

We know that marked increases have occurred in the prevalence of schistosomiasis in certain man-made lakes, but, since the full public health significance of the disease has still not been assessed in quantitative terms, longitudinal epidemiologic surveys must be made to obtain such assessments. The changing ecology of the impoundments must be observed, and human settlement and activity must be borne in mind if we are to improve both water and man management in relation to these changing conditions.

Such continuous observations obviously call for a special project that would be worthy of interagency support on an international basis. From the start it should have a clear concept of the objectives sought with provision at the planning stage for appropriate funding and specialized personnel. There is also a need for a training center, where health personnel from various countries can gain the additional expertise necessary to understand the problems of man-made lakes. It is encouraging that a project of research on the epidemiology and methodology of the control of schistosomiasis in the major man-made lakes in Africa is being supported by the United Nations Development Project following a request by the World Health Organization. The extension of research and monitoring activities to embrace all disease vectors and the underlying ecology of the lakes appears necessary to ensure that their health hazards be continually kept to a minimum.

Acknowledgments. This paper was prepared by the Secretariat of the World Health Organization at its Geneva headquarters, Drs. G. Webbe, B. B. Waddy, and C. R. Jones acting in a consultative capacity.

Health Problems of Man-Made Lakes: Anticipation and Realization, Kainji, Nigeria, and Kossou, Ivory Coast

B. B. Waddy

World Health Organization, Kainji Lake Research Project, Lagos, Nigeria

I was concerned with the Volta River Preparatory Commission in the 1950's and in 1960 visited Wadi Halfa, which, it had just been announced, was to be inundated in the waters of Lake Nasser. I acted as health consultant to the Joint Engineering Consultants for the Niger dam (Kainji) project during the feasibility study, visited Kainji again in 1964, and since 1968 have been a member of the international staff of the Kainji Lake Research Project. In 1969 I was a member of a United Nations special mission to the Bandama Valley project in the Ivory Coast.

I have therefore had considerable experience in anticipating what may happen to communities that are to be displaced by the creation of man-made lakes. Unfortunately, it is seldom possible to go over the ground again personally to see how close prediction and realization turn out to be. It is both exciting and enjoyable to have had such an opportunity at Kainji.

GEOGRAPHIC INTRODUCTION

The climate and vegetation zones change with remarkable consistency according to latitude all across west Africa. From the Atlantic coast facing southward to about 8°30'N is forest country, and from 8°30' to about 12°N is savanna, becoming progressively drier toward the north. Kossou and the Bandama Valley run north from 7°N and are therefore in forest country, even if most of the trees have been destroyed by shifting cultivation. Kainji Dam lies at about 10°N, and Yelwa, at the north end of the lake, is just south of 11°N. Therefore Kainji Lake is in typical mid-savanna country.

The population density of the Bandama Valley is estimated at 15–40 people/km^2 (quite high for rural west Africa) and is likely to rise to an average of 60 people/km^2 solely as a result of resettlement. This density is too high for the continuation of the traditional method of shifting cultivation. In contrast, the country around what was the Niger, the land above the dam at its southerly end, was very sparsely populated; much of the environs of the river in this zone was deserted. Around the northern end of what has become the lake, there were more people, perhaps an average of 20 people/km^2.

Savanna dwellers tend to be more outward looking, and forest dwellers tend to be more introverted psychologically. Furthermore, there is a long tradition among savanna people of traveling to look for paid farming work. A farm is a farm to a savanna farmer, wherever it may be. In the Kainji area, there was plenty of land available for resettlement not far from the inundated zone and among people of the same ethnic groups as those displaced. But in the Bandama Valley those people interviewed in 1969, if they could be persuaded to believe that their impending move was in fact inevitable, simply asked for another forest area to occupy. This ideal cannot be realized without moving them hundreds of kilometers to the San Pedro development area in the southwest of the country. In the Bandama Valley, land for resettlement can be obtained only at the begrudged expense of shifting cultivators further back from the river.

There were many contrasting factors between the Niger and the Bandama valley communities, all tending to favor smooth resettlement without disastrous setbacks in the Niger Valley and the reverse in the Bandama Valley.

HEALTH PROBLEMS OF DISPLACED COMMUNITIES

The first, and potentially most important, problem is the psychological shock caused by enforced removal from traditional homes with cultural, religious, and trading focal points and ancestral burial grounds. The Niger resettlement has been almost free from this potentially long-lasting and crippling malaise, since the distances to be moved were small (the longest and quite exceptional being the move of 48 km from Bussa to New Bussa) and since there was no cause for friction over ethnic differences and possession of land. In contrast, it seemed to the United Nations mission in 1969 that this problem was likely to be particularly severe in the Bandama Valley.

Changed and closer contacts with other communities and an increased population density facilitate the transmission of diseases that existed formerly, if at all, only at a low endemic level. Communicable diseases, whether vector-, air-, or water-borne, require an appreciable population density according to the degree of infectiousness of the disease in question, and the mixing of previously unassociated communities notoriously favors epidemics of communicable disease. The rise in population density around Kainji has been too small to produce any such effect so far, though the neglect of environmental sanitation, even in architect-designed resettlement villages, and the rapid increase of unsanitated fishing villages along the lakeshore leave no room for complacency. In the Bandama Valley everyone will have to get used to the entirely new idea of using latrines instead of polluting the ground indiscriminately.

Failure to persuade a community to move at the appropriate moment can have truly disastrous consequences. Axiomatically, the dam waters must rise for the first time during a rainy season, which comes between the times of planting and harvesting. If farms are planted in a valley that then becomes inundated, the crop for an entire year is lost, and famine is inevitable. This danger is recognized, and the World Food Program is ready to help.

There are, however, secondary dangers. A community that has been fed gratis for a year or two may have little inclination to revert to the hard labor of farming, a state of affairs that is said to be persisting around one or two man-made lakes. Also, every community of primitive farmers has 'famine foods,' gathered from the surrounding bush if a harvest fails. In a new area, roots and other plants that seem to be the familiar famine foods may be similar but toxic plants. In at least one instance when Lake Kariba filled, many lives were lost by poisoning [*Gadd et al.*, 1962].

On the west side of Kainji Lake, agricultural resettlement was remarkably orderly, mainly through the devoted work of one man. On the east side, there was some delay in allocating new farming land; also, the valuable onion farming traditionally carried on between low and high water on the riverbanks was disrupted completely for one year and partially for two. The result was an undoubted nutritional shortage for a year or two but by no means a disaster. Two years after the first filling of Kainji Lake, the whole lakeside community was farming with a will and fishing with even more enthusiasm; it was feeding itself and (to judge by lorry traffic and depots of fish, groundnuts, and shea nuts to be seen in certain places) producing an export surplus. It will be fortunate indeed if the Bandama Valley community keeps up its morale in such a way.

HEALTH PROBLEMS OF EXISTING COMMUNITIES

As far as we can see, around Kainji there has been little trouble or distress in communities living in reception areas for the same reasons that enabled the displaced communities to move with so little disturbance. There is still no excessive pressure on the land, and the incoming communities were of the same ethnic groups and came from nearby, not as strangers. Foge Island, now under the lake waters, used to provide valuable dry-season grazing for the cattle of the Fulani, and these large herds now have to migrate further afield. They must pass over a certain amount of farmland, and no doubt cause some irritation.

In the Bandama Valley reception zones the established communities will be as liable as the incomers to exacerbations of disease, and a new way of life (fixed instead of shifting cultivation and the necessity of learning sanitary principles) will also be forced on them.

Below a dam the river levels depend on the whims of those who control the spillway. There is no certainty that downriver communities will be adversely affected, but their problems should not be forgotten because they do have to learn new relations with the river and the balance of water-associated diseases may be changed. Below Kainji Dam the fishing has been so good that, for example, the people of Kpatachi Island, 3.6 km below the dam, did not even take time off to plant their farms in 1969.

SPECIFIC PROBLEMS OF WATER-RELATED DISEASES

Onchocerciasis is transmitted in west Africa by *Simulium damnosum,* a fly that breeds only in running water. It tends to be hyperendemic around African rivers, and the Niger and Bandama valleys in the neighborhood of their dams were seriously affected. Blindness rates up to 9% have been found in villages near the old Niger, and a check near the Bandama revealed 15% blindness in one unselected village and 20 blind out of the small but uncensused population of Kossou itself. Especially in the savanna, mass blindness and the pestilential attention of *S. damnosum* result in depopulation near rivers [*Waddy,* 1969]; the west bank of the Niger was virtually uninhabited for some 40 km above the damsite.

There has never been any doubt of the effect on onchocerciasis transmission of creating a lake. *S. damnosum* ceases to breed in the now static water, and transmission ends abruptly. (Onchocerciasis is a very chronic disease and can progress even to blindness in persons infected earlier, but this problem is different.)

Below a dam, *Simulium* breeding may actually be accentuated, as it was for a time at Volta, but Kainji, a small lake fed by a large river, needs much more variation in spillway manipulation than Volta, a large lake fed by a relatively small river, does. Thus the rise and fall in river levels below Kainji Dam has so far been enough by itself to prevent *Simulium* breeding, to the great benefit of people such as those of Kpatachi Island. These fishermen used to become infected while they were working on the river, and many of them became blind. It may be hoped that infection will be prevented in the Bandama Valley.

It has always been assumed that the creation of a lake must result in increased transmission of schistosomiasis (bilharzia). This disease has always been endemic in the Niger and Bandama valleys, and the increased population density will certainly favor transmission. Kainji Lake filled for the first time in 1968 but only to 140 meters above sea level; it filled to 142 meters for the first time late in 1969. Early in 1970 it was not possible to find snails at several points on the periphery. The implication was that they had not yet migrated so far, not that they would never appear. More recently, it has been easy to find snails in the few places searched, but there is a possibility that schistosomiasis transmission is no longer occurring in some resettled villages where it used to be endemic. The urgent need is for as many surveys as possible as soon as possible to provide base line data that can be compared with future survey results.

In the Bandama Valley, schistosomiasis transmission may take place at any inhabited part of the lake perimeter, and there will be a special hazard in the proposed large-scale irrigation project in relation to the Red Bandama Valley.

There can be no question of attempting to control water snails all around the lake perimeter, but possibly something can be done at selected points of danger, such as where roads approach and ferries cross the water.

Trypanosomiasis, African sleeping sickness, is a disease that can literally wipe out entire communities. It is carried by the tsetse fly, which lives and breeds in waterside-fringing vegetation in the savanna; it can move about more freely in the humid atmospheric conditions of the forest. Changed relations between vegetation and water are liable to create new tsetse haunts. A detailed survey covering every human being from the entry of the Niger into Nigeria down to the dam has failed to reveal a single case of sleeping sickness, but the watch must be maintained. In the Bandama Valley with its thicker vegetation the danger is greater (and is fully recognized by the health authorities).

Many intestinal infections have always been as common as, say measles, in rural west Africa, but to one who has worked in the west African bush since the 1930's the modern phenomenon is the appearance of paralytic poliomyelitis. It used to be thought that polio did not exist in the rural tropics. The experience of susceptible young expatriate soldiers during the 1940's showed that the very reverse was true; as a generalization, polio viruses were circulating with such freedom that infants obtained their immunity (or died) at a very early age, and paralyzed victims were not seen. Almost any disease can exist undetected in the rural tropics if it is not looked for specifically, but polio victims do not hide (like leprosy sufferers) or sit at home (like the blind), they move about to markets and other places, and they are obvious at a long distance. Neither I nor my colleagues of the 1930's saw polio paralysis, and I believe that it was not there to be seen.

Polio tends to become an epidemic disease causing paralysis when improved sanitation prevents the universal circulation of polio viruses and the infection of young infants. As a result, many children grow up to be fully susceptible when an epidemic strain of virus is introduced. Abidjan, in the Ivory Coast, has obviously been passing through this unfortunate stage of development. Paralyzed limbs can be seen not only in street beggars but also in smartly dressed young men and girls. The danger of a spread of epidemic polio in the Bandama Valley seems to be considerable, but a vaccination campaign was already being planned in 1969.

In rural Nigeria, victims of paralytic polio seem to be quite common; I have even seen pastoral Fulanis with paralyzed limbs. Sanitation is not better now, except in a few towns, and the explanation may be that the epidemic strains of virus circulating in towns have penetrated to rural areas. Extensive epidemics of polio could occur in rural areas without being noticed, and the time is certainly ripe for a vaccination campaign.

CONCLUSION

All in all, resettlement at Kainji has been an almost painless and highly successful operation. The outstanding failures have been the neglect of environmental sanitation and communications. Only one new road was made in the lake area to replace the old road, now partly inundated, along the west side. There is no road along the east side of the lake, and even the tracks used by contractors building resettlement villages have disappeared after three or four rainy seasons. The vital importance of communications in every aspect of human ecology, including health, was forgotten in the Kainji resettlement. In the architect-designed villages, no sanitation whatsoever was provided, and the wells are open topped.

The Bandama Valley is much better served by roads, and the Ivory Coast has a very vigorous and efficient department of social medicine. Despite, or even because of, the magnitude of the problems involved, the Bandama Valley resettlement may yet turn out to be a triumphant success.

REFERENCES

Gadd, K. G., L. C. Nixon, E. Taube, and W. H. Webster, The Lusitu tragedy, *Cent. Afr. J. Med.*, *8*(12), 491–508, 1962.

Waddy, B. B., Prospects for the control of onchocerciasis in Africa, *Bull. WHO, 40,* 843–858, 1969.

Summary: Outdoor Recreational Use of Man-Made Lakes

G. DOUGLAS HOFE, JR.

Bureau of Outdoor Recreation, U.S. Department of the Interior
Washington, D. C. 20240

Water, outdoor recreation, and tourism are very often interdependent. A discussion on outdoor recreation or tourism usually leads to a discussion of some form of basic water resource: a lake, a stream, a pond, or a pool. The fascination man exhibits toward water in its many and varied forms is the basis for the present locations of many of the finest tourist centers of the world. A report by the *National Technical Advisory Committee* [1968] made the following observations:

> It is not surprising that water has occupied an important position in the concerns of man. The fate of tribes and nations, cities, and civilizations has been determined by drought and flood, by abundance or scarcity of water since the earliest days of mankind.
>
> Artists have reflected man's fascination with water. Literature and art of a variety of cultures dwell upon brooks, waves, waterfalls and lakes as superlative among the delights of the environment.
>
> Aesthetically pleasing waters add to the quality of human experience. Water may be pleasant to look upon, to walk or rest beside, to contemplate. It may provide a variety of active recreation experiences. It may enhance the visual scene wherever it appears, in cities or wilderness. It may enhance values of adjoining properties, public and private. It may provide a focal point of pride in the community.

About one quarter of all U.S. outdoor recreation is dependent on the availability of water. Participation in swimming, fishing, boating, ice skating, and water skiing accounted for 2.8 billion activity days in 1965 and is projected to increase to 7.7 billion by the year 2000. The popularity of water-dependent outdoor recreational pursuits is further indicated by the following statistics. During the summer of 1965, 48% of the population 12 years of age and older went swimming, 30% went fishing, and 24% went boating.

The presence of water adjacent to recreation and tourism centers adds an additional dimension to the importance of water. Activities such as camping, picnicking, walking for pleasure, driving for pleasure, and sight-seeing are enhanced by the presence of water; two thirds of all designated publicly administered recreation areas either have a water body within their boundaries or are adjacent to accessible water.

Man-made lakes provide expanded opportunities for both water-dependent and water-enhanced outdoor recreation use. Their development has created water surface areas where they were scarce or nonexistent before. The role of man-made lakes will increase sharply in the future as natural water bodies are used to capacity.

OUTDOOR RECREATION IN RIVER BASIN PLANNING AND DEVELOPMENT

Before I discuss man-made lakes and their problems and opportunities, a brief review of the emergence of outdoor recreation in water resource development as it generally relates to our oldest water resource agency, the U.S. Army Corps of Engineers, is in order.

The federal government constructed only a few reservoirs prior to the first Flood Control Act in 1936. Construction on a large scale began in the late thirties, but it was nearly stopped during World War II. After the war the reservoir construction program was greatly increased. During the postwar years the increasing American population found it had more leisure time, more disposable income, and more mobility for outdoor recreation activities. Reservoirs constructed primarily for navigation, flood control, hydroelectric power, irrigation, and similar purposes became an important recreational resource.

The rapid growth in the demand for recreation at and the use of federal reservoirs created new problems in policies, planning procedures, economic evaluation, and cost sharing.

The heart of the U.S. Army Corps of Engineers' recreation authority is in section 4 of the 1944 Flood Control Act, which states that the chief of engineers is authorized to construct, maintain, and operate public park and recreational facilities in reservoir areas under the control of the Department of the Army and to permit the construction, maintenance, and operation of such facilities. Although the section has been amended several times, the most important amendment was in 1962, when the recreation authority was broadened to cover all types of water resource projects. This authority gave the army considerable latitude for federal involvement in the planning and development of recreation at reservoirs. However, the Bureau of the Budget and the appropriations committees of Congress generally held to a minimum the responsibility of developing the recreation potential of reservoirs.

In 1958, Congress enacted the Fish and Wildlife Coordination Act, which provided for equal consideration of fish and wildlife conservation along with other purposes of water resource developments and for some additional opportunities to include recreation in reservoir planning and development.

In 1960 the Senate's Select Committee on National Water Resources published its comprehensive appraisal of the water resources of the nation and needs for their conservation and development. The report recognized that a major part of the outdoor recreation potential is associated with water areas and recommended adoption of the policy that the recreational potential of all federal reservoirs be developed for public use.

The Outdoor Recreation Resources Review Commission, in its 1962 report to the President and Congress, recommended that recreation be given full consideration in the planning, design, and construction of water resource projects. The commission also pointed out that water is a prime factor in most outdoor recreation activities.

Two important pieces of legislation, the Federal Water Project Recreation Act and the Water Resources Planning Act, were passed in 1965. The basic purpose of the Federal Water Project Recreation Act was to assure that 'full consideration' be given to the opportunities that a water resource project affords for outdoor recreation and for fish and wildlife enhancement. The act also required that nonfederal public bodies bear not less than one-half the separable costs of the project allocated to recreation and fish and wildlife enhancement and all the costs of operation, maintenance, and replacement associated with recreation and fish and wildlife.

The objective of the Water Resources Planning Act was to provide for the optimum development of the natural resources of the nation through the coordinated planning of water and related land resources, the establishment of a Water Resources Council and river basin commissions, and the provision of financial assistance to the states to increase state participation in such planning. The Water Resources Council is charged with establishing principles, standards, and procedures for federal participants in the preparation of comprehensive regional or river basin plans and with formulating and evaluating federal water and related land resource projects.

The Wild and Scenic Rivers Act, passed in 1968, provided a missing link in water resources planning. Through the act,

> . . . Congress declares that the established national policy of dam and other construction at appropriate sections of the rivers of the United States needs to be complemented by a policy that would preserve other selected rivers or sections thereof in their free-flowing condition to protect the water quality of such rivers and to fulfill other vital national conservation purposes.

At this point I would like to refer to two actions that can add significant new dimensions to water development projects. First, is the President's proposed reorganization of the executive branch. One of the purposes of this reorganization is to coordinate the planning of projects better so that we get the most benefit from every dollar expended.

Also, a growing concern for the enhancement and preservation of the environment has caused us to reexamine the old planning concepts in water resource development. No longer does a project deserve construction merely because it provides multiple purposes. The National Environmental Policy Act of 1969 requires that the effect of a project be examined in relation to all purposes, including outdoor recreation, and that any effects on the environment be fully evaluated. My opinion is that this blending of man-made lakes with the overall goals of environmental protection will be the single most important aspect of water resources development in this country and the world.

RECREATION USE OF MAN-MADE LAKES

I highlighted earlier the importance of water to outdoor recreation and tourism. Four U.S. agencies have the primary responsibility for the planning and development of federally assisted water projects in this country. They are the Tennessee Valley Authority (TVA), the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Soil Conservation Service. Through the efforts of these agencies, thousands of man-made impoundments have been made available for recreation purposes and use.

Almost 262,600 ha of reservoir water surface and over 17,699 km of shoreline provided by TVA reservoirs have furnished the basis for a flourishing development in water-based recreation that has expanded steadily over 30 years. In 1969, for example, use of the impoundments for swimming, water skiing, boating, and fishing and use of adjacent areas for camping, picnicking, and other leisure-time activities resulted in a total of almost 47 million visits.

Attendance at U.S. Army Corps of Engineers reservoirs has increased from 16 million in 1950 to 276 million in 1970. The corps operates some 300 reservoirs providing over 1,616,000 ha of water surface area for public use. Facilities range from primitive campsites providing only minimum facilities for the health and safety of visitors to elaborate marine hotel complexes offering facilities for people unwilling or unable to cope with a primitive experience.

During the past decade, visitor days of recreation use increased about 170% at Bureau of Reclamation projects, from about 20 million visitor days in 1958 to 54 million in 1969. Federal reclamation projects provide 686,800 ha of water surface, 18,664 ha of shoreline, 640 developed campgrounds, 767 picnic areas, and 23,400 tent and trailer spaces.

Although the Soil Conservation Service is limited to providing assistance to states and local units of government for lakes of <25,000 acre-feet of storage for all purposes, it has contributed greatly to outdoor recreation opportunities. Throughout the United States, construction of over 5500 watershed structures has been assisted by the Soil Conservation Service. Since 1962, when recreation became a project purpose, over 400 of these reservoirs have been built with planned public recreation facilities. Although they are not comparable in size individually with the large lakes created by the agencies cited previously, their number and ready availability within short travel distances make these lakes an important factor in the water recreation picture.

Although the Federal Power Commission is not a construction agency, it has an important mission in promoting the installation of recreational facilities at the projects that it licenses. In seeking to assure that the natural resources of the nation are made available to all citizens, the commission has licensed 515 reservoirs providing a combined water surface area of 727,200 ha and approximately 5200 public access areas.

In addition to the specific agencies mentioned above, many states, cities, counties, private corporations, and individuals have constructed impoundments for a variety of purposes, including water supply and power generation. An additional benefit of such construction is outdoor recreation.

ECONOMIC IMPACT OF TOURISM AT MAN-MADE LAKES

Many people have attempted to measure the economic impact of recreation, an activity that produces benefits that are largely intangible. Measuring recreation impact is more difficult than measuring industrial impact because there is no central source for expenditure data. Recreationists visit the area only briefly and are difficult to identify and observe. Their economic expenditure records are unwritten and uncertain. Nevertheless, most experts agree that man-made lakes and the associated development of recreation facilities and tourist centers do generate a substantial impact, parts of which occur in the immediate reservoir area.

Badger [this volume] observes that the creation of new man-made reservoirs and the development of recreation facilities win new converts to water-based outdoor recreational activities and stimulate additional use by 'preconditioned users.' Fishermen, boaters, and water skiers quickly move onto reservoirs as they are completed and have tremendously increased the use of water-based recreational facilities. He uses an input-output analysis with a 17-sector model to measure the economic impact of water and related land-based recreational facilities on the regional economy.

A recent report by the Bureau of Reclamation provided similar conclusions. They found that recreationists visiting Shadow Mountain Lake and Lake Granby had a mean expenditure for the visit of $36.98 within a 40.23-km radius of the reservoirs, or $3.05 per visitor day. The average group visiting Horsetooth Reservoir spent $10.15 during their visit, or $1.16 per visitor day.

Increases in property values due to the three reservoirs between 1946 and 1968 totaled $8,134,000 distributed as follows: land value, $5,160,000; improvements, $2,152,000; and recreational facilities, $822,000. The annual recreation-related impact for the three reservoirs during 1968 totaled $4,882,000 distributed as follows: retail sales, $2,912,000; boat sales, $1,792,000; and operation and maintenance costs of recreation facilities, $178,000.

The impact of individual man-made lakes depends on the location, the type of development, and many other factors, but, as can be seen, it is substantial.

PROBLEMS AND OPPORTUNITIES

A great number of outdoor recreational activities are either dependent on or enhanced by water. With increases in population, income, mobility, leisure time, and education coupled with changes in age group relationships and technology, recreation may well be the primary nonconsumptive goal of water resource development in the future. Even the short-range demand for water-based outdoor recreational activities may very well surpass the wildest dreams of all water resource planning and development organizations. If future demands for recreation are to be met, a close look at all existing and planned projects, regardless of size, must be made. These must be developed to their highest recreational potentials. In other words, water resource projects should be maximized for recreational benefits.

With the ultimate goal of providing various types of high-quality recreational facilities capable of meeting the demand in future decades, the general problems focus on five major areas: legislation, conflicts, research, quality, and quantity. The nature and complexity of the recreation picture makes a clear-cut distinction between these areas almost impossible. A discussion of any one area overlaps with discussions of the others.

Legislation. Many of the problems that will be mentioned in my subsequent discussion will require changes in existing policy or initiation of entirely new legislation. Advances are presently being made in some of these areas, but others are still left untouched. Some advances expected in the upcoming decades will deal with single-purpose water resource developments for recreation and alternative cost-sharing programs. I assume that legislative problems are not common only to this country.

Conflicts. Conflicts with other uses of both land and water resources are presently, and will continue to be in the future, major problems of concern to recreation planners. Developments for each use must lie within reasonable limits of compatibility with other uses. For example, the pool levels for flood control, power generation, and water storage purposes must fluctuate, but constant-level pools are most ideal for recreational use. Although conflicts with present uses of water and related land areas are expected to dwindle in the future, there will undoubtedly be conflicts between recreation and other unforeseen water uses.

Various recreational activities also compete and are often in direct conflict with one another. Certain areas will have to be closed to particular uses if ultimate quality and quantity standards are to be met. This zoning practice, little used today, will be of increasing importance in future decades.

Research. Despite fine individual efforts in recreation research, little is known about the total recreation picture. All phases of recreation, from the design and maintenance of facilities to sociologic and environmental factors affecting recreational motivation and use and demand estimation, are in need of further study.

The resource planner can make sound decisions concerning outdoor recreation and resource allocation only after all effects and contributing factors have been analyzed properly.

Quality. The final judgment in determining a quality recreational experience rests with the recreationist. Our problem in this area is to provide the controls that will insure compliance with known standards relating to quality (even though they are inadequate). Often more research into the effects of various elements on quality is needed along with further research on visitor preferences and satisfaction. Specific areas requiring additional study are water quality, site quality, esthetic quality, and the contributions and effects of these factors on the quality of the recreational experience.

Problems are common near many water resource development projects. However, the complexity and extent of such problems vary with the development. We must concern ourselves with the total recreation and tourism environment. The planner's task does not stop at the edge of the water.

Quantity. Present estimates of the amounts and kinds of outdoor recreation activities and facilities that will be needed in the future are based on present use patterns and conditions. Experience has taught us that predictions about what people wish in the way of outdoor recreational experiences cannot be estimated with certainty. Creation of additional recreational resources must have a limit. Beyond this limit, which will probably be reached in the next few decades, fuller use of existing resources and facilities will be the only solution.

There are many specific problems that are included in one or more of these general problem areas. The following are some of the more important of these specific problems that are either current or can be anticipated in the future.

Improvement of existing recreational areas and facilities. At the present time, many man-made lakes have not been developed to their full potential. The ultimate development of existing recreation resources should be considered in conjunction with new lake areas. Also, as advances are made in design and more is learned about the recreationist, these advances should be applied to existing recreational developments at previously constructed lakes in addition to new or planned impoundments.

Zoning for recreational use. In the future, compatibility between water-related activities may well depend on the zoning of recreational areas, which may be done by: (1) defining the purpose of a recreation area and allowing only those activities that are compatible with one another and with the general purpose or (2) zoning activities at multipurpose recreation areas so that conflict does not arise. Water may be zoned for fishing, swimming, boating, and water skiing.

Role of recreation in multipurpose water resource developments. There must be compatibility; the limits within which each use can function purposefully and economically must be calculated. Somewhere within the limits of each use, there is likely to be a common area of fluctuation, where all uses are compatible. Although in this common area the ultimate economic benefit may not be realized for any single use, the ultimate multiple economic benefit may be realized.

Sometimes recreation should be considered the primary purpose of a water impoundment, and flood control and hydroelectric power should be considered secondary. Then the limits of water level fluctuation that can be tolerated from a recreation point of view would serve as the guidelines within which the water level most desirable for flood control and hydroelectric power must fall.

Single-purpose recreation developments. At some point in the future, recreation may be considered the sole purpose of many more water impoundments. Such a time will come when dams or reservoirs are no longer needed or desirable for power, flood control, or navigation purposes.

When we reach such a point, people will have more leisure time, both a longer vacation and a much longer weekend. Thus much more use would be made of any recreation area. Such an area could receive on weekdays the intensive use that it receives, at present, on Sundays. Therefore, without additional facilities, weekly use of the area due to greater activity throughout the weekdays might be 3 times the present weekly use.

Location of water resource developments and recreational use. Activities to be included at a project or the general purpose of a project should vary according to location. For example, a project located near heavily populated areas will serve urban day use recreational wants. It will receive intensified use, and such use will probably not deteriorate the value of the resource. A wilderness area and a weekend use area will receive far different patronage, and the function or purpose will differ from that of the urban day use area.

In the future, more stress should be placed on small water impoundments located near cities, which would serve the growing needs of the rapidly expanding population of our metropolitan areas.

Floodplain zoning for recreational use. More should be done to encourage preservation of green areas along many waterways. These areas would provide excellent opportunities for seasonal recreational use and eliminate many costly water resource developments for flood control purposes. Floodplain zoning for recreational use would be of extreme importance in urban areas, where flood damages are greatest and outdoor recreational resources are scarce.

When our thinking 'evolves' to a point where we start planning in terms of 'flood damage reduction,' then floodplain zoning, green belts, and flood-proofing techniques will logically be forthcoming.

CONCLUSION

In summary I would like to emphasize the following points.

1. Water is an important ingredient to the outdoor recreation experience. Man-made lakes are one means of providing water-dependent and water-related opportunities.
2. The integration of outdoor recreation and associated environmental concerns in the characteristic framework for water resource development has been a slow process and is continuing to evolve.
3. Man-made lakes provide one alternative solution to providing water for recreation and tourism. A balance among reservoirs, natural streams, and rivers is needed in recreational development.
4. Outdoor recreation and tourism, as they relate to water, provide a challenge in both problems and opportunities. Lack of information in many areas and the dependency of the total outdoor recreation experience on the environment in which it occurs furnish both a challenge and a problem. The opportunity to provide needed water-related areas and facilities within reach of all segments of the population is yet another challenge. On the subject of opportunity I would like to stress the importance of acquiring the needed land base adjacent to water areas for both initial and future development. Without this basic resource the potential of many water areas for recreational use is severely restricted.
5. The economic impact of recreation reservoirs can be substantial. It influences areas in the immediate vicinity of the development as well as the areas from which the visitors originate. The impact is exhibited in many ways, including increased land values, retail sales, boat sales, increased investment in land improvements, and additional employment.
6. Outdoor recreation is a valid objective of water development and can occur in conjunction with and to the mutual benefit of other water uses, both consumptive and nonconsumptive. Proper planning with these objectives in mind can help to provide a better environment in which we all can live, work, and play.

REFERENCES

Badger, D. D., Economic impact of water-based recreation, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

National Technical Advisory Committee, Water quality criteria, Washington, D. C., 1968.

Economic Impact of Water-Based Recreation

DANIEL D. BADGER

Department of Agricultural Economics, Oklahoma State University
Stillwater, Oklahoma 74074

This paper reports the results of recent studies to: (1) analyze the economic impact of water-based recreation (in terms of income, output, and employment) on regional economies, (2) estimate impacts on land values, and (3) analyze a few of the noneconomic or externality-type effects of water-based recreation. Finally, I would like to suggest some alternative research approaches that would provide information needed by policy makers and resource planners in developing new water-based recreational facilities and in improving the management policies of existing facilities to provide a higher level esthetic experience for more people.

The creation of new man-made reservoirs and the development of recreational facilities win new converts to water-based outdoor recreational activities and stimulate additional use by 'preconditioned users.' Fishermen, boaters, and water skiers move quickly onto reservoirs as they are completed and have increased the use of water-based recreational facilities tremendously.

Recreation is now recognized as a legitimate purpose or output of water resource development projects. It is no longer a 'tagalong' thrown in 'just for good measure' in developing man-made lakes. However, the greatly increased use of recreational activities at our man-made lakes has burgeoned greatly only in recent years. The advent of more leisure time, higher levels of incomes, more and better highways, and more private transportation allows greater fulfillment of the desire of people to recreate and/or relax in a water surrounding.

Many of us, as construction agency planners, government policy makers, and university researchers, have not aided in making this transition to true multiple-purpose development. We have not seriously considered how recreation 'relates' as one of many purposes. In general, dams have not been located to maximize economic, social, and esthetic benefits to the public from the resulting recreational use; i.e., this output is still considered a by-product of development for other purposes.

MEASURING ECONOMIC IMPACT

Two generally accepted techniques have been used to estimate outdoor recreation benefits and/or the economic impact of outdoor recreation in a regional economy. The first technique relates to the various methods used in recent years by economists to estimate demand curves for selected recreational activities [*Clawson,* 1959; *Knetsch,* 1964*b*; *McNeely,* 1968; *McNeely and Badger,* 1968; *Merewitz,* 1964; *Wennergren,* 1965]. By the use of such estimates and attendance patterns, recreationists' expenditures can be totaled to provide some indication of the 'value' of outdoor recreation. However, such demand measurements do not consider all the aggregate or macro effects of water-based recreation.

The second technique is based on the multiplier approach to determine the direct, indirect, and induced effects of outdoor recreational expenditures. By developing a recreational sector for an input-output model, we can trace the effects of such expenditures on other sectors of a regional or national economy and can derive multipliers for calculating the income, output, and employment effects of outdoor recreation. This technique requires detailed planning data for the different sectors of the economy. It has limitations, such as an assumed level of technology and linearity or constant relationships among sectors. However, it is a valuable technique in analyzing economic impacts.

Some input-output studies in other regions will be summarized in this paper. However, I will focus primarily on a recent input-output study of our Oklahoma water-based recreational laboratory.

INPUT-OUTPUT AND RELATED ANALYSES

Several recent input-output studies have focused on the economic impact in a region due to the development of water-based outdoor recreational facilities. A Cornell University evaluation of the recreational impact of a small Corps of Engineer reservoir (485 ha) concluded:

> the introduction of reservoir recreation has been a mild and seasonal stimulant to economic growth. Any problems or costs such as traffic congestion, vandalism, noise, etc., were minor and primarily on hot weekends. Overall, the introduction of the lake and accompanying recreational facilities has been an asset to the rural residential environment. It is likely that the reservoir recreational investment will help attract new residents in the future.
>
> *Hinman* [1969, p. 63]

An earlier Oklahoma study concluded:

> The local gross income per dollar of direct and total recreational income is much smaller than for agriculture. That is, there is only $1.17 in gross income to the economy per dollar of direct recreational receipts, and $1.13 per dollar of total receipts . . . . Thus, there is a smaller multiplier effect (a greater amount of leakage) associated with recreational income than that associated with agricultural receipts.
>
> *Jansma and Back* [1964, p. 14]

There have been dramatic increases in certain types of businesses as a result of the availability of water-based recreational activities. Sales of all types of pleasure boats, particularly the outboard types used for fishing and water-skiing, have increased tremendously. For example, in 1968 an estimated 36,554 boats less than 4.88 meters in length, 6655 boats between 4.88 and 7.62 meters, and 1211 boats longer than 7.62 meters were moored on the 26 Tennessee Valley Authority lakes. These boats had an estimated value of over $55 million. In addition, over 3000 houseboats valued at almost $10 million were in use on those lakes.

The Tennessee Valley Authority estimated that the total value of both public and private recreational facilities and improvements at these 26 lakes was almost $287,000,000 in 1969, more than a 100% increase from the $121,000,000 of 1960.

However, from a regional standpoint the point of purchase for each of these boats and for other recreational equipment is needed to determine the value of such imports to the regional economies where the lakes are located. Some studies have concluded that much of the impact on employment, output, and incomes is lost to the rural local area economies, since many of the boats are manufactured and sold in urban centers [*Badger,* 1970*a*]. On the other hand, from a national standpoint the water-based recreational activity provided by our man-made lakes has created new markets, new jobs, and some distribution of income effects.

Economic benefits from water-based outdoor recreation are generally widely scattered. Owing to imports of both capital and consumption goods into the rural area, a high percent of the recreationists' expenditures in the area may flow back out of the local economy. Also many of the items used in recreation are purchased outside the area and are thus imported into the local areas for use by the recreationists.

Often not only capital but also personnel are imported into the area to manage the recreational complex. It is difficult to convince policy planners that individuals lacking capital, managerial skills and experience, and/or successful farming experience are unlikely to be able to develop and manage a recreational enterprise successfully. Certainly, some job opportunities are available when recreational facilities are developed on and around our man-made lakes. However, most of these jobs are seasonal in nature, and the wages paid for them may not be high by the standards of today.

WATER-BASED RECREATION IN OKLAHOMA

The 50 states now have thousands of hectares of recreational areas and many excellent facilities in conjunction with large-scale federally financed water development projects. For example, Lake Texoma in south central Oklahoma and north central Texas with 37,650 ha of surface area and Lake Eufaula in eastern Oklahoma with around 42,900 ha of surface area are two examples of large water-based recreational complexes. Around these lakes are many public and private recreational sites. In Oklahoma, only 2 (Alabaster Caverns and Red Rock Canyon) of our 22 state parks and recreational areas are not associated with or built on a natural or man-made lake. Adding to our water-based recreational orientation are the many excellent recreational facilities on 27 Corps of Engineer and Bureau of Reclamation reservoirs already constructed or under construction.

Better roads, more cars, and more leisure time for Oklahomans and out of staters have helped increase attendance at the 60 public recreational areas in Oklahoma, which are primarily water based. Attendance at Oklahoma's public recreational facilities increased from 25 million visits in 1963 to 42 million visits in 1969. Much of this increased recreational use has been on and around the four new Corps of Engineer reservoirs completed since 1963 and two new Bureau of Reclamation reservoirs completed since 1965. Better measurement techniques may account for some of this rapid increase, but it is readily apparent that recreational use of existing and newly opened water-based facilities continues to increase rapidly.

INPUT-OUTPUT ANALYSIS IN SOUTHEASTERN OKLAHOMA

In many recent efforts, either the geographic area studied has been very small or the data have been aggregated to such an extent that the effects of specific types of recreation are not known. We have recently completed a study, using input-output analysis, to measure the economic impact of water and related land-based recreational facilities on the regional economy of southeastern Oklahoma.

The current economic base of the region relies heavily on the livestock industry, mining, and a limited variety of manufacturing activities. However, Arrowhead State Park, Robber's Cave State Park, Lake Wister State Park, and Beavers Bend State Park are all located within the region. Three of these state parks are adjacent to large man-made reservoirs. In addition, five new reservoirs are currently under construction, and two others are authorized for future construction. These bodies of water promise to add to the potential for outdoor recreation development in the region.

Building on an earlier Oklahoma State University study using a 16-sector input-output model for the Kiamichi district in southeastern Oklahoma, we attempted to measure the economic impact of outdoor recreation in this part of the Ozark region (an area of depressed or low per capita income and high unemployment). We developed building block data for a seven-county area and derived the recreation multipliers in Table 1.

TABLE 1. Values and Rankings of Recreation Multipliers for Water-Based Recreation Impact, Southeastern Oklahoma

Recreation Multiplier	With Households Exogenous	With Households Endogenous
Output	1.18 (ranks 5th)	2.20 (ranks 13th)
Income	1.07 (ranks 14th)	1.77 (ranks 5th)
Employment	1.10 (ranks 13th)	1.59 (ranks 17th)

The input-output model for the seven-county region had 17 sectors. Thus the rankings of the recreation multipliers are based on the 17-sector economy.

For employment multipliers developed by using regional employment-output ratios (households being endogenous to give the induced effects of local household expenditures), recreation ranks last of the 17 sectors, but only 6 other sectors have a significantly greater impact than recreation does. They are food manufacturing, apparel manufacturing, lumber manufacturing, personal services, repair services, and professional services.

We concluded that increased expenditures in the outdoor recreation sector will have a favorable effect on regional income, particularly when direct, indirect, and induced effects are considered. However, the employment multipliers calculated by using regional employment-output ratios indicate that development of the recreation sector will do little to alleviate the regional unemployment problem [*Mapp and Badger,* 1970].

We recognize that use of our water-based recreational facilities is seasonal in nature; many activities associated with outdoor recreation do not provide year-round employment. Thus public expenditures to attract manufacturing sector activities will do more to relieve unemployment than public expenditures to develop water-based recreational facilities in southeast Oklahoma.

However, when recessions, such as the one in 1970, occur, these small manufacturing industries in rural areas can be hurt badly, the only employment base of the local area being disrupted. On the other hand, there is some evidence that recreation, measured by visitor days, continues to increase even in recession or 'economic slowdown' years, such as 1958, 1960, 1967, and 1970.

Despite the high leakage due to imports of goods and services into our rural areas for purchase and consumption by recreationists, water-based recreation does have a favorable impact on these local economies. *Schmedemann and McNeely* [1967] indicated that recreational users may sometimes be a deterrent or have a negative impact on local areas because of wear and tear on roads, public utilities, schools, hospitals, and other community service institutions. There are some situations in which tourists or recreational users have done more economic harm than good to a community. Obviously, repair costs resulting from vandalism to signs and buildings and clean-up costs due to littering are some of these economic losses.

However, in the cases in Oklahoma with which I am familiar, federal construction of large multiple-purpose reservoirs has meant better state or federally financed access roads to the recreational areas, higher tax revenues from increased property values, and high-priced land around the water-based recreational area that is being sold not only for cabins and other private uses but also for recreation-related businesses, such as bait and tackle shops, restaurants, cafes, boat storage facilities, and so on.

IMPACT OF WATER-BASED RECREATION ON LAND VALUES

Construction of a reservoir and the subsequent public and private development of water-based recreational activities stimulate increased activity in property exchanges (transactions) of nearby land. Some recent studies have analyzed the impact of reservoir development on land use change and land values [*Prebble,* 1969; *Waldrop and Badger,* 1966; *Epp,* 1970; *Romm,* 1969; *David and Lord,* 1969].

> Land use shifts from nonproject to project oriented uses, property values change, and some land owners gain economically. However, other land owners who are forced to sell their land for construction of the reservoir, do not obtain large economic gains.
>
> *Prebble* [1969]

Knetsch [1964*a*], in a study of land value changes near Tennessee Valley Authority reservoirs, concluded that

> the increased sales prices of land established in the real estate market reflect values due entirely to location on or near reservoir projects. These increased prices represent the capitalization of values derived from such locational advantage.

Results of a similar study of property transfers near a 910-ha water-based state park in Pennsylvania indicated

> that public investment in water based recreational areas can significantly influence the value of rural property.... The park has a significant impact on the structure of the land market surrounding the park.
>
> *Schutjer and Hallberg* [1968, p. 582]

Still another study has concluded that increases in recreational uses of our man-made lakes 'should accelerate the current economic impact on land values, particularly if the administering agency can maintain or improve the quality of recreational opportunity' [*Milliken and Mew,* 1969, p. 99]. Although that analysis was based on a study of three small Bureau of Reclamation reservoirs in Colorado, similar conclusions have been reached on the basis of studies of larger man-made reservoirs [*Morgan,* 1970] and smaller multiple-purpose upstream detention structures developed in coordination with municipalities [*McNeely,* 1968].

When land is acquired for reservoir construction or any other public development project (highways, urban renewal, military bases, and so on), initial concern and criticism relates to the adverse effect such a shift of property from private to public control will have on the tax base of local governments and school districts. Because of the concern and criticism, construction agencies and public management agencies have established policies of school district subsidies and/or reimbursement of part of the revenues collected (for grazing and recreational use, for example) to local governments. Some school districts are provided with new buildings in a new location by the construction agency involved.

However, there is research evidence that the increased values of nearby private lands favorably impacted by the reservoir more than offset the loss of tax revenues in a fairly short period of time [*Bates,* 1969]. A recent study concluded:

> In the areas studied, the appreciation in value of surrounding areas occurred very rapidly. In twelve of the fifteen development areas, the total value of taxable real estate remaining was higher the year after acquisition began than it was the previous year.
>
> *Epp* [1970, p. 18]

Obviously, when land values increase, tax values increase, and the resulting higher tax revenues to local governments should assist many local areas greatly in their efforts to provide good quality services and to remain or to become viable economic areas. Often much of the land around our reservoirs is still in an undeveloped state. As new access roads are built and more recreational sites are added, the net impact will be for more nearby land transactions, and the upward trend in land values will continue.

The major difficulty in making general assessments about tax revenues is that school districts and other public services are generally funded on county or sometimes township boundaries. If by chance most of the land acquired for the reservoir is in one political boundary and the economic activity (including land transactions) from recreational developments occurs in other political districts, inequities may occur as a result of the water-based recreational impact.

IMPACT ON ENVIRONMENTAL QUALITY AND OTHER EXTERNALITY CONSIDERATIONS

The general philosophy of the construction agencies is that water projects should be developed to accommodate large numbers of users. However, *Lawyer* [1970, p. 8] points out that

> facilities and lands must be developed only to a degree consistent with the reasonable estimate of project carrying capacity . . . . We recognize, therefore, that to sustain the quality of the recreation experience at our projects, some restrictions on total amounts of development and the numbers participating in given activities at any one place or any one time will be necessary.

The qualitative experiences received by recreationists at a man-made lake may be either beneficially or adversely affected depending on the use patterns, timing of visit, and so on. As more people use a given site past some critical use point of daily visitations, the esthetic experience declines.

Clawson [1963] summarized some of the outdoor recreational trends on federal reservoirs and indicated some of the recreational policy problems that must be faced in relation to water management. In discussing the cost of waste disposal programs as related to the quality of water needed for recreation, he makes the point that 'aesthetic considerations may be as important as economic ones.' That statement was made in 1963, but in view of recent national policies [*U.S. Congress*, 1962], as indicated by the establishment of the Environmental Protection Agency and the Environmental Quality Council and by the *Water Resources Council*'s [1969] proposed objectives of water resource development, esthetic considerations or quality of life considerations may be assuming a higher level of importance!

PUBLIC POLICY PERSPECTIVES AND SOME ALTERNATIVE RESEARCH STRATEGIES

The Outdoor Recreation Resources Review Commission reports recognized the importance of increasing public expenditures for development and operation of outdoor recreational facilities in connection with water resource development. Whether 'supply creates its own demand' is a moot point in this context. Our citizens have increased use of water-based recreational facilities in recent years. What once was considered to be an 'extra dividend' of water resource development is now considered to be equal to other purposes for which the public receives or obtains economic and esthetic benefits [*Kerr*, 1960].

Little or no thought was given initially to the depreciation of recreational sites and surrounding areas due to overuse or congestion, to the seasonality effects on both transportation facilities and business interests in surrounding communities, or to the ability of the community to provide such services. Research is certainly needed in these fields.

Similarly, too little effort has been devoted to the type of research needed to determine which groups of people are absorbing the costs and which groups are gaining the social and economic benefits. The operation and maintenance costs of such outdoor recreational facilities are becoming a much more significant expense to the public agencies providing them. Many equity and efficiency arguments over who benefits and who pays for the operation and maintenance of these recreational activities remain unanswered.

Probably most, if not all, public recreational facilities should be put on a self-sustaining basis through the imposition of user fees [*Badger*, 1965]. Others have come to the same conclusion on the basis of these and other reasons:

> If there are no externalities resulting from public investments in outdoor recreation facilities, then it follows that efficiency is attained when users bear the marginal costs which are incurred. Without charges to consumers, there is little incentive for them to make efficient use of recreation resources. The public provision of outdoor recreation

> in water projects is not done without cost and beneficiaries are clearly identifiable.
>
> *Knetsch* [1964*b*]

Although the user or admission fees charged by federal or state agencies were once considered 'verboten' for public use areas, they are generally accepted now by most of the public. Extension (by the 1970 Congress) of the Golden Eagle Passport Program until December 31, 1971, at an annual permit fee of $10.00 will allow additional revenues for use in the provisions of the Land and Water Conservation Fund Act [*U.S. Congress,* 1965].

Certainly, Congress and the Office of Management and Budget will have pressures for increased funding to continue developing water-based outdoor recreational facilities. Additional policy planning is needed to determine just what percent of our national budget can (and/or should) be devoted to the development of additional water-based outdoor recreational complexes, to the improvement of existing facilities, and to the insatiable operation and maintenance needs of all our public facilities.

The rationale and basic framework have been provided for some type of rationing system in the use of our water-based recreational facilities. Research is needed to determine how best to establish such a management policy to provide higher quality recreational experiences at reasonable prices. The majority of those who recreate at our man-made lakes have the buying power to pay for their recreational experience. Most recreationists would be willing to pay a small cost if they were assured a higher quality esthetic experience from their visit.

Thus I see the need for more sophisticated research on ramifications of admission or user fee policies (perhaps even a multiple-price policy based on day of week, holidays, working days, or season of year) as a must for planning future recreational developments. We certainly do not have all the answers on demand for recreation activities.

> Accurate estimates of both present and future consumer demand are needed to prevent surpluses of some types of [water] recreational developments and deficits of others.
>
> *Schmedemann* [1966]

I visualize at least three different research areas relating to the interrelationships of water-based recreational facilities, the use of these facilities by man, and the resulting economic impact.

The first research area is the development of more sophisticated techniques for measuring demand for and economic impact of selected water and related land-based recreational activities. This would involve interviewing present users and potential users, obtaining actual receipts and expenditures at and near the complex, and then performing a statistical demand analysis [*McNeely and Badger,* 1967, 1968] and an input-output analysis [*Mapp and Badger,* 1970].

A second research area would be a socioeconomic analysis of the economic management problems and potentials of water-based recreational complexes that would include an analysis of the economic and legal implications of charging user fees for selected recreational use [*Badger,* 1965; *Badger et al.,* 1966, 1970; *Heard and Badger,* 1967].

A third research area would be the development of ways to measure the environmental externalities associated with the various multiple uses of land and water as they involve water-based recreational activities [*Badger,* 1970*b*]. What are the third-party effects or social costs and benefits involved in the different water-based recreational activities? How might we improve the quality of the experiences from use of the man-made lake for outdoor recreational activities?

Not all the qualitative experiences relating to recreational use of the reservoir facilities and/or activities can be quantified or even catalogued in a qualitative scale of values. One study stated: 'The long-term benefits to society as a whole may well be measured in terms of the physical and mental well-being of the populace' [*Milliken and Mew,* 1969, p. 109]. The difficult part is attempting to measure 'well-being.'

New guidelines from the Water Resources Council indicate four national objectives for water resource development: national income, regional development, environmental enhancement, and the well-being of the people. Recreational development, as one of the many purposes of water resource projects, provides both market-valued and nonmarket-valued benefits to each of the four national objectives. Possibly, some adverse effects may enter into environmental enhancement and the well-being of the people. Further analyses of water-based recreational activities on existing and authorized man-made reservoirs are needed to determine the nature and size of these effects. Also additional research should indicate what complementary or related developments are needed to achieve the greatest possible increases in the economic growth of the region where most of these water-based recreational facilities are located.

SUMMARY AND CONCLUSIONS

Increased recreational use on and around our man-made lakes is projected over the next 30 years on the basis of all known trends relative to the preferences of our citizens and income and spending patterns. New technological developments and mass production techniques using new materials, such as fiber glass, will continue to stimulate sales of pleasure boats, fishing rods, and water skis. Boats in particular have been brought within the spending power range of millions of Americans.

The recreating public, no matter where their homes are, receive leisure time qualitative benefits from the use of water-based recreational developments. Public expenditures for state and federal recreational developments on our man-made lakes have resulted in economic benefits as well as social and esthetic benefits for many of our citizens. Land values have been favorably affected, although some private property owners have gained no real benefits from the development of man-made lakes. In some cases, adverse environmental effects have been noted. Such social diseconomies or adverse externalities may increase if we do not reinforce our efforts toward proper management of our recreational facilities to prevent overcrowding and the resulting physical deterioration of the site.

Research is needed on how to measure some of these externalities as well as on how to develop improved techniques for measuring economic impacts and better methods for measuring both potential and actual demand for selected types of water-based recreational activities. More effective planning for location of recreational facilities on a geographic or regional basis and for specific site location of these facilities in a given area will be possible only with more investments in basic and applied socioeconomic research.

REFERENCES

Badger, D. D., Recreational considerations in water planning, paper presented at 10th Annual Water for Texas Conference, Tex. Water Resour. Inst., Tex. A&M Univ., College Station, Nov. 22, 1965.

Badger, D. D. (Ed.), Attaining economic development: How the Great Plains can contribute to the U.S. economy, *Gt. Plains Agr. Counc. Publ. 49,* 234 pp., Okla. Agr. Exp. Sta., Stillwater, Oct. 1970*a*.

Badger, D. D., Environmental impact of water resource development projects, *Okla. Agr. Exp. Sta. Misc. Publ.,* 1-14, 1970*b*.

Badger, D. D., W. W. Payne, and N. R. Cook, Community benefits in the upper Wildhorse Creek watershed, *J. Soil Water Conserv., 21*(2), 45-46, 1966.

Badger, D. D., Q. R. Tipton, and G. E. Laughlin, Legal and economic aspects of limiting liability when private property is used for outdoor recreation in Oklahoma, *Progr. Rep. P-627,* 45 pp., Okla. Agr. Exp. Sta., Stillwater, Jan. 1970.

Bates, C. T., The effect of a large reservoir on local government revenue and expenditure, *Res. Rep. 23,* 137 pp., Water Resour. Inst., Univ. of Ky., Lexington, 1969.

Clawson, M., Methods of measuring the demand for and value of outdoor recreation, *Rep. 10,* Resour. for the Future, Washington, D. C., Feb. 1959.

Clawson, M., *Land and Water for Recreation,* pp. 1-144, Rand McNally, Chicago, 1963.

David, E. L., and W. B. Lord, Determinants of property value on artificial lakes, *AE 54,* Dep. of Agr. Econ., Univ. of Wis., Madison, May 1969.

Epp, D. J., The economic impact of recreational water reservoir development on land use, business enterprises, and land values, *Pa. Agr. Exp. Sta. Bull., 764,* 1-22, 1970.

Heard, A. L., and D. D. Badger, Potentials and problems of farm based recreational enterprises in Oklahoma, *Okla. Agr. Exp. Sta. Processed Ser., P-570,* 1-35, 1967.

Hinman, C. R., The impact of reservoir recreation on the Whitney Point microregion of New York State, *Tech. Rep. 18,* 62 pp., Cornell Univ. Water Resour. and Mar. Sci. Center, Ithaca, N. Y., Aug. 1969.

Jansma, J. D., and W. B. Back, Local secondary effects of watershed projects: A case study of Roger Mills County, Oklahoma, *ERS 178,* Econ. Res. Serv., U.S. Dep. of Agr., and Dep. of Agr. Econ., Okla. State Univ., Stillwater, May 1964.

Kerr, R. S., *Land, Wood, and Water,* p. 143, Fleet, New York, 1960.

Knetsch, J. L., The influence of reservoir projects on land values, *J. Farm Econ., 46*(1), 231-243, 1964*a*.

Knetsch, J. L., Economics of including recreation as a purpose of eastern water projects, *J. Farm Econ., 46*(5), 1148-1157, 1964*b*.

Lawyer, D. E., Recreation boom, *Water Spectrum,* summer 1970.

Mapp, H. P., and D. D. Badger, Input-output analysis of the economic impact of outdoor recreation in a low income area, *Proc. West. Agr. Econ. Ass., 43,* 1970.

McNeely, J. G., Jr., Statistical estimation of demand for selected recreational activities, Ph.D. dissertation, Dep. of Agr. Econ., Okla. State Univ., Stillwater, May 1968.

McNeely, J. G., Jr., and D. D. Badger, The use of Markov chains in projecting recreation attendance patterns, *Proc. Agr. Econ. Rural Sociol. Sect. Ass. S. Agr. Workers,* 1967.

McNeely, J. G., Jr., and D. D. Badger, Demand for selected recreational activities in south central Oklahoma, *Okla. Agr. Exp. Sta. Tech. Bull., T-126,* 1–44, 1968.

Merewitz, L., Recreational benefits of water resource development, Harvard Water Program, Harvard Univ., Cambridge, Mass., June 1964.

Milliken, J. G., and H. E. Mew, Jr., Economic and social impact of recreation at reclamation reservoirs, Denver Res. Inst., Univ. of Denver, Colo., March 1969.

Morgan, W. C., A study of the social and economic effects of Keystone Reservoir on the community of Mannford, Oklahoma, M.S. thesis, Dep. of Civil Eng., Okla. State Univ., Stillwater, May 1970.

Prebble, B. R., Patterns of land use change around a large reservoir, *Res. Rep. 22,* 133 pp., Water Resour. Inst., Univ. of Ky., Lexington, 1969.

Romm, J., The value of reservoir recreation, *Tech. Rep. 19,* 99 pp., Cornell Univ. Water Resour. and Mar. Sci. Center, Ithaca, N. Y., Aug. 1969.

Schmedemann, I. W., Water based recreation research, paper presented at Annual Meeting of Soil Conservation Society of America, Albuquerque, N. Mex., Aug. 17, 1966.

Schmedemann, I. W., and J. G. McNeely, The impact of recreation on local economies, paper presented at Annual Meeting of Western Farm Economics Association, Las Cruces, N. Mex., July 21, 1967.

Schutjer, W. A., and M. C. Hallberg, Impact of water recreational development on rural property values, *Amer. J. Agr. Econ., 50*(3), 572–583, 1968.

U.S. Congress, Policies, standards, and procedures in the formulation, evaluation, and review of plans for use and development of water and related land resources, *Senate Doc. 97,* 87th Congress, 2nd Session, May 29, 1962.

U.S. Congress, Land and Water Conservation Fund Act, *Public Law 89-578,* 89th Congress, 1st Session, 1965.

Waldrop, J. E., and D. D. Badger, Effects of upstream watershed development on prices and values of farmland in the upper Washita River basin, *P-529,* Okla. Agr. Exp. Sta., Stillwater, March 1966.

Water Resources Council, Report to the Water Resources Council by the special task force, Procedures for Evaluation of Water and Related Land Resource Projects, Washington, D. C., June 1969.

Wennergren, E. B., Value of water for boating recreation, *Utah Agr. Exp. Sta. Bull., 453,* 1–27, 1965.

Perception, Attitude Change, and the Multiple Use of Domestic Water Supply Reservoirs

DUANE D. BAUMANN

Department of Geography, Southern Illinois University
Carbondale, Illinois 62901

In 1960 the Senate Select Committee on National Water Resources [*U.S. Congress*, 1962] recommended 'that recreation be recognized as an appropriate use of domestic water supply reservoirs and watersheds.' In a report prepared for the *Outdoor Recreational Resources Review Commission* [1962] the authors noted that city water supply reservoirs could be opened to recreation under appropriate conditions. In many places throughout this country, recreationists clamor with little success for changes in policies that prohibit fishing, boating, and swimming in community water supply reservoirs. Their plea is intensifying in light of the growing demand for water-oriented outdoor recreation, a result of our rising per capita incomes, increased mobility, and leisure time.

Many health officials and water superintendents and some sanitary engineers, however, doubt the value of allowing recreational activities on a community's drinking water supply reservoir. They believe that reservoir recreation would degrade the quality of the drinking water and increase the chance of a water-borne disease epidemic. Other obstacles to allowing reservoir recreation include the notion that the incidence of costs would fall on all consumers for the benefit of a minority of recreationists. Also to some the idea of allowing swimming in domestic water supply reservoirs is esthetically disturbing. Moreover the *American Water Works Association* [1958] and the *New England Water Works Association* [1958] do not recommend the recreational use of domestic water supply reservoirs.

Yet the proponents of multiple use of domestic water supply reservoirs claim that recreation would not endanger public health or deteriorate the quality of the drinking water and that it could be economically self-supporting.

In this paper the extent of recreational use of domestic water supply reservoirs in the United States is described and analyzed, the literature regarding the effects of recreation on water quality is reviewed, and a hypothesis is formulated for the persistence of the restrictive policies. The data were gathered from a literature review, a nationwide mail questionnaire for water superintendents in 256 urban places, a mail questionnaire to personnel in public health departments in each state, and personal interviews with 26 water managers in Texas, Kansas, Illinois, and Massachusetts. The economics of reservoir recreation, the implications of court precedents, laws, and public opinion, and the role of the community decision-making process are described and analyzed in another paper [*Baumann*, 1969].

USE OF DOMESTIC WATER SUPPLY RESERVOIRS FOR RECREATION

State surveys have been prepared by the *Commonwealth of Massachusetts* [1957], the *California Department of Public Health* [1961], and New York [*Van Nierop*, 1966]. Also *Wurtz et al.* [1959] completed a survey of 28 cities concerning the nature of recreational activities on municipal water supply reservoirs.

Most communities permit recreation on domestic water supply reservoirs. Of the places for which data were compiled, only 32% prohibited all types of recreational activities. But in the Northeast and Far West most communities (61%) restrict all types of recreational activities from domestic water supply reservoirs. In the rest of the country, recreational activities are permitted on the domestic water supply reservoirs in all but 8% of the communities.

In the Northeast the New England communities employ the most restrictive policies, and, in the Far West, Washington and Oregon enforce the most restrictive policies. For example, in Massachusetts approximately 70% of the communities prohibited all types of recreation from reservoirs, whereas, in New York, only 50% of the communities restricted reservoir recreation.

Of the places in the Northeast and Far West that allow some type of reservoir recreation, none in the Far West and only 7% in the Northeast permit bodily contact activities, such as swimming, wading, and water skiing. In the rest of the United States approximately 50% of the communities allow swimming in the drinking water supply reservoir.

MANAGERIAL PERCEPTION

A resource is culturally defined. To the water managers in the Northeast and Far West, domestic water supply reservoirs are not considered a recreational resource as well as a community water supply. However, in the rest of the country, most water managers believe that one can go 'swimming in his drink.'

Among the water managers who restrict reservoir recreation the most frequently espoused reasons are the fear of an increased health hazard and the possible deterioration in the quality of drinking water. Other obstacles include anticipated managerial problems, increased costs, and a public that finds the idea of bodily contact recreational activities in the drinking water supply repulsive.

According to the data from the mail questionnaires and personal interviews the northeastern and far western water superintendents doubt the efficacy of water treatment technology. In Massachusetts none of the interviewed managers considered chlorination an adequate safeguard under conditions of full recreational use of the water supply reservoir. But these same water managers perceive chlorination to be an effective safeguard against disease transmission when recreational activities are prohibited! Moreover, unlike the water managers in the rest of the country, the northeastern managers doubted the efficacy of filtration plus chlorination in controlling viricidal and bacterial disease transmission if recreation were allowed. Whose views are scientifically sound, those expressed in the Northeast–Far West or those espoused in the rest of the country? Do recreational activities on a domestic water supply reservoir jeopardize public health?

RECREATION AND WATER SUPPLY RESERVOIRS: A SOURCE OF POLLUTION?

This conflict is not unique to the United States; it is also a concern in England, East Germany, and the Soviet Union. In the United States there are a few scientific studies that have sought to measure the amount of pollution attributed to recreational activities. The conclusions of these studies can be grouped into three different viewpoints: (1) that recreational activities produce no significant measurable pollution in domestic water supply reservoirs, (2) that recreational activities are a major source of contamination, and (3) that only certain kinds of recreational activities can contribute markedly to the pollution load of a reservoir.

Recreation as a minor source of pollution. From a study of a 282.8-ha water supply reservoir *Roseberry* [1964] concluded that intensive recreational use of the lake and watershed was not reflected in the bacterial counts at the intake tower. He noted that, before any additional treatment cost would be incurred, the pollution load would have to increase significantly. In a study by the *California Department of Public Health* [1961], coliform bacteria was measurably higher in lakes where recreation was allowed; however, the differences were not considered important, since all the coliform counts were at the level characteristic of clean water. In 1955 a committee appointed by the Governor of Connecticut gathered information regarding the recreational use of domestic water supply reservoirs, concluded that no outbreaks of disease could be attributed to it, and recommended the recreational use of all filtered water supplies (State of Connecticut, unpublished report, 1956). Again in Connecticut *Bock et al.* [1965] concluded that Hartford's water supply reservoir should be open to recreation and 'that based upon epidemiological evidence, there is no risk at all associated with the recreational use of water supply reservoirs.'

Several other studies note the absence of a meaningful relationship between recreational activities and bacterial densities in water [*Arnold et al.*, 1948; *Radke*, 1964; *Hopkins*, 1954]. In fact, *Payette* [1956] observed that 'on numerous occasions, the highest bacteria counts have occurred at times when no recreational activities were in operation.' However, others speak with as much certainty but with different conclusions.

Recreation as a major source of pollution. The decline of coliform bacteria was observed in the tap water in Springfield, Massachusetts, after fishing was prohibited from the domestic water supply reservoir [*Karalekas and Lynch*, 1965]. Not only was the coliform count relatively low, but the water was not even chlorinated. In a similar study in Hartford, Connecticut, the bacteriologic counts (coliform) of two reservoirs, one with recreation and the other with no recreation, were compared during a 2-year period [*Minkus*, 1965]. Although the coliform count was higher at all times in the reservoir where recreation was allowed, the cause of the differences is not certain. For example, a peak coliform count occurred in February, a low recreational use period. Similar conclusions were derived from a similar study in Massachusetts [*Commonwealth of Massachusetts*, 1957].

Unlike the studies in the previous section the nature of these studies demonstrated a lack of rigor, analytical methodology, and candid interpretations of the results. Yet other studies emphasize the effects of specific types of recreational activities on the quality of water.

Specific types of recreational activities as a source of pollution. In England the *Institute of Water Engineers* [1963] recommended the prohibition of only swimming and water skiing because such activities were considered potential sources of contamination. *Korsh* [1958], in the Soviet Union, noted that houseboats, cattle watering, spring runoff, and a community of 200 persons near the shore contributed measurably to the pollution of the surface water.

In summary, I conclude that no measurable increase in the pollution load occurs from recreational activities on domestic water supply reservoirs. Nevertheless, since the recreational activities allowed on reservoirs have been observed to infest water with a small amount of bacteria and viruses, the question is raised whether conventional treatment processes are adequate to produce safe potable water.

EFFICACY OF WATER TREATMENT TECHNOLOGY

As was mentioned previously, the effectiveness of conventional techniques of water treatment, sand filtration, and chlorination is doubted by many water managers. From the available evidence, however, I conclude that both laboratory and field data appear to support the conclusion that conventional treatment techniques can produce safe potable water from even grossly polluted sources. Emphatically, *Clarke and Chang* [1959] conclude that:

> Although most viruses examined are unquestionably more resistant to free chlorine than are coliform bacteria, virus destruction is possible through pre-chlorination practices with a free chlorine residual of 1 parts per million for 30 minutes, provided that virus particles were not embedded in particulate organic matter that could serve as a protective envelope.

A particular problem is the transmission of viruses that are entrapped in particulate organic matter. The chance of occurrence of such transmission is indeed slight in systems where filtration and flocculation are included in the water treatment processes.

Further summary evidence is provided by R. Dean [*Berg*, 1965, p. 470], who notes

> . . . that we can make a better quality water by treating sewage than is available in many of our cities. Controlled treatment of a known hazardous raw material can produce a safer product than routine treatment of a deteriorating source. Viruses can be removed from heavily polluted water by suitable treatment and the cost is not unreasonable.

Therefore in light of the insignificant amount of pollution produced by recreational activities on reservoirs and the effectiveness of properly operating treatment technology all types of recreational activities can be permitted on domestic water supply reservoirs without any measurable increase in the risk of water-borne disease. The cost of proper treatment, which should be employed even if recreation is not permitted, is therefore not prohibitive.

The policy of watershed protection with chlorination, which excludes human trespass (recreation) from the reservoir, can be considered an inadequate safeguard in the production of drinking water. Filtration plus chlorination are recommended for every surface water supply to prohibit the transmission of pathogenic bacteria and viruses that may be enveloped in particulate organic matter. Ironically, in the regions where recreation is restricted from the domestic water supply reservoirs, many systems rely solely on chlorination. For example, in Worcester, Massachusetts, the water is not filtered, but human trespass is prohibited from the reservoirs in the belief that the result is safe potable water.

Since a growing demand for water-oriented outdoor recreation exists and there is a wealth of scientific information regarding the efficacy of water treatment technology, why have not the policies that restrict reservoir recreation accommodated the concept of multiple use? At the moment, communities in the Northeast and Far West, like those elsewhere, strive toward the abatement of stream pollution so that, in addition to other reasons, people may fish and swim, but the domestic water supply reservoirs remain a hallowed area.

ATTITUDE CHANGE AND THE RECREATIONAL USE OF DOMESTIC WATER SUPPLY RESERVOIRS

Among the several theories of attitude change *Festinger*'s [1957, 1964] theory of cognitive dissonance may, when it is applied to this problem, enhance understanding of the persistence of the contemporary perceptions of water managers in the Northeast and Far West. Why, in the face of contradictory scientific evidence and a burgeoning demand for outdoor recreation, are these perceptions slow to change?

In essence, the theory holds that men seek harmony or consonance among their cognitions: attitudes, beliefs, opinions, and knowledge. When these cognitions are not in agreement, dissonance is created. Consequently, the person attempts to reduce the dissonance in several ways. First, he may change his mind or the environmental stimuli that cause the dissonance. Or he may acquire information that supports his views in an attempt to reduce the relative dissonance. As a fourth alternative he may merely consider the problem unworthy of his attention; that is, he will cope with the dissonance produced from a problem perceived to be trivial.

Accordingly, the data gathered in this study suggest that the water managers may have reduced dissonance in all these ways. Few, if any, appear to have changed their own viewpoints. Instead they appear to have gathered social support for the present policies. The American Water Works Association, the New England Water Works Association, the state health departments, and consumer or public opinion provided the desired support. And some water managers commented that not only are the proponents of reservoir recreation a small vocal minority but that there exists an abundance of lakes in the area for water-oriented recreation. However, the *Outdoor Recreational Resources Review Commission* [1962] noted that in the Northeast in particular there exists a large unfulfilled demand for swimming.

In summary, the perceptions of the water managers in the restrictive regions, formed in an earlier period, resist change. But as a possible result of the increasing affluence and demand for water-oriented outdoor recreation the magnitude of dissonance may become so great as to require water managers to change their own cognitions and/or behaviors in an effort to harmonize with the changing social and technological environment.

REFERENCES

American Water Works Association, Recreational use of domestic water supply reservoirs: Statement of policy, *J. Amer. Water Works Ass.*, *50*(5), 579–580, 1958.

Arnold, G., et al., Public use of reservoir lands and waters, *J. Amer. Water Works Ass.*, *40*(7), 945–960, 1948.

Baumann, D. D., The recreational use of domestic water supply reservoirs: Perception and choice, *Res. Pap. 121*, Dep. of Geogr., Univ. of Chicago, Ill., 1969.

Berg, G. (Ed.), *Transmission of Viruses by the Water Route*, p. 470, Interscience, New York, 1965.

Bock, P., E. Pyatt, and J. De Fillippi, Water resources planning study of the Farmington Valley, *Rep. 7223-154*, Travelers Res. Center, Inc., Hartford, Conn., 1965.

California Department of Public Health, Recreation on domestic water supply reservoirs, Berkeley, 1961.

Clarke, N. A., and S. L. Chang, Enteric viruses in water, *J. Amer. Water Works Ass.*, *51*(10), 1299–1317, 1959.

Commonwealth of Massachusetts, Special report—Relative to the preservation of the purity of certain water supplies within the commonwealth, *Senate Rep. 665*, Dep. of Public Health, Boston, 1957.

Festinger, L., *A Theory of Cognitive Dissonance*, Stanford University Press, Palo Alto, Calif., 1957.

Festinger, L., *Conflict, Decision, Dissonance*, Stanford University Press, Palo Alto, Calif., 1964.

Hopkins, E. S., Views on watershed control: A symposium, *J. Amer. Water Works Ass.*, *46*(5), 403–417, 1954.

Institute of Water Engineers, Draft report of the council on recreational use of waterworks, *J. Inst. Water Eng.*, *17*(1), 71–114, 1963.

Karalekas, P., and J. Lynch, Recreational activities of Springfield, Massachusetts, water reservoirs: Past and present, *J. N. Engl. Water Works Ass.*, *79*(1), 18–31, 1965.

Korsh, L. Y., On the question of using drinking-water reservoirs for purposes of physical culture and sport (in Russian), *Vodosnabzh. Sanit. Tekh.*, *5*, 20–23, 1959.

Minkus, A., Recreational use of reservoirs, *J. N. Engl. Water Works Ass.*, *79*(1), 32–40, 1965.

New England Water Works Association, Policy statement relative to recreational use of public water supplies, *J. N. Engl. Water Works Ass.*, *72*(3), 1958.

Outdoor Recreational Resources Review Commission, Water for recreation—Values and opportunities, *Study Rep. 10*, p. 42, Washington, D. C., 1962.

Payette, R. C., Large water reservoirs have recreational potential, *Amer. City*, *71*(9), 133-134, 1956.

Radke, R. A., Quality control conflicts in an expanding society—Municipal watershed access, in *Water Resources Management for the Needs of An Expanding Society*, pp. 159-161, University of Washington, Seattle, 1964.

Roseberry, D. A., Relationships of recreational use of Forrest Lake to bacterial densities, *J. Amer. Water Works Ass.*, *56*(1), 43-49, 1964.

U.S. Congress, Select Committee on National Water Resources, Water resource activities in the United States: Water recreation needs in the United States, *Comm. Print 17*, p. 4, 86th Congress, 2nd Session, 1962.

Van Nierop, E. T., *A Framework for the Multiple Use of Municipal Water Supply Areas*, Cornell University Water Resources Center, Ithaca, N. Y., 1966.

Wurtz, C. B., T. Dolan, and C. Bridges, Survey of multiple-use reservoir practices in the United States, *Trans. Amer. Fish. Soc.*, *88*, 45-49, 1959.

Summary: Terrestrial Ecosystems

ELWOOD A. SEAMAN

Bureau of Reclamation, Washington, D. C. 20240

It is quite revealing to search the literature for studies of terrestrial plants and animals in relation to man-made lakes and find so little data on the before and after effects of an impoundment on their ecology. Thirty years ago I distinctly recall many discussions in ecological groups expressing the need for intensive studies of a new impoundment basin followed by a study of what actually happened. In the interim the talk has persisted, yet not much research has been conducted on terrestrial ecosystems before and after impoundment.

Hesse [1937] pointed out in 1924 that four fifths of the known species of animals are terrestrial despite the fact that the surface of the oceans and inland water combined amounts to about 362,250,000 km^2 whereas the total land surface is only 147,650,000 km^2. No matter where a man-made lake is developed, there is apt to be animal life affected. Of course, man-made lakes also affect plant life in a like manner. To use land for a water impoundment is justifiable only when the good to mankind (both the intangible and tangible benefits) outweighs the effect on the environment. It is not easy to weigh these considerations, and herein lies a controversy that intensifies as more people question the advisability of creating impoundments.

I take the view that benefits have to be weighed carefully in the planning stage so that the greatest good can be attained. In this discussion I do not wish to do battle with this subject; I only wish to point out that greater concern needs to be given to the terrestrial forms than has been given over the years. The present awakening of the public on these issues may very well bring about proper attention to these matters. This subject is discussed ably by *Lagler* [1969] and by *Bardach and Dussart* [this volume].

LOSS OF HABITAT

Since it was simple to recognize that man-made lakes forced stream-inhabiting animal life to move out to other niches in the surrounding territory, it likewise should have been recognized that a detailed study of these reactions was necessary. Here again, the intention for such study turned out to be mostly talk. The literature was searched only to find no evidence of any mark and recovery studies prior to impoundment. One would think that wildlife biologists or mammalogists would have tagged stream-dwelling mink (*Mustela* sp.), muskrat (*Ondatra* sp.), woodchuck (*Marmota* sp.), and other such small mammals for future recovery in order to determine their movements following flooding of their habitat. Further, tagging of deer (*Odocoieus virginianus* or *O. hemionus*) or elk (*Cervus canadensis*) would appear logical for the same reason, or the recent better method by using telemetry would also seem logical.

If, in fact, such studies were conducted, they have not been reported in literature except perhaps as an incidental part of another study. I apologize for my failure to locate these studies should they exist. In numerous discussions with colleagues in Washington, D. C., the prevailing opinion is that such studies were contemplated but were not carried out. Undoubtedly, the concept that a hopeless condition existed (a loss beyond the view of recovery) influenced many decisions for funding these studies.

The report on fish and wildlife resources affected by the proposed Rampart Canyon Dam and Reservoir Project on the Yukon River in Alaska (Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior, unpublished report, 1964) is a good example of the preimpoundment study of terrestrial life. No mark and recovery and/or telemetry studies were made. This Rampart report is an example of the type of study that should be done in great detail on any future large man-made lake.

The caring for isolated mammals during the impounding of Lake Kariba in Africa was apparently an assistance program, not a scientific study. As far as I can determine from the literature, no extensive scientific study was conducted on the terrestrial life of that basin.

FORESTS, INSECTS, AND BIRDS

Elimination of trees and shrubs by burning, cutting, chipping, or smashing is viewed as a total loss to the ecosystem of the impounded basin except for the nutrient value that they have when they are left to rot in the water. Trees left standing can provide some benefits to fish but may be a hazard to boats.

No special studies have been noted on the determination of what happens to insect life following impoundment of a man-made lake. Birdlife is discussed later in this paper.

BENEFITS TO SURROUNDING TERRESTRIAL LIFE

No discussion of an ecosystem associated with a man-made lake is complete without pointing up the significant benefits to birdlife, especially waterfowl of the nearly 2 million man-made farm ponds in the United States and Canada. Those ponds and other man-made reservoirs located in major waterfowl breeding grounds or situated along migratory routes serve such birds well. Some biologists feel that three species of waterfowl benefit greatly in North America from man-made lakes, especially large reservoirs, namely, the mallard duck (*Anas platyrhynchos*), pin-tailed duck (*Anas acuta*), and Canada goose (*Branta canadensis*). Many species of waterfowl feed in fields and use man-made lakes for resting and refuge from man and predators. Such lakes need not furnish foods in the form of invertebrate fauna or plant life if grains are readily available not too far from the lake.

L. Compton (unpublished notes, 1971) has pointed out that there are >2 million small ponds in the United States. They are being constructed at a rate of 60,000 per year. These ponds often create new aquatic habitats in areas where natural potholes dry up in drought years. They can increase waterfowl production significantly. In Montana [*Smith*, 1952; H. A. Hansen, unpublished notes, 1971], ponds constructed in an area previously devoid of aquatic habitat increased the production of waterfowl.

There are >58,000 ponds in the state of South Dakota, about 16,000 in North Dakota, and about 5000 in Minnesota. For these three states there is a total of 79,000 ponds. These states also have many natural lakes and potholes. Compton reports that 50% of these ponds produced ducks at the rate of 10 ducks per pond, and he states, 'The farm and ranch ponds in these three states can conservatively be said to annually produce in the neighborhood of 350,000 ducks.' Stock ponds in Canada and the northern Great Plains of the United States and Canada produce upwards of 1 million waterfowl per year according to a report by *Linduska* [1964].

So much for breeding of ducks in man-made ponds. Other than the obvious resting opportunities for migrating waterfowl, ponds attract the mourning dove in great numbers [*Peters*, 1961]. Doves need a dependable source of water to produce 'pigeon milk' for feeding the young. Man-made lakes often play a vital role for doves in this respect. The annual kill of doves by hunters in the United States runs between 25 and 40 million birds. Many biologists have associated this high rate of production with the establishment of man-made lakes.

Studies of man-made ponds in Missouri [*Greenwell*, 1948] showed a high use by muskrat, rabbits, raccoon, and bobwhite quail. *Shanks and Arthur* [1951] studied 40 farm ponds in Missouri and stated the following in regard to muskrat use: 'Without question, the thousands of farm ponds throughout the midwest (U.S.) provide an additional habitat type of importance.'

Antelope, deer, raccoon, opossum, skunk, and other small mammals have been attracted to small ponds, and many upland game birds such as prairie chickens have benefited from these impoundments. In studies in South Dakota, *Bue et al.* [1952] found 90 species of songbirds using small ponds.

Elsewhere in this volume, attention is given to various studies of Kainji and Kariba lakes in Africa. *Halstead* [this volume] has presented data on the evolution of the shoreline features of these two lakes. Halstead believes that large inland bodies of water lead to local climatic changes and states that all erosional features along the shores of man-made lakes can be attributed to storm action. *Bardach and Dussart* [this volume] do not agree with this climate effect. They feel there is inadequate data, as they put it, to permit firm judgment on whether man-made lakes have induced climatic changes.

Halstead's remarks on the inundated termite mounds in Lake Kainji are interesting. He describes the impounded termite mounds as novel microenvironments on the muddy lake floor. The sand and grit from the mounds was very evident in comparison to the thin layer of mud and silt elsewhere in the exposed drawdown areas. Halstead states,

> Erosion was confined to the vicinity of obstacles, such as houses, trees, and termite mounds . . . . The spreading of termite mound sediments together with the fine sands heralded the first stage of the establishment of a genuine lacustrine regime.

One of the problems of man-made lakes is the damage that takes place to soils that are exposed at drawdown or eroded at the waters' edge even under nonfluctuating water levels. The Soil Conservation Service of the U.S. Department of Agriculture is testing a series of plants, grass, sedges, and shrubs for establishing across-the-waterline slopes of lakes. *Young* [this volume], a regional plant materials specialist, has determined that a native grass, maiden cane (*Panicum hemitomon),* shows promise of being suitable for this purpose. It is limited, however, to the humid section of the southeast United States. Yet, good results are noted when this grass is used north and west of its normal range. Additional research is needed to further expand its natural range.

In the arid regions of the United States, plant growth is needed on exposed drawdown banks where blowing dust is a problem. It is hoped that Young's future research will include these areas for testing.

One of the better designed and managed man-made lakes in an urban area is Lake Burley Griffin, Canberra, Australia. Terrestrial ecological problems were taken into account during the planning stages of this lake, and intelligent management followed during construction and later operation of the waters impounded on the Molonglo River. *Minty* [this volume] has reported on this lake. He points out that great concern was raised prior to establishment of this lake over the possible pollution problems, mosquito breeding, water quality, meteorology (fog), fish, aquatic plants, and so forth. Each of these topics was investigated carefully in the design stage. Steps were taken to minimize these problems, and none proved insurmountable. Over 55,000 trees have been planted in the lake's shoreline and vicinity.

Various environmental problems were ironed out by construction of a hydraulic model. Lake Burley Griffin is a good example of successful integration of the various professional disciplines working together in the design, construction, and operation of a man-made lake. Scientists, engineers, and landscape architects worked hand in hand on this project.

ADJUSTMENTS IN ECOLOGICAL MANAGEMENT

Certain techniques, or adjustments, are being made at man-made lakes to satisfy needs of terrestrial plants and animals. Browse improvement for deer and elk can be improved by controlled burning techniques, as applied, for example, at Dworshak Reservoir in Idaho, which is now under construction (Bureau of Sport Fisheries and Wildlife, U.S. Department of the Interior, unpublished report, 1970). These actions are taken to mitigate (replace in kind) the loss of 6,070 ha of terrestrial wildlife habitat in the reservoir. The measures are designed to increase the big-game carrying capacity of the existing habitat nearby.

Wildlife food plots (such as grains and grasses) are often developed for deer, turkey, and waterfowl. Where it is permitted, grazing for cattle and sheep is controlled by fences when that grazing is destructive to native vegetation.

Where endangered plant and animal species exist in the vicinity of a man-made lake, steps are often taken to establish a refuge for their preservation. Where possible, water level fluctuation is controlled in order not to jeopardize terrestrial forms.

NEEDS FOR PRESERVATION AND MANAGEMENT OF TERRESTRIAL FORMS

The need for funding more ecological research is great. Although the Food and Agriculture Organization and other organizations are spending considerable sums on certain large lakes (such as Volta, Kariba, Kainji, and Nasser), there is no doubt that more intensive investigations are essential. The tendency is to place most of the attention on the aquatic ecosystems, whereas terrestrial research is less intensive.

Bardach and Dussart [this volume] have limited their discussion to large man-made lakes, roughly those 4000 man-made lakes in the world used for hydroelectric power generation, flood control, and agricultural irrigation purposes. At this point I want to express my feeling, shared by *Mermel* [1958], that a world registry of man-made lakes with dams of >15.24 meters in height should be established (see also *Fels and Keller* [this volume]).

I would like also to point out that, here in the United States, Public Law 91-190, The National Environmental Policy Act of 1969, requires an environmental impact statement to be filed with the Council on Environmental Quality on all major federal actions that significantly affect the environment. To adequately prepare such a statement, preimpoundment studies must also be taken to properly assess the impact the new reservoir will have on the environment in the area. Effects upstream, downstream, and adjacent to the reservoir should also be studied. The terrestrial ecosystem is an important part of this study that should be covered as well as the other environmental parameters discussed in this volume.

REFERENCES

Bardach, J. E., and B. Dussart, Effects of man-made lakes on ecosystems, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Bue, I. G., L. Blankenship, and W. H. Marshall, The relationship of grazing practices to waterfowl breeding populations and production on stock ponds in western South Dakota, *Trans. N. Amer. Wildl. Conf., 17*, 396–414, 1952.

Fels, E., and R. Keller, World register on man-made lakes, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Greenwell, G. A., Wildlife value of Missouri ponds, *Trans. N. Amer. Wildl. Conf., 13*, 271–281, 1948.

Halstead, L. B., Evolution of shoreline features of Kainji Lake, Nigeria, and Lake Kariba, Zambia and Southern Rhodesia, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Hesse, A., *Ecological Animal Geography*, John Wiley, New York, 1937.

Lagler, K. F. (Ed.), *Man-Made Lakes, Planning and Development*, Food and Agriculture Organization, Rome, 1969.

Linduska, J. P., *Waterfowl Tomorrow*, Bureau of Sport Fisheries and Wildlife, Fish and Wildlife Service, U.S. Department of the Interior, Washington, D. C., 1964.

Mermel, T. W., *Register of Dams in United States*, McGraw-Hill, New York, 1958.

Minty, A. E., Lake Burley Griffin, Australia, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Peters, H. S., The past status and management of the mourning dove, *Trans. N. Amer. Wildl. Conf., 26*, 371–374, 1961.

Shanks, C. E., and G. C. Arthur, Movements and population dynamics of farm pond and stream muskrats in Missouri, pamphlet, Missouri Conservation Commission, Division of Fish and Game, 1951.

Smith, R. H., A study of waterfowl production on artificial reservoirs in eastern Montana, *J. Wildl. Manage., 17*, 276–291, 1952.

Young, W. C., Plants for shoreline erosion control in southern areas of the United States, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Evolution of Shoreline Features of Kainji Lake, Nigeria, and Lake Kariba, Zambia and Southern Rhodesia

L. BEVERLY HALSTEAD

Department of Biological Sciences, University of Ife, Ile-Ife, Nigeria

The damming of major rivers and the consequent formation of large inland bodies of water lead to local climatic changes. All erosional features along the shores of man-made lakes can be attributed to storm action. Since access to the lake for whatever purpose involves traversing the shoreline, the evolution of different coastal features will determine the siting of man's multifarious activities on the lakeside.

The impoundment of Kainji Lake on the River Niger and Lake Kariba on the Zambezi River allows comparisons to be made that are particularly useful. Both lakes are situated in comparable climatic zones; yet the physical characteristics of these two reservoirs are quite dissimilar (Table 1).

Lake Kariba was impounded in 1958 and reached its full storage capacity in 1963; in contrast, Kainji Lake took only 2½ months to fill. In spite of these striking differences, the development of shoreline features would seem to be comparable insofar as it is possible to judge. It must be remembered that Kainji Lake is now (1971) only 3 years old, whereas Lake Kariba is over 10 years old. In general terms the shoreline features are determined by the original topography of the landscape, which is a reflection of the underlying geology. The actual development of particular features is the result of the sweeping of storms across open water. Areas of high relief, headlands, and exposed regions suffer the most intense erosion. Prevailing winds redistribute eroded material along the shores, where it accumulates in bays and sheltered areas. It is notable that deposited sediment can generally be shown to have been derived from adjacent strata. From a biological standpoint, Kainji Lake and Lake Kariba represent two contrasting types of freshwater ecosystems, but this difference has no influence on the evolution of shoreline features, which are initiated by storms. Since the relief at the margins of the lake will not be uniform, the erosive action will accentuate any differences. The prime prerequisites are simply a large expanse of water and a variegated topography, and, since these are common to virtually all major man-made lakes, it can confidently be predicted that the evolution of shoreline features will follow similar patterns.

This paper is based on two complete surveys of the shores of Kainji Lake 1 and 2 years after impoundment and on a survey of the southern shore of Lake Kariba from Mwenda to Kariba 11 years after impoundment. An account of shoreline features along the southern coast of Lake Kariba was given by G. Bond (unpublished report, 1965) on the basis of a 1-week cruise at the beginning of 1964 (i.e., 1 year after the lake had reached its full storage capacity) and has enabled the changes at particular localities from 1964 to 1969 to be documented. The detailed surveys at Kainji Lake in 1969 and 1970 record the initial stages of shoreline evolution but already demonstrate that the major areas of erosion and deposition are firmly established [*Halstead*, 1971*a*].

KAINJI LAKE IN 1969

The large annual drawdown, which exposes a third of the area of the lake floor, facilitates the study of the effect of the reservoir on the old topography. On the occasion of the first drawdown after impoundment I examined the shore at 45 localities around the lake (Figure 1).

In regions bounded by resistant rocks of moderate to high relief the shores were scoured clean of vegetation and soil; in some places, cliffs 5 meters high had formed. Reworked gravels or gravels newly derived from adjacent rock types formed characteristic terracing, which represented the successive retreats of the strand, each scarp being a minor storm beach with a layer of sand or grit at the foot that marks the

TABLE 1. Physical Characteristics

	Length, km	Area, km^2	Volume, km^3	Maximum Depth, meters	Water Level Fluctuation, meters	Outflow to Volume
Kainji Lake	136	1250	15	55	10	4:1
Lake Kariba	280	5544	160	93	3 to 4	1:9

This table is based on data from the Niger Dams Authority and the Nuffield Lake Kariba Research Station.

waterline. As one retreats from the line of the maximum extent of the lake, there is a patchy zone of partially eroded soils, which gives way to uneroded soils, which subsequently bear a veneer of sand or silt. With the exception of scoured rock surfaces, strandlines of rafted plant debris were in evidence all around the lake margins. They were most notable toward the damsite, where a thick layer of carbonized plant debris was found beneath a layer of silt.

In areas of low relief and in inlets and drowned tributaries, erosion was confined to the vicinity of obstacles, such as houses, trees, and termite mounds. The most extensive alluvial flats seemed to have been covered by a thin layer of mud or silt, but around the termite mounds there was a cover of clean sands and grits. This material had originally been retrieved from the subsoil by termites, and the destruction of the mounds redistributed it. Furrows of formerly cultivated land tended to become filled with locally derived sands, again mainly from termite mounds. The significance of the termite sands is that they must have provided novel microenvironments on the otherwise muddy lake floor. In the mud-covered flats, there was little evidence of recolonization by land plants. However, where there was a sand or grit cover, recolonization was extensive, lush meadows often being present.

These features are illustrated in the summary diagram (Figure 2). A detailed and profusely illustrated account of the situation at the first drawdown has been published elsewhere [*Halstead*, 1971*a*].

KAINJI LAKE IN 1970

During the second drawdown a further survey was undertaken, most of the previously examined localities being revisited. The main areas of erosion showed little change from the previous year. The gravel terracing appeared rather more extensive, and there were cliffs some 10 meters high in places. This effect occurred to some extent because the lake level was allowed to rise another 2 meters by control at the damsite.

In contrast, the regions of low relief showed a number of striking changes. Sands and grits derived from termite mounds were now spread over large areas. There was no longer any sign of a deposit of silt or mud over the flats. In many areas, there was instead a layer of fine brown sand that did not seem to be locally derived. Toward the damsite, there were strandlines of rafted plant debris on which plant recolonization had been initiated. In general, rafted plant debris was minimal, but recolonization was very extensive and was especially noticeable where it had been absent the previous year. These regions supported an enormous population of the freshwater mussel *Mutela dubia* (Gmelin), which had undergone a population explosion since the first drawdown [*Halstead*, 1971*b*].

The conditions recorded during the second drawdown seem likely to persist with only minor modifications in subsequent years. The observations made in 1969 recorded the destruction of the original terrestrial habitat. The removal of the plant cover was assisted by bush clearing over the greater part of the lake area. The fines of the soils seem also to have been redistributed and were deposited in regions of low relief. With the subsequent rise in lake level the bottom conditions did not undergo any further drastic changes; rather the situation stabilized. The spreading of termite mound sediments together with the fine sands heralded the first stage of the establishment of a genuine lacustrine regime. Furthermore, because of the drawdown and rapid plant colonization it would appear that an annual cycle will come into operation. The plant cover will be destroyed each year but will provide nutrients for benthonic organisms, which will

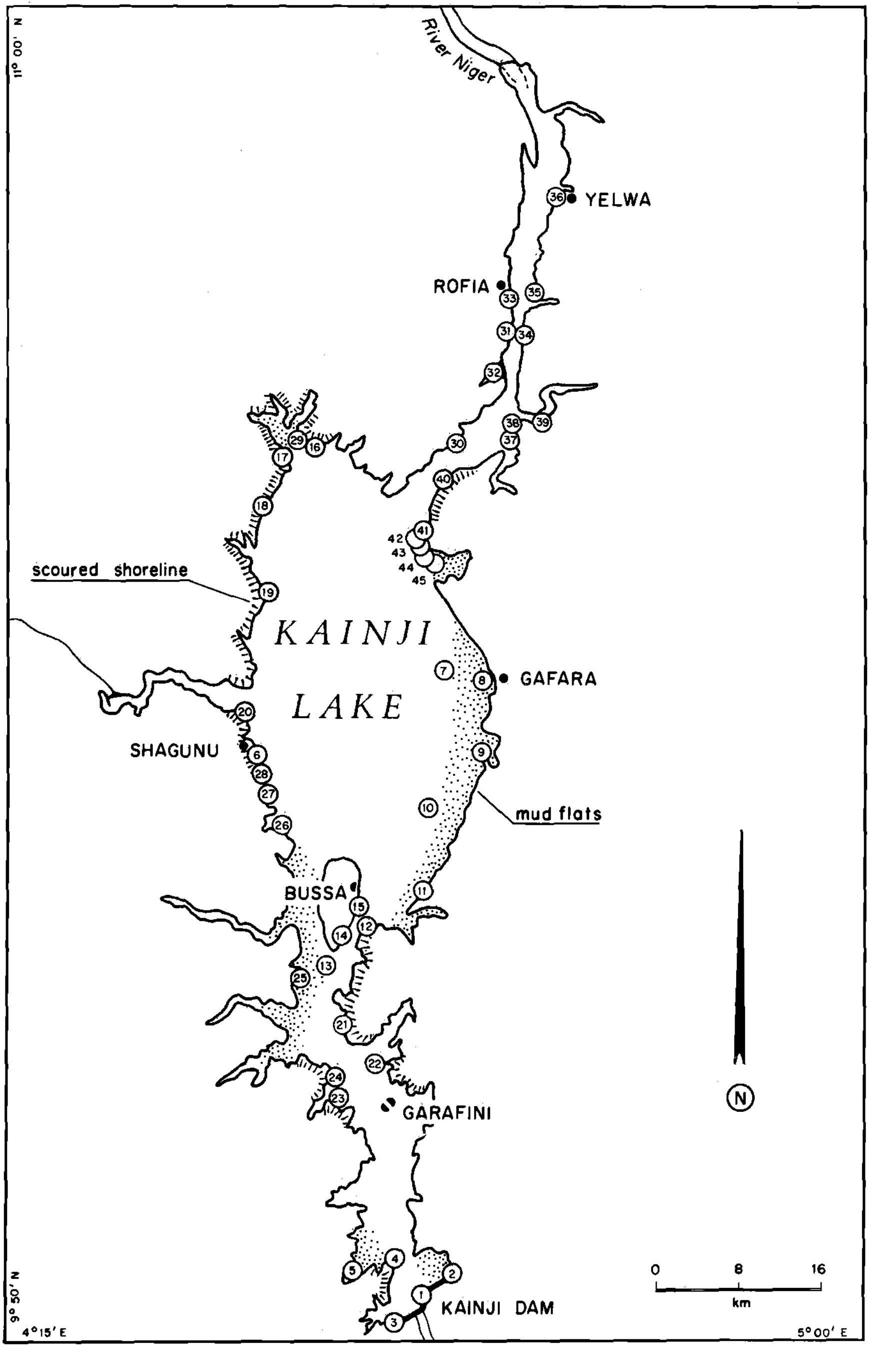


Fig. 1. Map of Kainji Lake showing the localities studied. Hachures indicate erosion, and stippling indicates deposition.

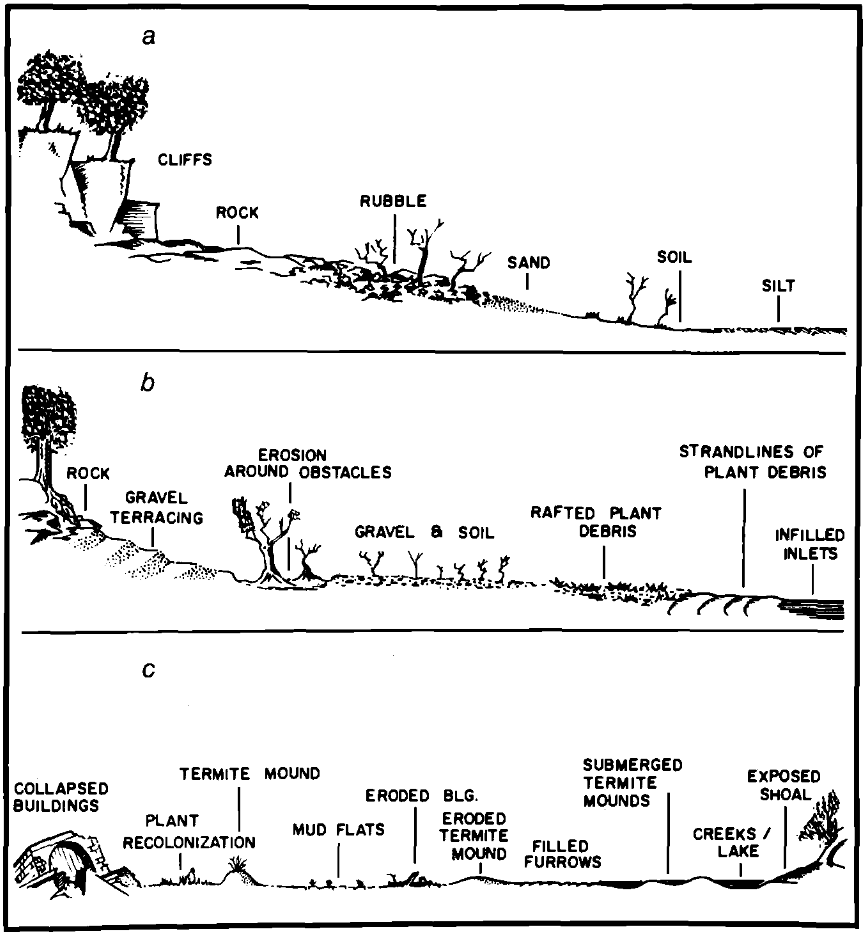


Fig. 2. Schematic shore profiles of Kainji Lake: (*a*) rocky coast, high relief, (*b*) gravel shore, medium relief, and (*c*) alluvial flats, low relief.

flourish. The productivity of the lake in these alluvial areas is likely to be maintained. The large influx of people between the two surveys would seem to suggest that this view is shared by the inhabitants of the region.

Only subsequent annual surveys, already planned up to 1974, will determine the exact way in which the lacustrine ecosystem finally stabilizes.

LAKE KARIBA IN 1969

Six months after Lake Kariba achieved its full storage capacity, G. Bond (unpublished report, 1965) surveyed the southern coast. Essentially, his observations recorded the amount of erosion that had taken place. Because the lake level was lowered by control at the dam from 480 to 472 meters OD, he was able to determine the amount of erosion by using the wave-cut platform as a datum line. He noted a few areas of low relief that had no evidence of erosion. Because the geologic formations have a regional dip to the southeast, the steep scarp slopes are on the southern shores, and the shelving dip slopes are on the northern shores. In consequence, erosional features can be expected to dominate the southern shores.

G. Bond (unpublished report, 1965) recorded cliffs 5–7 meters high and stony beaches with little rounding of pebbles, but he recorded no depositional features. During 1969 I traveled with Bond on the research vessel *Erica* from

Kariba itself along the southern shore to the research station at Sinamwenda. I disembarked at eight localities (Figure 3).

At Sinamwenda (Figure 3, location 1) the drowned valley of the river and its tributaries supports an extensive growth of *Salvinia*, the so-called Kariba weed. A small amount may become stranded on the beaches, but, since the inlets are sheltered, there is little evidence of either erosion or deposition. On the shores directly exposed to the main body of the lake, small cliffs are developed. These continue to location 2, where a fishing settlement is established on a flat shelving shore. On the lakeward side, strandlines of accumulated plant debris are present. Some of the plant debris is derived from the grasses that colonize the exposed flats (and support a game population), but most of it consists of rafted *Salvinia* mats. *Salvinia* flourishes in quiet waters, but mats are drifted into the lake, where they die and eventually are driven onto the shores. To the lee of the promontory of location 2, which is in another drowned river valley, there is a thick (up to 50 cm) deposit of rafted *Salvinia*.

The coastlines of low relief are regions of deposition of sediment derived from the destruction of the more adjacent areas of greater relief. This point is demonstrated by the situation at location 3, where a cliff some 20 meters high has developed. This headland faces the maximum extent of the lake, and storm waves with some 100 km of fetch break here with considerable violence. To the lee of this cliff, there is little sign of erosion; in fact, fine sands derived from the cliff are being deposited along this shoreline and can be observed clearly because of their bright red color, which displays a well-defined front.

The sheltered embayment (location 4) into which no streams drain showed no evidence of either erosion or deposition, nor did the lee of Namenbere Island with its shallows and shelving beaches (location 5).

Although the eastern limit of this island (location 6) seems to be sheltered, it is subject to

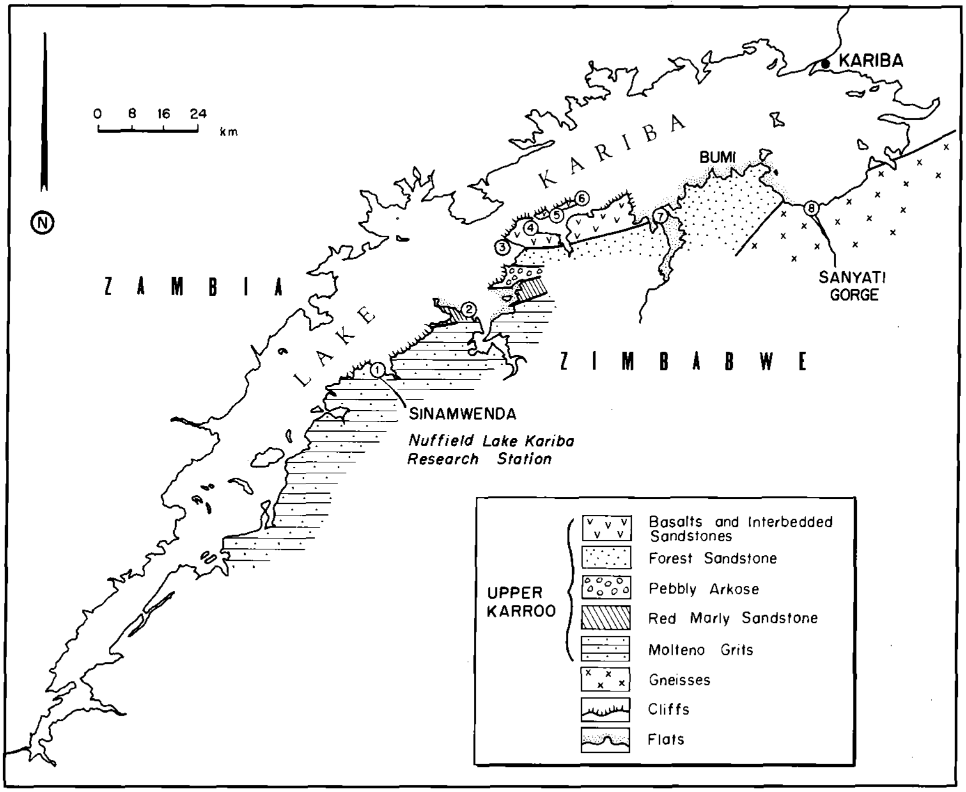


Fig. 3. Map of Lake Kariba showing the localities studied. Hachures indicate erosion, and stippling indicates deposition.

storms from the northwest. Small cliffs are developed with beach deposits of rounded pebbles and sands. These show the same type of terracing as that recorded at Kainji Lake. The drowned inlet north of Bumi (location 7), together with the flatland to the northeast, was difficult to enter but seemed to be comparable to the situation at location 2. Finally, the steep-sided gorge of the Sanyati River (location 8) also gave no evidence of erosion, the steep sides precluding any deposition at the margins.

In addition to the eight localities examined, note was taken of the parts of the shoreline along which cliffs were developed (Figure 3). The exposed headlands show the maximum degree of erosion and gradually taper off to about 2 meters. Although it is reasonable to infer that the shoreline features at Lake Kariba are now stabilized, it is evident that erosion and redistribution of the derived sediments continue. Apart from rafted *Salvinia* mats, there is no major deposition taking place.

CONCLUSION

The two surveys of Kainji Lake and the visit to Lake Kariba enable the evolution of shoreline features to be predicted with some confidence, at least in general outline. The first stage is related to the drowning and destruction of the old environment. The nature of this destruction is dependent on the speed at which the reservoir fills. The plant material and soils in the central parts of the basin are likely merely to be submerged. The distribution of nutrients derived from the breakdown of plant material will depend on the degree and type of stratification that develops. Once the lake has achieved its full capacity, wave action will lead to the removal and redistribution of soils and sediments. Erosion of shores of medium and high relief and the formation of cliffs and the concomitant formation of wave-cut platforms will present the most dramatic evidence of the evolution of shoreline features. The eroded materials will accumulate in embayments, and spits will form (Figure 3, location 2; Figure 1, location 9). Flat shelving shores will also be regions of deposition, and the material deposited on them is likely to be reworked local sediments.

Once the soils and plants have been destroyed, the shoreline will stabilize into major regions of deposition and erosion. With drawdowns the flats will quickly become colonized by terrestrial plants, which will be killed by subsequent rises in water level. This state of affairs is likely to encourage detritus-feeding fishes and provide the basis of a fishing industry. Unless the vegetation is cleared prior to flooding, these more productive regions of the lake will be difficult to enter. This situation exists between locations 2 and 3 and locations 7 and 8 at Lake Kariba and between locations 24 and 26 at Kainji Lake, where there had been no appreciable bush clearance. Dead trees and shrubs effectively prevent access to the shore, even in the smallest of boats.

The shallow lake shores have the greatest potential for fisheries and recreation; the cliffs provide ideal exposures for geologists.

Acknowledgments. I am greatly indebted to my friend, Dr. Tony Imevbore (Ife), for his help and encouragement in this work and for the provision of facilities for the Kainji surveys. Thanks are also due to Professor Geoff Bond and Professor T. G. Miller (Salisbury) for their kind hospitality during my visit to Kariba.

REFERENCES

Halstead, L. B., The shore-line of Lake Kainji, A preliminary survey, *J. Mining Geol., 6*, 3–22, 1971*a*.

Halstead, L. B., Freshwater bivalves on the shores of Lake Kainji, *Nigerian Field, 36*, 135–139, 1971*b*.

Plants for Shoreline Erosion Control in Southern Areas of the United States

W. C. YOUNG

USDA Soil Conservation Service, Fort Worth, Texas 76110

Two problems have triggered Soil Conservation Service studies of plants that grow 'across the waterline.' One problem is the wave action damage on man-made lakes, especially the damage to earth-fill dams, and the other is stream channel damage, particularly in excavated channels in connection with small watershed projects.

This paper deals with searching for and testing plants that will do a better job of protecting the medium-size earth-fill dams typical of Public Law 566 [*U.S. Congress*, 1954] watershed projects. The water side of 'larger' earth-fill dams is usually faced with riprap or some other wave-damage-resistant material. Farm ponds usually require no more than the establishment of grasses and legumes adapted to the site in which they are built. Our problem is dams between these extremes.

In a natural ecological situation where the slope is gradual, we find plants rooted in the water, plants across the waterline, and plants above the waterline. Our previous work centered on plants for use above the waterline, and on the whole this has been quite successful. Now we are working on plants to use across the waterline and are beginning to study in the water types. We recognize that we will still have a problem in securing plants for locations where water levels fluctuate between wide extremes and sometimes for considerable durations.

The problem is one not only of size of impoundment but also of geographic location, general topography, direction of the prevailing storm track, length of wind movement across the water, and engineering of the structure itself. These and other factors determine whether a particular earth-fill structure must be protected by riprap or beach berm or whether it can be protected by vegetation alone or in combination with a berm.

Another factor appears to be policy. Woody plants have not been permitted, even in areas where they are adapted and could probably do the job. Why they have not been permitted is not clear.

We hope to find that many moderate-sized dams can be protected by adapted plant material. If effective plants can be found, perhaps many dams that now must be riprapped can be treated with the much more economic vegetative measures.

Public Law 566 [*U.S. Congress*, 1954] floodwater-retarding dams vary greatly in release rates, which are determined chiefly by flood-routing needs. So a situation can arise in which plants above the permanent pool waterline are covered with water for days at a time after a period of heavy rainfall. On the other hand, in the drier parts of the country, water levels may recede and may remain much below the designed permanent pool level for long periods. This drought condition might adversely affect the waterline vegetation on the dam. It would also leave considerable areas of the dam face unprotected as the waterline lowered.

This sort of situation could occur as a result of evaporation or by drawdown of the water for uses such as irrigation.

The wave action problem occurs primarily in the drier sections of the country that have low or relatively even relief. Wave action damage can occur almost anywhere, but, in the East, tree growth helps break up low-level wind velocities, even in low-relief topography.

The dam problem and the channel problem have one thing in common. If protection is to be by vegetative means, the plant must withstand intermittent inundation and drought stress. The more the plants can withstand, the better. The plant will also need to be heavily rooted to be able to take a beating and still give the desired protection.

EVALUATION TESTS

The Soil Conservation Service began an evaluation program at its Coffeeville, Mississippi, Plant Materials Center about 7 years ago to test plants that will grow across the waterline. We began with herbaceous plants. We made a modest collection of about 15 species that were known or thought to be known to grow across the waterline. A series of plots was designed so that rows approximately 10 meters long with a constant grade were in water 15.24 cm deep at one end and were 15.24 cm out of the water at the other. Each of the species was planted for the full length of a row. All the plantings were made by vegetative transplants and were watered sufficiently on the dry end to initiate new growth. Water was kept on the wet end constantly for a period of 3 years [*Ahlrich*, 1965, 1966, 1967].

The materials selected showed sharp contrasts. Giant cut-grass (*Zizanopsis milliacea* (Michx.) Doel & Aschers) grew exceedingly well in the water but stopped almost exactly at the waterline. So did some others. Maiden cane (*Panicum hemitomon* Schult.) [*Hitchcock*, 1950] was outstanding in its response. It grew well in the water and out. The plant height was greatest at the deepest end of the row and shortest at the driest end, but the plant maintained a solid row and proliferated outward from it for the entire length.

One rush and one sedge, both unidentified but indigenous, gave similar results except that their outward proliferation (spreading) was very slow. Although they are prodigious seeders, we have been unable so far to germinate the seed.

Another plant, *Echinochloa holubii* (Stapf) Stapf (no common name), an introduction (PI-207924) from South Africa, performed about as well as the rush and sedge, and it did produce seed that we could germinate. But it turned out to be only marginally hardy at the Mississippi location.

The herbaceous plant that has up to now shown the greatest promise for holding down wave action damage across the waterline under the widest variety of site and soil conditions and over the widest geographic area is maiden cane (Figure 1). So most of the rest of this paper will describe our findings on this plant.

NATURAL DISTRIBUTION OF MAIDEN CANE

Maiden cane is a native grass occurring in freshwater marshes and on wetlands from the New Jersey coast southward coastally to Florida and around the gulf coast into Texas. In Louisiana it is known as 'paille fine,' pronounced 'pie fēēn.' It also occurs in Brazil. In the United States it reaches inland on the lower Coastal Plains of the Atlantic seaboard for considerable distances, colonies occurring with regularity up to 161 km inland. It occurs generally across the Florida peninsula. Inland colonies in Alabama, Mississippi, eastern Louisiana, and southwest Georgia become more scattered. West of the Mississippi River they reach northward again with regularity up to around Alexandria, Louisiana, and for considerable distances up the tributaries of the Sabine and Trinity rivers into Texas.

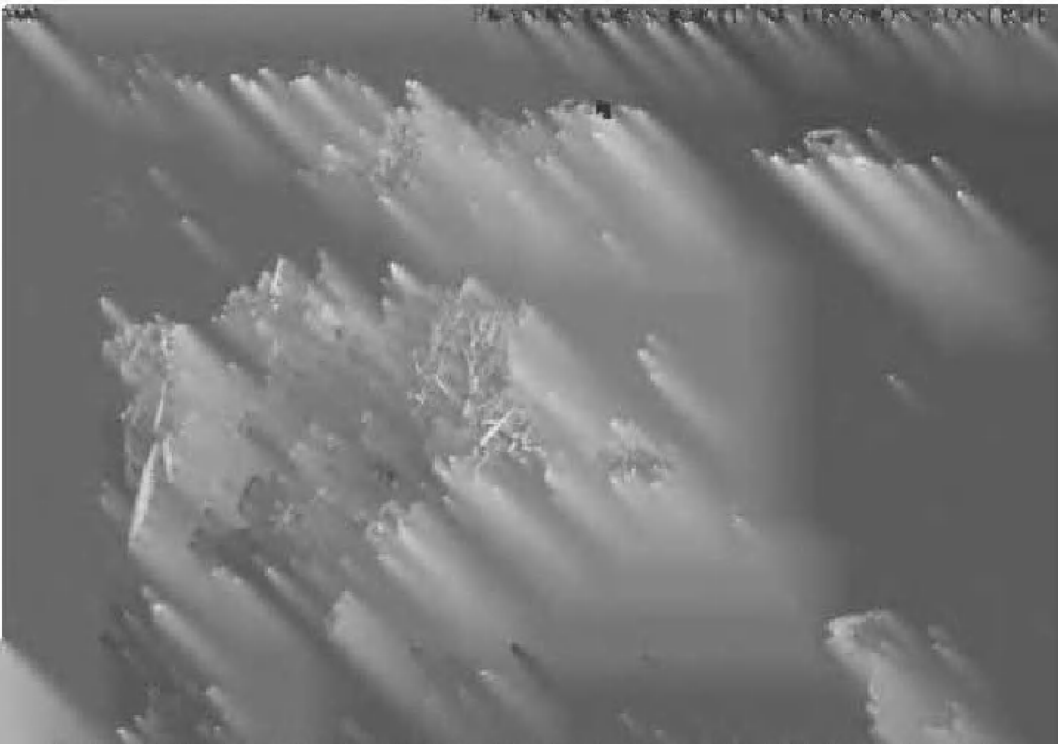
I have seen significant colonies of maiden cane isolated from the general distribution. We expect to get the best material for our particular needs from inland and more northerly colonies, since many of the places where we would like to use the grass are inland, westward, and northward of its general natural distribution pattern. It is an important range grass, and heavy grazing has certainly played a part in restricting its distribution [*Yarlett*, 1965].

The natural confinement of maiden cane to wet sites makes it appear that water is an obvious factor in limiting its distribution. The extent to which cold limits it is still undetermined.

Morphologically, the grass is a rhizomatous perennial, deciduous with frost. Seed stalks and apparently sound seed are produced sparingly and sporadically, sometimes in spring, sometimes in fall, and occasionally in both spring and fall. Their production appears to be a response to day length, not to temperature. Seed collected from natural stands have never been sprouted in Soil Conservation Service plant materials centers by using normal grass-seeding methods, even when they were planted on wetlands where natural stands had occurred previously. The subject of seed production and germination needs further study, since direct seeding would be cheaper than vegetative transplanting.

TESTS AT SOIL CONSERVATION SERVICE CENTERS

The first material that we obtained was from Nassau County, Florida. In addition to the rows



[illegible]

[illegible]

uniformly treated plots on a wet site but were not subjected to flooding. In the 3 years that they have been observed, some characteristics have contrasted greatly. An example is the variation in mature height, which ranged from 30 to 120 cm. There are differences in stem size, stems–unit of area, rhizome length, foliage abundance, and other things. This information has not yet been summarized, nor have we determined all the qualities that we need. It is significant, though, that the species contains the variability that should provide a plant made to order for any job.

A much wider assembly of maiden cane has been undertaken at the Brooksville, Florida, Plant Materials Center. Over 100 accessions were assembled during 1970 for a better view of the variations that occur in the species. Thus it should be possible to select with more confidence the variants most suited to the need.

In the meantime we chose our most northern accession and increased it for trial purposes directly on the sites concerned. We had already gained a little experience in the direct application phase in North Carolina by using local materials and transplanting them to the test sites. Most of this work was done along stream channels and on the spoil banks. Although it was important in providing leads to potentiality and feasibility, it did not have the control that we can give such a trial in a center or with purposefully grown material. We did find that transplanting was easy; maiden cane would grow on a variety of sites, such as those at the base of the stream channel, on the stream bank itself, and even on top of excavated channel spoil.

Asexual production of material is no problem. The area established for rhizome production has proved to be capable of the production of nearly 1¼ million rhizomal pieces per hectare per year (B. B. Billingsley, oral communication, 1970). At this rate the production from a hectare would plant 34 to 45 km of row.

Tests to determine the time of planting indicate that any month of the year seems adequate. After 2 years of testing, in which material was dug and planted once each month, adequate stands were secured each period in the first year of tests. However, stand failures occurred in the January and February plantings of the second year (1970), probably in part because of the damage noted in the production field referred to earlier. The only caution to be observed in planting on local sites concerns winter dormancy. If there will be severe washing or wave action on the site through the winter, the planting pieces may be washed away before growth is resumed in the spring. On the whole, spring and summer plantings seem to be more in order if they are made in time for the plants to become well anchored.

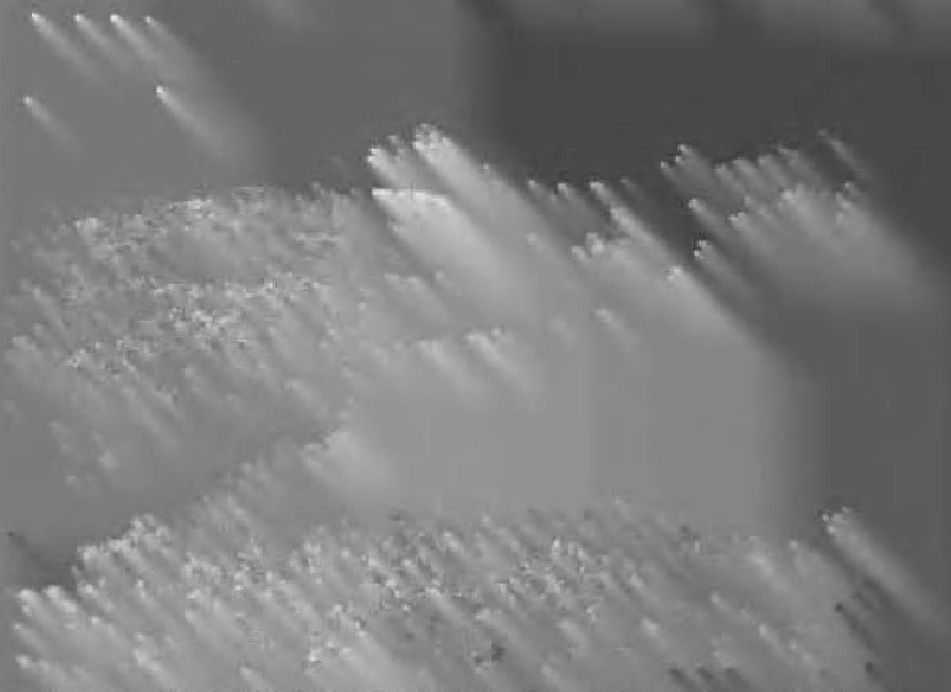
Maiden cane plot plantings of more than a 3-year duration have been observed on dams in North Carolina. They rank high in wave action control in comparison with switch grass (*Panicum virgatum* L.), Bermuda grass (*Cynodon dactylon* (L.) Pers.) weeping love grass (*Eragrostis curvula* (Schrad.) Nees), sericea lespedeza (*Lespedeza cuneata* (Dumont) G. Don), and other combinations of plants, primarily because maiden cane can actually grow in water. The other materials will withstand considerable inundation but do not grow in water.

More experience has accrued from stream channel plantings than from plantings on dams, but the methods, timing, fertilizing, and handling of the materials and the protection secured are similar.

For example, adequate maiden cane stands were secured in a stream channel in Mississippi in 1970 by planting rhizome pieces at the rate of 9 to 12 pieces per meter in July. The growth was good, and the stand will probably expand rapidly with fertilization. In a 4-year-old stream channel planting the plants have stopped the erosion at the base of the bank and are actually collecting sediment and stabilizing the bank by growing upward. Thus we know that the plant will withstand a considerable degree of high-velocity scouring action and will still hold. This channel is approximately 3 meters deep and about 6 meters across at the bottom. It has run bank-full each year since the maiden cane was planted. During the second year of this test, annual plants, among which barnyard grass (*Echinochloa crusgalli* (L.) Beauv.) was the most prominent, were sown at the base of the bank and were fertilized in untreated parts of the same channel. They provided about the same amount of vegetative cover by the end of the growing season as the maiden cane did but were swept out completely by late winter and early spring high-water flows.

Plantings of maiden cane were made in 1970 along the planned waterline across the faces of dams in several states from North Carolina westward to eastern Oklahoma and Texas. If the experience with the plots holds up, these should do well.

[illegible]



[illegible]

woody plants are under study. We are looking at native and introduced willows, several species of alder, and other woody plants.

Fertility plays a key role in establishment on disturbed or eroded sites in aquatic situations as it does in terrestrial situations. When a dam is built, the soil material is almost always nearly devoid of some necessary plant nutrient. Therefore fertilizers are usually used in establishing vegetation on the dam. This need for fertilizer, particularly nitrogen, accounts in part for the success achieved with certain legumes and with the invasion of plants like hazel alder, since they are both symbiotic (nitrogen fixers).

In trials with plants below the waterline, doubts were held as to whether they could be fertilized economically. As a test a pelleted form of ammonium nitrate was used for planting maiden cane on a dam in about 30 cm of water. The pellets settled to the root zone readily, and the response was about the same as would be expected in terrestrial plot work. The number of stems per unit of area about doubled, and the height of the culms increased. But more important the rate of spreading of the plot laterally along the face of the dam was nearly double that of the unfertilized condition.

SUMMARY

The establishment and management of upland herbaceous materials for earth-fill dams has for the most part been worked out, but wave action damage produces a need for something more resistant to this action. Maiden cane is a good plant to grow across the waterline, since it will grow actively in 30 cm or more of water. In the humid section of the South it grows adequately on upland soil as much as 2.4 to 3 meters above the waterline. It is doing a good job of stabilizing earth-fill dams in areas where it occurs naturally. The Soil Conservation Service has grown it for 8 years north and west of its natural range with good results, but tests are under way to assess its limits.

Vegetative protection to earth-fill dams may require a further combination of plants including a beach berm on which in the water types, across the waterline types, and then above the waterline types could be established. Woody plants may be needed also. Parts of all these problems are under observation and study, both on Soil Conservation Service plant materials centers and on sites in the field, but much remains to be learned.

REFERENCES

Ahlrich, V. E., Annual report of the Coffeeville Plant Materials Center for 1965, Coffeeville, Miss., U.S. Dep. of Agr., Soil Conserv. Serv., State Office, Jackson, Miss., 1965.

Ahlrich, V. E., Annual report of the Coffeeville Plant Materials Center for 1966, Coffeeville, Miss., U.S. Dep. of Agr., Soil Conserv. Serv., State Office, Jackson, Miss., 1966.

Ahlrich, V. E., Annual report of the Coffeeville Plant Materials Center for 1967, Coffeeville, Miss., U.S. Dep. of Agr., Soil Conserv. Serv., State Office, Jackson, Miss., 1967.

Daubenmire, R. F., *Plants and Environment, A Textbook of Plant Autecology,* 2nd ed., John Wiley, New York, 1959.

Gamble, M. D., and E. D. Rhoades, Effects of shoreline fluctuation on grasses associated with upstream flood prevention and watershed protection, *Agron. J., 56*(1), 1964.

Hitchcock, A. S., Manual of the grasses of the United States, *U.S. Dep. Agr. Misc. Publ., 200,* 1950.

Klingebiel, A. A., and P. H. Montgomery, Land capability classification, *U.S. Dep. Agr. Handb., 210,* 1961.

O'Neal, T., The muskrat in the Louisiana coastal marshes, Fed. Aid Sect., Fish and Game Div., La. Dep. of Wildlife and Fish., New Orleans, 1949.

U.S. Congress, Watershed Protection and Flood Prevention Act, *Public Law 566,* 83rd Congress, 2nd Session, Aug. 4, 1954.

Yarlett, L. L., Important native grasses for range conservation in Florida, U.S. Dep. of Agr., Soil Conserv. Serv., Gainesville, Fla., 1965.

Lake Burley Griffin, Australia

A. E. MINTY

National Capital Development Commission, Canberra, Australia

When the Australian government launched an international competition in 1911 for the design of its national capital, Canberra, it envisaged a man-made ornamental lake within the city. As it happened, a lake became the central feature of the winning design by the Chicago architect, Walter Burley Griffin. He planned to dam the Molonglo River, which flowed through the Canberra site, and to form three formal water basins that would bound and reflect the main government buildings on three sides. Flanking these central pools would be two informal lakes. Griffin's city was largely a landscape composition in which buildings would be subordinate to the surrounding hills and mountains and the whole would be bound together by the lake.

The development of Canberra began in 1913, but another 47 years elapsed before the construction of Lake Burley Griffin began, and it was 50 years after the foundation of the city when it was completed.

The lake in relation to the urban area is shown in Figure 1. It is 11 km long, its average width is 800 meters, and its capacity is 28 million m^3. The surface area is 720 ha, the average depth is 4.0 meters, the distance around the periphery is 34 km, and its normal level is 556.3 meters.

The lake was one of the first projects undertaken by the National Capital Development Commission, a comprehensive urban planning and development authority established by the Australian government in 1957 to plan and develop Canberra as the national capital. For 44 years the city had been growing around the lake site. In some parts of the central area, development was separated by open spaces up to 1600 meters wide that had been reserved for inundation. The lake reserves themselves were unsuitable for building sites. They comprised the Molonglo River and its broad floodplain, which was subject to severe flooding from a catchment area of over 1810 km^2. Visitors to the national capital were often surprised to see lucerne being harvested in the heart of the city on the river flats in front of Parliament House, and Canberra was often described as several suburbs in search of a city or as two towns separated by the Molonglo. The commission built the lake to stabilize water levels in the central area, to complete the main landscape framework for the major buildings of the capital (few of which had been built), to integrate the apparently scattered city, and to provide attractive and valuable recreation and parklands in the center of a capital that had been conceived as a garden city.

In addition to straightforward engineering considerations the lake design had to take a number of other factors into account. Fears were expressed in Canberra that the lake might upset the ecological balance of the area, disturb the meteorological pattern by increasing fogs, create a breeding ground for mosquitoes in the center of the city, lead to a rise in groundwater levels, detract from the 'natural' landscape of the Molonglo River, become polluted in various ways, and cause nuisances, such as undue noise from the operation of speedboats. Moreover, because Canberra was the national capital and a widely admired 'planned garden city' and because the lake was its central feature, a high standard of finish was demanded. The commission was determined to provide it, and the design and construction of Lake Burley Griffin was its earliest major venture in multidisciplinary urban design. It involved engineers, architects, town planners, landscape architects, ecologists, biologists, and economists.

REGIONAL SETTING

The lake is in the valley of the Molonglo River and has a catchment upstream of 1810 km^2 divided into three principal subcatchments: the

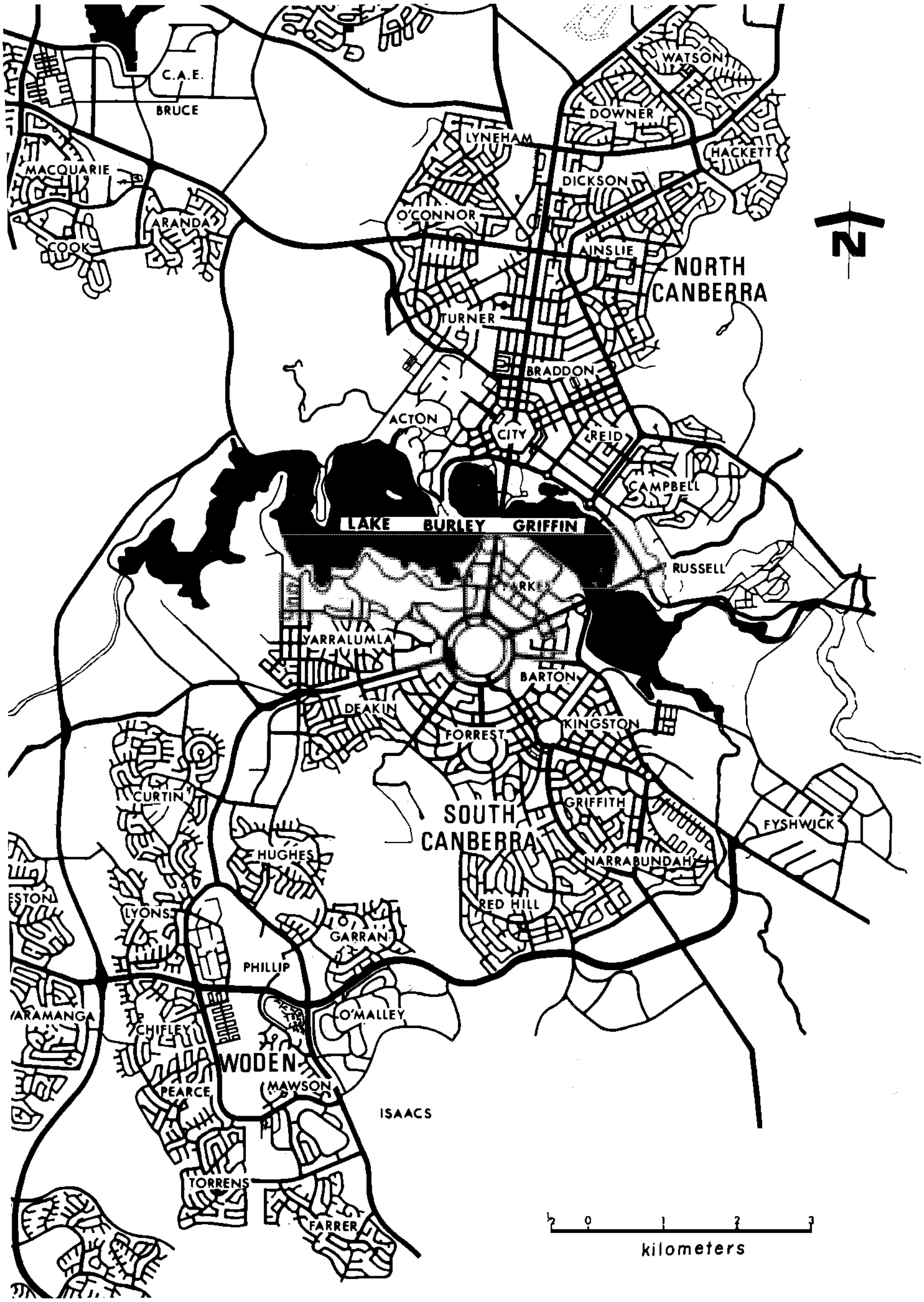


Fig. 1. Lake Burley Griffin in relation to Canberra.

Queanbeyan River, 970 km²; the Molonglo River, 570 km²; and Jerrabomberra Creek, 130 km². About half the catchment is undulating country used for grazing and agricultural purposes, the average elevation being 610–760 meters. The other half of the catchment is dry schlerophyll country rising to 1610 meters.

FLOOD PREDICTIONS AND FREQUENCIES

The 1810-km² catchment area has a rainfall that varies between 686 mm in the Canberra area and 1143 mm in the more mountainous areas rising to 1520 meters. A number of significant floods have occurred over the years. The highest actually gaged was 960 m³/sec, but an earlier flood was assessed at 3400 m³/sec, although it was not actually gaged.

After the relation between discharge and return frequency was assessed, the design standard chosen for the lake was 5660 m³/sec with a recurrence interval of 200 years. Major structures were examined to ensure that catastrophic damage would not take place under 8500 m³/sec.

Discharges of 850 m³/sec have already been handled through the dam by progressively opening and closing a series of gates. There has been virtually no variation in top water level in the parliamentary areas. Discharges up to 2270 m³/sec can also be handled without any serious change of level in the parliamentary areas. Above 2830 m³/sec some walls in the parliamentary areas would be overtopped, and under the design flood with a recurrence interval of 200 years a rise of 4 meters is predicted in the parliamentary areas. Development in the possible areas of inundation has been designed to allow flooding without damage.

SEDIMENTATION

With a catchment area of 1810 km² and a storage capacity of only 28 million m³, sedimentation of the lake has always been regarded as the most serious problem.

Much work has been done on assessing the net rate of accumulation of sediments in the lake. Detailed investigations were made of the soil conservation work necessary on both pastures and stream banks. Arrangements were made between the commonwealth authorities of the national capital and the state authorities of New South Wales for the implementation of a program valued at Aust$600,000. Another program valued at Aust$300,000 has now been completed within the commonwealth areas.

Immediately upstream of the lake is a wide flat floodplain. Serious consideration was given to using this floodplain to encourage the deposition of sediments using a porous rock-fill weir to build up floodwaters, the sediments being dropped by the lowering of velocities. The first estimate of trap efficiency was 72%. However, this proposal is considered unnecessary.

On the basis of sediment-rating curves of up to 280 m³/sec the early estimates were 200,000 m³/yr of suspended sediments plus about 45,000 m³ of bed load. Thus 250,000 m³/yr of sediment is entering the lake, which has a storage capacity of only 28 million m³.

Before the lake was filled, a number of cross sections were flattened and carefully surveyed across the bed of the lake to allow measurement of the change in bed level over the years. To date, little change has been recorded except in the immediate vicinity of the dam, where levels have increased by about 0.6 meter in 20 meters.

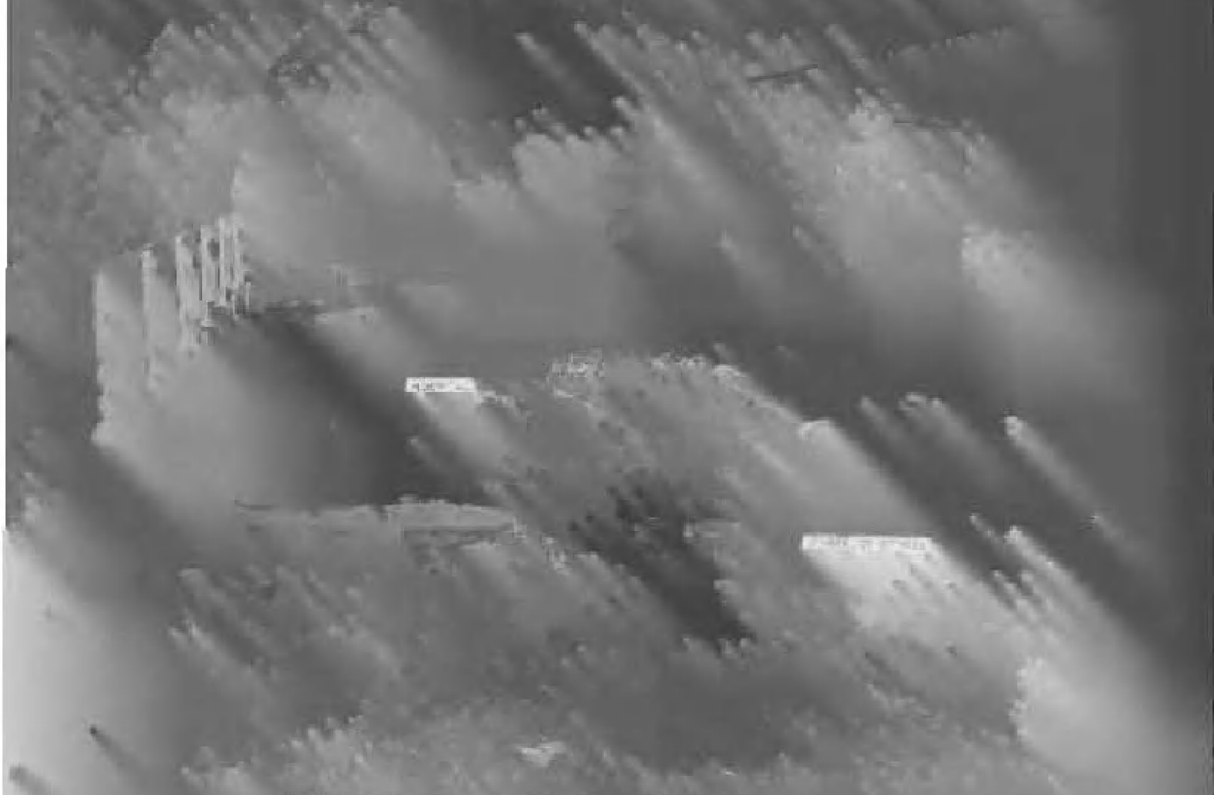
In 1966 it was possible to take advantage of a discharge of 560 m³/sec to measure the effect of incoming sediments. On this occasion the cross sections above were used together with tube samplers inserted into the bed of the lake to produce a record of the soil horizons. Both systems correlated reasonably well and indicated an annual average inflow of about 160,000 m³/yr.

Bed load traps have been provided at the two main entry points to the lake. Since the city uses 150,000–200,000 metric tons of sand and gravel per year, these traps are valuable on two counts and should eliminate most of the bed load.

The five large flap gates on the dam represent a high proportion of most flood cross sections. All these gates are lowered for discharges above 2270 m³/sec. Hence the trap efficiency for the lake is expected to be reasonably low for high discharges. A long-term average of 50% could mean a net accumulation of 80,000 m³/yr. In contrast to expectations the accumulating sediments are being transported down to the dam and are not building up at the sudden enlargement represented by the upstream end of the lake. Another city water supply dam will probably be built 32 km upstream of the lake on the largest tributary.

For all these reasons the original sedimentation problem seems to have been reduced to acceptable proportions.

[illegible]



[illegible]

Commission engaged the Snowy Mountains Authority. Their studies showed that, besides the normal mechanical movement of small particles in the water, another flocculation process was occurring. Dr. C. J. Shepherd of the Commonwealth Scientific and Industrial Research Organisation, who was engaged to study the process, confirmed the presence of bacteria that produced polysaccharide gums and agreed that the spontaneous flocculation of colloids was possibly due to these gums.

METEOROLOGY

Fogs. In the investigation stages the assessment was made that the incidence of fogs would increase only within about a few hundred meters of the lake edge. Studies, which are still continuing, have demonstrated so far that the incidence of fogs at the nearby airport has not increased since the creation of the lake.

Droughts and evaporation. In the early investigations it was calculated that, if the Canberra lake had been in place over the most unfavorable recorded period, the top water level would have dropped a maximum of 1020 mm. During the very serious drought between 1965 and 1968 the lake dropped a maximum of 460 mm.

POLLUTION

Sixty-one river kilometers upstream of Canberra at Captains Flat in the state of New South Wales, there was a copper-lead-zinc mine, which was closed in 1962 just before the lake was filled. In 1943 a slime dump at the mine collapsed, and the estimated 30,000 m^3 of tailings (siliceous gangue, pyrite, galena, chalcopyrite, and sphalerite) that was washed downstream sterilized river flats. Pollution of the Molonglo River was reduced when the mine closed but still persists because of emerging groundwater and leaching from old dumps.

The variation of zinc concentrations has been studied. On the lake bottom, zinc precipitates vary between 1000 and 2000 ppm, a normal concentration being 50 ppm. Several hundred metric tons have accumulated in the lake since it was filled. Although the effects are still being studied, they are as yet unpredictable. The accumulations might eventually become toxic to fish and affect plant life on the lake bed and thus turbidity. Typical lake water quality data are shown in the appendix.

Biological pollution in the lake is comparatively insignificant. In the swimming season, *E. coli* counts of >5 per 100 ml are rarely recorded at any of the eight testing points and are always associated with heavy rainfall. Other parameters, such as total coliform and *F. streps*, give similarly low results.

BIOLOGY

The ecology and biology of the lake were the subject of several studies. In the early stages of development a detailed ecological survey was made to identify possible problems and provide a basis for comparison after the lake was filled.

The fishing potential of the lake, particularly in relation to metallic pollution, was one of the important early detailed studies. The studies completed have included detailed laboratory and field tests of zinc toxicity levels for brown and rainbow trout, catfish, crucian carp, and macroinvertebrate fauna. The need for fish ladders was reviewed but rejected. More than 100,000 yearling trout have already been released in the lake, and a continuous monitoring program has shown that after 1 year they are of a legally catchable size and weigh 400–500 grams. For each of the next 2 years they add 450 grams, but then their growth slows down a little.

The possibility that the lake would prove to be a breeding ground for mosquitoes was a matter for public concern before the lake was constructed. Scientific advice at the time suggested that there would be little cause for concern, and the fears were never realized. To minimize aquatic weed growth, the lake edges were designed to slope sharply to a 2.13-meter depth without structural support, and, since there are no shallow areas of still water without fish, the breeding of mosquitoes has been prevented.

The depth of the lake has also controlled the excessive growth of aquatic weeds fairly effectively. In the shallower areas around the edges the main problem species of submerged weeds continues to be curly pondweed (*Potamogeton crispus*), but floating pondweed (*Potamogeton tricarinatus*), ribbon weed (*Vallisneria* sp.), and *Egeria densa* are spreading slowly in various parts of the lake. The growth of these weeds has been controlled mainly by the use of aqualin, although herbicides such as diquat, paraquat, casoron, and fenac have also been tried and others will be tested in the future. Aerial photography has been used for maintaining surveys of the extent of aquatic regrowth, but the turbidity of the water limits its accuracy.

GROUNDWATER

The possible effects of the lake on groundwater were the subject of a study by the Australian Bureau of Mineral Resources. Seven bores were sunk in the lake area, and seasonal fluctuations in them were measured against a remote control bore that had been sunk several years before. The results led to the treating of several low areas with drainage blankets and backfill and the provision of an additional pump in one large building near the lake.

LANDSCAPING

The London-based architectural and town-planning firm of William Holford and Partners was responsible for the general landscape design of the lake environment. The landscape can be described only briefly here.

The lake foreshores provide more than 280 ha of parklands with a wide range of recreation and park environments, including boat harbors, yacht bays, picnic areas, ferry terminals, gardens, wooded areas, scenic drives, open parkland, and grassed areas.

An important design principle was to preserve overall the natural lion-colored Canberra landscape with its preponderance of eucalypts. Within this broad general framework a wide variety of 'exotic' areas, including a 30-ha ornamental garden and areas planted with colorful shrubs and trees, was provided. More than 55,000 trees have been planted according to a carefully prepared scheme. A boat harbor and a series of ornamental ponds were built on marshy areas near the lake edge.

Six islands were constructed in the lake, and one of them accommodates a carillon of 53 bells in a slim three-column triangular tower 50 meters high. The largest bell weighs 6 metric tons. In the central basin a jet of water rises to a height of 140 meters.

ENGINEERING DESIGN

The dam creating this lake is a concrete gravity type with five 34-meter steel flap gates fitted to the crest by horizontal hinges at the bottom of the gates. Each gate is supported by four hydraulic cylinders, which swing the gate from the open position below the horizontal to the closed position nearing the vertical. This arrangement was chosen to give a neat structure devoid of cumbersome headgear. Two thirds of the lake volume is retained by the gates rather than by the concrete. A floating caisson was provided for gate maintenance.

The creation of a lake 11 km long through the heart of the city naturally calls for bridges. The position and capacity of these were decided after the normal citywide transportation studies. At this stage the bridge over the dam is supplemented by one six-lane bridge of 317-meter span and one four-lane bridge of 275-meter span, both in post-tensioned concrete.

The wide range of investigations identified a number of principles that should guide the design of formal, semiformal, and natural lake edges.

LAKE USE AND MANAGEMENT

The postlake decision to ban powerboats received general community approval. Sailing of centerboard yachts is the most popular activity. After a trial period the Health Department gave positive support for swimming in the lake. The high percent of calm days allows quite a number of rowing clubs to operate.

Most of the detailed investigations carried out in the formative stages are being continued for surveillance of water quality, sedimentation rates, and research, since they may be needed for efficient management.

COSTS

Cabinet approval to build the lake scheme was based on an expenditure on the lake itself of no more than Aust$5.0 million (1960–1963). Final accounting processes showed that the dam, plus the lake edges and everything else arising from the decision to build the lake, totaled an expenditure of Aust$5.10 million by the time the lake was filled in May 1964. The major bridges had to be built even if the lake was not built, since the very large floods that intermittently inundated the central areas had to be bridged. Similarly, the foreshore development, as distinct from the development of the lake edges, was not regarded as a charge against the cost of the lake.

PROBLEMS AND ENVIRONMENTAL EFFECTS

In review, many of the factors above are simply routine, albeit skilled, processes, for example, the return frequencies of different-sized floods. The effect of various discharges is also determined simply by hydraulic model.

On the other hand, prediction of the extent of suspended sediment and bed load that will enter the lake and prediction of the trap efficiency of the lake are still difficult processes in which to achieve accuracy with confidence. The means of measuring accumulation of sediments is also difficult in a shallow lake.

Turbidity built up by wind agitation prevents the photosynthetic stabilization of lake beds, which would lead to the reduction of turbidity. Biological flocculation as occurring in Lake Burley Griffin is helpful but as yet is not a process that can be created or greatly accelerated.

Biological pollution can be retained at levels acceptable for swimming despite waste water plants immediately upstream.

Experience with the cavernous limestone foundations of foreshore buildings showed the need to develop down the hole geophysical techniques in addition to the conventional techniques with both explosives and geophones on the surface.

Finally, the successful completion of a man-made lake like Lake Burley Griffin is due to the successful integration of engineers, architects, landscape architects, and scientists over a very wide range of disciplines and subdisciplines.

SUMMARY

The Canberra lake was built primarily as a means of stabilizing the water level in the central areas of the national capital and to provide a central landscape feature for the city. Previously, the national capital read as two different cities separated by an empty floodplain. Landscape and civic design continuity has now been provided to unify the city.

When the decision was made in 1959 to proceed with the lake scheme, there were many critics and opponents, but now that it is completed citizens and visitors express unanimous enthusiasm.

APPENDIX: LAKE WATER QUALITY DATA

*p*H	
Surface water	7.3–7.8
Bottom sediments	6.9–7.3
Dissolved solids	140–190 ppm
Suspended solids	2–10 ppm
Calcium hardness	30–50 ppm $CaCO_3$
Total hardness	60–100 ppm $CaCO_3$
Total alkalinity	40–60 ppm $CaCO_3$
Dissolved oxygen	
Surface water	7–9
Above bottom	3–8
Sulfate	15–25 mg/l
Phosphate	0.1–0.3 mg/l
Nitrate nitrogen	0.1–0.3 mg/l
Sodium	5–9 mg/l
Potassium	1.5–2.5 mg/l
Iron	0.4–1.0 mg/l
Silica	2.0–5.0 ppm
Zinc	
Ionic	0.1–1.0 ppm
Precipitates in bed	1000–2000 ppm
E. coli	arithmetic mean 4 parts/100 ml
Total coliform, *F. streps*	similar order to *E. coli*
Water temperature	
Surface	24°C summer maximum to 8°C winter minimum
Bottom	17°C summer maximum to 6°C winter minimum
Evaporation	0–48 points 'A' type pan
Turbidity	
Minimum	4 J. T. units
Normal calm conditions	8 J. T. units
Rough conditions	70 J. T. units

Effects of Man-Made Lakes on Ecosystems

JOHN E. BARDACH[1]
School of Natural Resources, University of Michigan, Ann Arbor, Michigan 48104

BERNARD DUSSART
Muséum d'Histoire Naturelle, Limnologie Tropicale, Paris, France

Man-made lakes range from the size of a pond to the size of an inland sea. More than 400 artificial lakes have been created in the world to date; they represent 300,000 km^2 of new aquatic ecosystems with a total volume of 4000 km^3. Forty or so of them have a surface area of over 1000 km^2, whereas others are much smaller and exert only a very local influence on the terrestrial ecosystems that surround them. The frequently nonlinear processes in the life histories of man-made lakes, from the first predevelopment surveys to the aging of the lakes themselves, strongly influence the dynamics of the ecosystems in which they are located. Since man-made lakes are built to serve man, he must be of uppermost concern in the consideration of how they alter the ecological dynamics of their environs and what off-site effects they might have. Large expenditures are involved in their construction, and effects on the ecosystem should therefore be expressed in economic terms whenever it is possible. The following examples are selected accordingly.

Ecosystem changes have, in the past, frequently been neglected in cost-benefit considerations. Many are appraised only belatedly, as perturbations that should have been calculated as costs become apparent. The lack of ecological input is not altogether surprising, since most man-made lakes have as their primary purpose the generation of power. Political considerations aside, a favorable cost-benefit ratio for power production alone usually justifies their construction. Engineers and economists are perhaps fortunate that dam building and the forecasting of power are more easily quantified than the population dynamics of an often rich and varied biota in and around the intended reservoir site and in those off-site locations that may be affected. Perusal of the proceedings of the 1968 Conservation Foundation sponsored Arlie House conference on the ecological aspects of international development [*Milton and Farvar,* 1972] suggests that postimpoundment activities such as permanent irrigation agriculture are more easily quantified than those over which there can as yet be little or no manipulative control, such as the changes from a lotic to a lentic biota. Thus changes in ecosystem components and processes easily fall into the category of unforeseen side effects, a category of events that frequently confront technological societies.

Space limitations restrict the present treatment to examples of large rivers or river systems with wide impacts. It should be noted that the unused hydroelectric potential of the world lies largely in the tropics [*Warren and Rubin,* 1968], where life processes often proceed faster than they do in the temperate zone and ecosystem changes become more quickly apparent, a contingency that has to be considered in planning. Tropical areas are also stressed here because means to cope with ecological perturbations are less well known in these regions than in the temperate zone. There is still a great shortage of expertise and knowledge in tropical ecology, though two recent symposiums on man-made lakes [*Lowe-McConnell,* 1966; *Obeng,* 1969*a*] contain valuable information on which this paper can in part draw.

Ecosystem changes due to man-made lakes can occur on or off site. On-site changes include the watershed above the dam, or a part thereof, a section of the river below the dam, and the area

---

[1] Now at Hawaii Institute of Marine Biology, University of Hawaii, Honolulu, Hawaii 96822.

surrounding the dam that can or will be irrigated as a result of the existence of the dam. They also include the translocations of people. Off-site changes affect conditions far below the dam, such as alteration of the salinity in the estuary of the river and changes in the sediments that the river carries into the sea. Within these two categories, further divisions can be made according to the ecosystem components that may be affected directly, such as climate, the terrestrial and aquatic biotas (especially as they relate directly to man), and man himself.

CLIMATE

Few man-made lakes have been in existence long enough for the collection of meteorological data that would permit valid judgments on whether such climatic changes as may have been observed near them are indeed attributable to their having been established. In addition, there is often a lack of valuable meteorological information from periods antedating the dams.

Data from the Lake of Geneva [*Blavoux et al.,* 1962], and from at least one station on the 776,994-ha Volta Lake [*De Heer Amissah,* 1969] suggest a lowering of the mean maximum monthly temperature and a rise of the mean minimum monthly temperature. Rainfall data from the same area are inconclusive. Truly arid zone lakes, man-made or natural, are not likely to contribute to increased atmospheric moisture in their environs. The air is usually so dry that the vapor will not form clouds because of the lack of dynamic processes capable of producing local ascending air motions. The enormous scale on which the hydrologic cycle operates further mitigates local measurable effects [*McDonald,* 1962].

Yet speculations have been made about on- and off-site climatic effects of reservoirs much larger than those now in existence or contemplated for the near future. In fact, such effects would be intentional, rather than accidental, should very large man-made lakes be constructed within a century or two to counteract such technologically induced warming of the atmosphere as might arise as a consequence of large increases in energy production by man [*Fletcher,* 1969]. Prominent here are the ideas of creating a Siberian sea by damming of the Ob, Yenisei, and Angara rivers and the attendant transformation of arid zone reflectivity by irrigated areas to the south of the gigantic lake. In the tropics, there has been speculation about the feasibility of creating Congo and Chad seas by damming the Congo at the Stanley Canyon and at the same time diverting the Congo tributaries into the present Lake Chad basin. The water surface so created would cover 10% of the African continent and would furnish vast irrigation possibilities for desert areas, which would in their turn add to atmospheric moisture.

There is no question that man-made lakes of such magnitude would radically affect the climate of the region concerned. The Siberian project and particularly the African project would be sited in regions of relatively low rainfall, where a lowering of the temperature and an increase in air moisture would be beneficial. The direct economic impacts of such climate changes might be difficult to quantify, but attempts to do so would be helped by the continued and often reinforced accumulation of climatic data from existing reservoirs.

ON- AND OFF-SITE EFFECTS OF CHANGES IN RIVER FLOW

An early consequence of reservoir building is the modification of the river flow and hence of its sediment-carrying capacity. Sediments are deposited in the man-made lakes; if the lake is large, like Volta Lake, it may nevertheless have very clear water and a lowered productivity at the downstream end [*Entz,* 1969]. Furthermore, turbidity currents can become established; and their deposits may lead to anaerobic sediments of little value to aquatic life. Especially in monsoon climates these same sediments have been deposited to a great part on the floodplains, where they have supported a rich, albeit seasonal, agriculture before the construction of the dam. More permanent and stable agriculture demands different and larger economic inputs than more traditional practices do. The loss of these sediments to the floodplain agriculture, which is often called primitive but is nevertheless ecologically sound, has not received the attention that it deserves.

Further downstream the changed river regime can often affect deltaic and even marine fisheries, which thrive because of seasonal loads of nutrient and silt in the effluent cone of the river. Southeastern Mediterranean fish concentrations, mainly of sardines, have declined since the closure of the Aswan High Dam.

The southeastern Mediterranean fish concentrations and the fishery resources of the Nile delta lakes, which were similarly affected, are valued at US$20 million annually [*George,* 1972]. It is debatable whether the income from Lake Nasser fishery, which is still to be established, will equal this sum. The changed regime of the Nile also caused the deltaic coastline to retreat and thereby endangered man-made coastal structures.

PLANT COVER

The change in the flow pattern of water and the depth of standing water leads to considerable transformation of the plant cover. Low-lying soils and plant associations show much change; certain species disappear, whereas others (that are more hygrophilic) find conditions that favor their development greatly. A major change in vegetation also results from the opportunities for irrigation that a man-made lake confers to its downstream areas.

The inventory and study of biotic communities prior to impoundment is an exercise that not only facilitates prediction of change but also enables a more rational exploitation of the areas surrounding and downstream of the new lake. Study prior to impoundment also provides a base line by which zonal changes after flooding can be evaluated and thereby assists greatly in the planning and development of agriculture and forestry.

BIRDS AND TERRESTRIAL WILDLIFE

Shortly after the closure of a dam the establishment of a man-made lake results in two prominent types of effects on birds and mammals. The first may enhance the carrying capacity of the watershed region for the mammalian and avian fauna by providing new nesting, feeding, and watering possibilities, but the second will counteract the first through the flooding of valuable mammalian wildlife habitats. (The effects of inundation on insect and other invertebrate components of the land fauna have to date received little consideration.)

Most information on interactions between man-made lakes and wildlife is available from the temperate zone, where the value of the fauna is considered to be mainly recreational. In the tropics, mammalian and avian wildlife may have recreational importance (e.g., the African Game Reserves), but the animals also still provide a major source of protein. A sizable part of the U.S. hunting take of aquatic game birds (valued at over US$100,000,000/yr) is taken from man-made waters of various kinds, mostly marshes, which also contribute to the abundance of fur-bearing species. The amount of shallow water strongly influences the carrying capacity for semiaquatic and aquatic warm-blooded wildlife, and the frequent fluctuations in water level resulting from reservoir operations mitigate the value of man-made lakes as bird and small-mammal habitats [*International Union for the Conservation of Nature and Natural Resources,* 1964]. The fluctuations in water level have to be considered in the overall planning for a multiple-use water regime for the reservoir.

Large deep man-made lakes can reduce the area of wildlife habitat in their watershed. The best niches for wildlife usually exist along river courses, and most species of large and small game have territories, home ranges, and feeding circuits associated with the mainstream and/or its tributaries. These will disappear in the flooded area. As the behavior traits of the animals make them cling tenaciously to their home grounds, the arrival of the water spells death for most terrestrial creatures. The biomass destroyed is often considerable, appearances notwithstanding. At Lake Afobaka (Surinam), on the Brokopondo, more than 10,000 land animals, turtles, tapirs, snakes, sloths, and so on, were collected after sampling had led zoologists to believe that the region to be inundated no longer harbored any more large animals [*Leentvaar,* 1966; *Walsh and Gannon,* 1969]. Native hunters may further decimate wildlife stocks when flooding begins, a kind of salvaging that might well be condoned since rescue operations, well-organized as they may be, are likely to be woefully inadequate [*Asibey,* 1969].

It is certainly possible that large dams might be instrumental in eliminating unique wildlife habitats and might endanger the survival of rare space-restricted species. The cuprey (*Ovibos moschatus*) of northern Cambodia might be so affected if the Mekong dam at Stung Treng were to be built. Although such rare wildlife species would be considered in the planning of man-made lakes, there are other wildlife-related effects that are not.

Savanna and grassland regions in the tropics support a large biomass of herbivores, part of which can be managed for harvest on a sustained yield basis [*International Union for the Conservation of Nature and Natural Resources,* 1963;

Talbot, 1968]. Through this ecologically sound land use pattern, such yields can exceed or equal those obtainable from raising cattle in the same locations. Inundating the land eliminates these possibilities for all time, and the management of the lake substitutes the production of water-derived proteins for game use. The potential benefits and costs of game farming versus fishery management might well receive greater attention in the planning and decision-making process.

For instance, the northern Cambodian plains adjacent to the Mekong and the large tributaries of the Mekong below Khone Falls are thought to support concentrations of ungulates as dense as those in Africa. The Stung Treng Dam envisaged there would cover around 8000 km^2 of such land. By analogy with still speculative considerations of African game farming, sustained game yields of US\$600–900/km^2/yr are possible [*Stier,* 1970].

At a prospective fish yield of around 50 kg/ha under semi-intensive management, probably comparable in intensity to that that would have to be established for game farming, 1 km^2 of Stung Treng Lake would produce at least 5 metric tons of fish. These may be valued conservatively at US\$0.10/kg (after management costs are subtracted) and thus represent an income of US\$500/km^2/yr. Thus the potential for protein production in this particular case seems to be of the same order from game ranching as it is from fisheries with the proviso that neither the savanna nor the lake would produce uniform yields over a large area [*Holden,* 1969]. Game ranching has other economic benefits. A selective harvest of horn- and antler-bearing males would add to the profits obtained from meat, a good set of antlers fetching about the same revenue as the flesh of the animal. Hides represent an additional potential benefit. Finally, sustained yield game ranching and tourism are compatible to each other, and in Kenya the tourist industry, based on national parks, is now the country's largest single income earner, totaling several billion dollars a year.

CHANGES IN THE AQUATIC BIOTA

When a river is changed into a lake, the ecological effects on aquatic organisms fall into beneficial and harmful categories. A representative beneficial effect is a rapidly changing limnology with the possibility of tapping new fishery resources. Harmful effects include the blocking or interruption of fish runs, sometimes the diminution of marine fisheries as a result of changes in the discharge characteristics of the barraged river, and the possible spread of water-borne diseases.

The inundation by water of the terrestrial flora and resident fauna leads to the proliferation of bacteria and a depletion of oxygen soon after inundation not only in the deeper regions of the man-made lakes but also sometimes in some of its shore regions. Later, aerobic production increases, and the oxygen content per unit surface area rises substantially. *Entz* [1969] documented such an increase in Volta Lake from 25 to 160 g/O^2/m^2 during the first 4 years. The action of winds then tends to distribute the oxygen and to counterbalance the previously mentioned effects of organic decomposition. The resultant high but later declining organic productivity is eventually translated into secondary and tertiary consumers, which are harvestable by man.

Much has been written about the dynamics of fish and invertebrate populations in a new man-made lake contained by a dam. A larger river and its tributaries usually represent more varied habitats than a large lake does, particularly in the tropics; consequently, the number of species often diminishes.

The impact of impoundment on the mussel fauna of the Kentucky Reservoir on the Tennessee River is an example [*Bates,* 1962]. The family Unionidae, represented in the river by 11 species, was reduced to one species in the postimpoundment fauna, and the total number of mussel species was approximately half that of the unmanaged river. The unanticipated economic effect of this faunal simplification was the eradication of mussel species that supported a thriving button trade and that provided most of the inserts that were exported to Japan for cultured pearl production. Numerous people with special skills had to find new occupations, and a trade that earned foreign currency was virtually eliminated. *Bates* [1962] concluded that 'the early natural assemblages (of mussel species) may suffer to the point of extinction.'

Comparable reductions in the number of species have been noted in the fish faunas of rivers and their associated man-made lakes [*Sidthimunka et al.,* 1968]. However, the numbers of individuals of those fish species that are able to adjust to the new lentic regime can increase greatly in the first few years after inundation, when nutrients from the previously aerated soils become dissolved in the water.

Whether the new fisheries that may result are well exploited or not depends on the adjustment of the human populations to the new situation. The lack of detailed quantitative information on the processes that accompany impoundment still poses difficulties for optimal management decisions, especially if potential benefits are not anticipated. On the Nam Pong Reservoir in Thailand, for instance, the production of 65 × 10^6 kw hr/yr was expected to provide a revenue of about US$750,000.

The additional US$500,000/yr from a fish harvest of 1200 metric tons in the third year of the existence of the lake, almost doubling the anticipated revenue, was entirely unexpected. There are other examples of changing fish faunas in man-made lakes. Sometimes the new limnological characteristics lead to high pelagic plankton production, but, if no plankton feeders of appropriate spawning habits existed in the riverine species complex, such fishes would have to be introduced to use the primary production of the lake. Plans are in hand for such introductions in several Mekong reservoirs. Introductions have already been made in Lake Ayamé (Ivory Coast), where *Tilapia nilotica* and *Heterotis niloticus* were established after it had been ascertained that no preadapted species were present [*Reizer,* 1968]. The measures were successful. A fisherman on this lake can, in theory, now earn 8 times the wages of an agricultural laborer.

There is often a reduction in organic productivity as a new lake becomes stabilized. After a peak in fish biomass, reached in 3–4 years, the fish yield declines after a variable number of seasons to a lower steady level. The entire period of stabilization may extend over a period of 20 years or more depending on the size, edaphic characteristics, and type of use of the reservoir [*Holden,* 1969]. These conditions are reflected well in the fish catch from Lake Kariba, which was nearly 800 kg/km^2 4 years after the dam was closed and dropped to about 270 kg/km^2 after 7 years.

Man-made lakes with different substrates and different limnological conditions have different stabilization histories, which may include the highly deleterious spread of floating vegetation. Unfortunately, too few details of the sequences in man-made lake maturation are known to enable valid predictions of potential fish production and therefore to facilitate the planning of optimally efficient fishery management provisions for any new lake.

In general, deeper lakes seem to be less productive than shallow ones are. Conditions vary widely, even in one lake. Although Lake Albert is not a man-made lake, it illustrates this characteristic, the annual catch being 33 kg/ha in the deep south end and 182 kg/ha in the shallow more easily fished north end [*Holden,* 1969].

Correlations of fish production with both depth and specific patterns of lake stabilization must be considered in the planning for optimal management and exploitation of fish stocks of reservoirs.

Immediately below the dam the river is also altered profoundly. The water is usually colder there than in the surface waters of the lake. It may also flow faster and in a more turbulent manner than it does in the river above the lake, and reservoir management exigencies may impose a pattern of diurnal and/or seasonal water fluctuations. These changed patterns of flow can attract certain fish species more than others and have led in some temperate zone reservoirs to the establishment of new salmonid sport fisheries. Corresponding data from tropical rivers below dams cannot as yet be found in the literature, though some data on this topic have in fact been obtained [*Sreenivasan,* 1968].

When the watershed harbors anadromous headwater-spawning species, the dam or dams pose barriers to such migrations. The migrations of the Atlantic and Pacific salmon are the best documented. Blocking of spawning migrations can be alleviated by enabling some fish to pass upstream by means of fish ladders or fish lifts or by establishing hatcheries or new spawning runs below the respective dams. Much money, time, and ingenuity went into the circumvention of man-made salmon barriers, but the devices developed to date by and large still leave much to be desired. The species of salmon primarily affected number five, all with somewhat similar habits. Large tropical rivers have an incomparably large number of commercial and anadromous species with widely differing migration habits [*Chevey and Le Poulain,* 1940]. Consequently, environmental triggers or conditions for migration also differ for various groups of species in such a river, so that it is almost impossible to design and extremely costly to build ladders to accommodate them all, or even only the most important 10 or 12 kinds. Higher dams on mainstreams in the tropics would therefore require research on the artificial propagations of migrant stocks rather than on providing physical access to the lost spawning grounds if important parts of threatened downstream fisheries are to be saved.

Apart from direct blocking of spawning runs a changed water regime below the dam may also eliminate or alter environmental triggers for the successful spawning of downstream populations. Thus *Hilsa* fisheries were eliminated from certain Indian rivers, probably through warming and a lowered flow rate. Detailed fishery biology investigations over many years prior to dam building are indicated if direct fish gains from man-made lakes are to be weighed against the possible fish losses of constructing a barrage in the river.

The change from a more or less rapid to a much slower water flow in a man-made lake and its associated waters, such as irrigation canals, affects yet another component of the aquatic fauna, namely, the various small invertebrate carriers of several tropical diseases. Among these, schistosomiasis is by far the most serious. Some of these diseases may be reduced when the carrier prefers a rapid rather than a slow water flow; for example, *Simulium*-carried blindness-producing onchocerciasis on Volta Lake [*Obeng,* 1969*b*] and others, including schistosomiasis-carrying snails, are favored by current reduction.

Bilharzia, present earlier to an unknown extent, may conservatively be expected to infect around 50% of the predominantly rural population of Egypt when constant irrigation, made possible by the High Dam, is available in most of the Nile Valley and the delta. This infection could easily result in a 30–50% reduction of work in each infected male [*Wright,* 1951]. If the infection figure was 50%, the work per man-day was evaluated at US$0.10, a man was estimated to work for only 150 days of the year, and 7 million among the 14 million working males were assumed (from infection expectations) to be afflicted, the losses could well amount to more than US$100,000,000/yr. Popular press reports tell of manual snail eradication in the Peoples' Republic of China, but chemical eradication is at present only possible against dense foci of snails; even then it is costly and cumbersome. The chemical treatment of the disease itself, notwithstanding promising developments by several prominent drug manufacturers, is not yet sufficiently advanced to consider mass application. Even when this can be done, it will probably be prohibitively expensive, at least for several years, and it always necessitates the knowledge of the distribution of the mussels in the lake and of the evolution of the biomass of these mussels during the same time. Early and complete ecological assessment can help greatly in this problem [*Wright,* 1951], particularly in forecasting probable contingencies and therefore costs.

These then are just a few examples of the ecosystem effects of man-made lakes, though they have perhaps been considered in a more encompassing manner than planning agencies have been wont to do, at least in the past. No mention has been made of the rescue operations for ecologically displaced humans, called resettlement, which are necessary when man-made lakes are built. Resettlement has strong ecological connotations [*Chambers,* 1970; J. Ingersoll, unpublished manuscript, 1968], since the resettled people are likely to exercise a different resource use pattern after their displacement. Here the ecologist must cooperate with the sociologist, the economist, the public health official, the agricultural expert, the civil servant, and the politician. Ecologists have often stressed the value of biotic diversity. Unmodified ecosystems are usually more diverse and more resilient than man-dominated ones are. Perhaps planning considerations for man-made lakes ought to include options of minimum as opposed to massive interference in ecosystem balance. The application of the systems approach to the planning and management of man-made lakes is clearly indicated, but this can only be effective if the data fed into such an analysis are adequate. To date, inputs to the planning and cost accounting of man-made lakes have been slanted in favor of the more easily quantifiable consequences, often computed in a random and piecemeal fashion. In order not to repeat costly schemes that are eventually abandoned or whose benefits prove to be far less than those anticipated, it is imperative to make provision for early and intensive fieldwork by ecologists prior to the construction of man-made lakes and to ensure the participation of ecologists in the planning and decision-making councils that consider the feasibility of river regulation.

REFERENCES

Asibey, E. O. A., Wildlife in the Volta basin, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 366–372, Ghana Universities Press, Accra, 1969.

Bates, J. W., The impact of impoundment on the mussel fauna of Kentucky Reservoir, Tennessee River, *Amer. Midl. Natur., 68*(1), 232–236, 1962.

Blavoux, B., B. Dussart, H. Maneglier, and C. Salvetti, La région du Leman au point de vue hydrométéorologique, *Le Globe, 102,* 49–68, 1962.

Chambers, R. (Ed.), *The Volta Resettlement Experience,* Pall Mall Press, London, 1970.

Chevey, P., and F. Le Poulain, La pêche dans les eaux douces du Cambodge, annexes and 3, 168 pp., Trav. Inst. Oceanogr. Indochine, Gouv. Gen. Indochine, Saigon, 1940.

De Heer Amissah, A. N., Some possible climatic changes that may be caused by the Volta Lake, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 73–82, Ghana Universities Press, Accra, 1969.

Entz, B., Caractéristiques limnologiques du lac Volta, le plus grand lac artificiel d'Afrique, *Nature Ressources, 5*(4), 10–17, 1969.

Fletcher, J. O., Controlling the planet's climate, *Impact Sci. Soc., 19*(2), 151–168, 1969.

George, C., The role of the Aswan High Dam in changing the fisheries of the southeastern Mediterranean, 1968, in *The Careless Technology: Ecology and International Development,* edited by J. P. Milton and M. T. Farvar, Doubleday, New York, 1972.

Holden, M. J., Problems in forecasting sustainable yields, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 190–194, Ghana Universities Press, Accra, 1969.

International Union for the Conservation of Nature and Natural Resources, Discussion of wildlife utilization in 'Conservation of nature and natural resources in modern African states,' *Int. Union Conserv. Nature Natur. Resour., New Ser., 1,* 19–24, 1963.

International Union for the Conservation of Nature and Natural Resources, Discussion of wildlife utilization of man-made aquatic habitats, Project MAR, The Conservation and Management of Temperate Marshes, Bogs, and Other Wetlands, *Int. Union Conserv. Nature Natur. Resour., New Ser.,* 358–396, 1964.

Leentvaar, P., Artificial reservoirs, The Brokopondo lake in Surinam, *Verh. Int. Ver. Limnol., 16*(6), 680–684, 1966.

Lowe-McConnell, R. H. (Ed.), *Man-Made Lakes,* Academic, London, 1966.

McDonald, J. E., The evaporation precipitation fallacy, *Weather, 17*(5), 1–9, 1962.

Milton, J. P., and M. T. Farvar (Eds.), *The Careless Technology: Ecology and International Development,* Doubleday, New York, 1972.

Obeng, L. E. (Ed.), *Man-Made Lakes, The Accra Symposium,* Ghana Universities Press, Accra, 1969*a.*

Obeng, L. E., The effects of inundation on the *Simuliidae* of the Volta basin, in *Man-Made Lakes, The Accra Symposium,* edited by L. E. Obeng, pp. 361–365, Ghana Universities Press, Accra, 1969*b*.

Reizer, C., Aménagement piscicole du lac artificiel d'Ayamé, *Cent. Tech. Forest. Trop. Nogent sur Marne Fr. Publ., 30,* 1–108, 1968.

Sidthimunka, A., M. Potaros, C. Booson, and O. Pawapootanon, Observation on the hydrology and fisheries of Ubolratana Reservoir (1965-1966), *Indo Pac. Fish. Counc. Publ., C68/TECFIS,* 1968.

Sreenivasan, A., Limnology of tropical impoundments, 1, Studies of two upland impoundments in Nilgiris, Madras State (India), *Phykos, 7*(1/2), 144–160, 1968.

Stier, J. C., An economic approach to African game cropping, M.Sc., Univ. of Mich., Ann Arbor, 1970.

Talbot, L. M., Wildlife in developing countries, in *Wildlife Resources in a Changing World,* pp. 46–55, The Conservation Foundation, Washington, D. C., 1968.

Walsh, J., and R. Gannon, *Sauvés des Eaux,* Stock, Paris, 1969.

Warren, M., and N. Rubin, *Dams in Africa,* Cass, London, 1968.

Wright, W. H., Medical parasitology in a changing world, What of the future?, *J. Parasitol., 37,* 1–12, 1951.

Water Transportation on Man-Made Lakes

M. I. Foster

Division of Navigation, Development and Regional Studies
Tennessee Valley Authority, Knoxville, Tennessee 37902

Inland water transportation, whether by poled flatboat or diesel towboat on natural rivers, canals, or man-made lakes, is important the world over and has been from time immemorial. Now its relative importance varies from nation to nation, depending not only on the basic water resources but also on the stage of development in a nation and the availability of alternative forms of transport. To preface my remarks about inland water transportation in the United States in general and on the Tennessee River in particular, I shall review briefly the role of inland waterways in some other nations.

The USSR is one of the large nations that makes good use of its waterways, which happen to be extensive. With its immense land expanse it ranks first internationally in the number and total length of its rivers. The total river network exceeds 3 million km. Some 144,000 km of improved waterways are used regularly for navigation, including the 3680-km Volga, the Don, and several other big rivers. Waterway transportation in the USSR is used for some 203 million metric tons of freight a year.

Statistics are not available to measure the Soviet inland water traffic that is attributable to rivers with dams and lakes. Some insight can be gained, though, by looking at the total hectare-centimeter capacity of navigable reservoirs as shown in the *World Register of Dams* [*International Commission on Large Dams*, 1964]. The USSR is also at the top of this list with almost two thirds of the total capacity in 1965. The United States ranks second with about 31% and is followed by Western Europe (including Great Britain) with about 3% of the total capacity of navigable reservoirs.

On this basis, inland water navigation on man-made lakes is not nearly as important in Western Europe as in the USSR and the United States. However, Western Europe has an excellent river and canal system, and the inland waterway carriers play an important role in its economy. The Alps drain north to the Rhine River, west to the Rhone, south to the Po, and east to the Danube, and there are many other navigable rivers and tributaries.

France, West Germany, and the Netherlands are the European inland waterway leaders with more than 17,600 km of commercially navigable waterways. Some 450 million metric tons of freight a year are handled on these channels; this volume is about the same as the volume handled in the United States. Volumes in the aggregate and also per kilometer of navigable channel are much higher in both Western Europe and the United States than in Russia. Most of the major commodities handled on Western European waterways are similar to those moving in the United States: petroleum products, coal, building materials, grain, chemicals, and other basic agricultural and industrial products. Two commodities that are handled differently are wine in bulk, since our potential volume is much smaller, and motor vehicles, which were barged here in sizable quantities at one time but are now handled mostly by rail and motor carriers.

NAVIGATION ON LAKE NASSER

The navigation construction phase of Lake Nasser on the Nile River is now in its final stages and is expected to be completed by the end of 1971. The emphasis in the river transport group is therefore still on the technical features of providing a good navigation channel and other necessary facilities.

One of the impressive features of Lake Nasser is its great size. The construction of the High Dam will cause the formation of one of the largest artificial lakes in the world, 500 km in length, 11 km in average width, and 98 meters in maximum depth. Replacing a relatively narrow river channel with a lake of this size makes the design and construction of the navigation channel of paramount importance. A navigation route with a surface level of 140 meters has been fixed from Aswan to Wadi Halfa as a basis for the navigable channel bed. Thus a navigable depth of 7 meters is ensured at the lowest expected water levels. The channel has been marked by 44 fixed towers of 5–37 meters in height, 18 floating towers of about 5 meters in height, and 125 buoys.

Different types of vessels are needed to operate on Lake Nasser, and the Suez Canal Authority is designing and building three ships for that purpose. They will be combination passenger-cargo craft and can transport 250 passengers and 450 metric tons of cargo with a speed of 23 km/hr at design draught of 3.31 meters. Maintenance facilities will have to be provided at locations on Lake Nasser, since there is no lock in the High Dam. A floating dock of reinforced concrete and another of steel for self-docking are being designed and fabricated.

U.S. INLAND WATERWAY SYSTEM

The United States has an extensive system of inland waterways consisting of a total in 1970 of 40,869 km. The standard depth for inland navigation channels in the United States is 2.7 meters, and the system has 25,080 km of channel that meet or exceed that standard.

By far the most important part of the inland waterway system is the Mississippi River–Gulf Intracoastal System, including the Tennessee River, which serves a vast mid-continent area reaching from Pittsburgh, Pennsylvania, to Sioux City, Iowa, and from Minneapolis, Minnesota, to Brownsville, Texas, and St. Marks, Florida. In 1969, the latest year for which final figures are available, about 220 billion metric ton-kilometers of freight, or 82% of the total inland waterway freight, moved on the Mississippi-gulf system, exclusive of the Great Lakes.

The physical advantages of this interconnected inland network are apparent. The main stem of the network, the Mississippi River, traverses the heartland of the United States, important tributaries reaching out directly both east and west to the farms and factories of 21 states. The southern base is the Gulf Intracoastal Canal, its 1819 km of minimum 3.6-meter channel reaching from Texas to Florida along the mineral-rich and fertile coastal plain. Connection is made with the Great Lakes system and the ocean port of Chicago via the Illinois Waterway. The largest barge tows travel the longest distances in the United States over the well-developed Mississippi-gulf system, and it is here that inland water transportation makes its greatest contribution to the American economy.

In the East the Atlantic Intracoastal Waterway and the New York State Barge Canal, which follows much the same route as the old Erie Canal, are the most important inland waterways. Also in the Atlantic system are the coastal rivers, such as the Hudson, Delaware, Potomac, and James, which serve some large interior cities and industries. In 1969 the Atlantic coast waterways moved about 39 billion metric ton–kilometers of freight, or 14% of the total.

On the Pacific coast the principal inland waterways are the Columbia River system in Washington and Oregon and the Sacramento River system in central California. Although the Pacific coast waterways are very important for some industries and cargoes, their traffic constitutes only a small part of the total, 4% or 12 billion metric ton–kilometers in 1969. In Alaska a number of rivers are navigable and have good potential for further development and use.

MAN-MADE LAKES

A major and indispensable part of the American network of navigable inland waterways is composed of the rivers that have been canalized by the construction of dams with navigation locks. These include practically all the rivers with the notable exceptions of the lower Mississippi River and the Missouri River. On the Mississippi an open river channel is maintained between St. Louis, Missouri, and the Gulf of Mexico by dredging, bank stabilization, cutoffs, and other work. Above St. Louis the river is canalized by 28 locks and dams. The Missouri River is an open stream in its navigable part between Sioux City, Iowa, and St. Louis. This section has a 2.7-meter project depth, but it has not yet been attained.

For over the water transportation a modern canalized river with its series of slack-water pools is much superior to an open river. The water level remains fairly constant year round, and thus towing operations are more efficient. Also stream currents are lower, and in many man-made lakes the depth of the channel is more than the standard 2.7-meter minimum. Greater lake depths improve the efficiency of towboats and lessen wear and tear on hulls. On the debit side of a river with dams are the locks, which must be negotiated. However, if these are well designed and engineered, the amount of time consumed in locking operations will not be excessive.

For a water transportation system the slackwater lakes formed by dams have a marked advantage in the area of terminal construction. Since water levels in canalized rivers are subject to less fluctuation, the necessary public and private terminal facilities can be provided with greater ease and economy.

FUTURE IMPROVEMENTS

The Army Corps of Engineers, the agency that has the responsibility for the national system, already has on its books more than $13 billion worth of work that is authorized but not yet built. Some of this work represents improvements on present waterways, and some represents extensions to the system.

The newest major authorized addition to the mid-continent system is the long-sought Tennessee-Tombigbee waterway, which would link Pickwick Lake on the Tennessee River with the Tombigbee River in Mississippi and thence with Mobile Bay and the Gulf of Mexico.

Another important waterway connector and shortcut is the Cross-Florida Barge Canal, which would extend between the northwest coast of Florida and Jacksonville, Florida, on the east coast via the Withlacoochee and St. Johns rivers. Although the Cross-Florida Canal project is about one-third completed, in January 1971, President Nixon ordered construction discontinued for environmental reasons. This action is being contested in the courts and may yet be rescinded.

Other major river improvements that have been authorized by Congress are the Trinity River in Texas, the Red River in Louisiana, and the extension of the Alabama-Coosa system in Alabama.

The rivers in the inland waterways are both canalized and open, and statistics on water-borne commerce are not reported in such a way that an accurate overall separation can be made between the two types. Some conclusions can be drawn by looking at the two open rivers, the Missouri and the lower Mississippi. In 1969 on the Missouri, about 900,000 outbound metric tons were moved, and about 4.5 million metric tons were moved locally, or a total of 5.4 million metric tons. On the lower Mississippi, about 9.9 million metric tons were moved locally, and the rest were moved over some other part of the system. This total of 15.3 million metric tons, which can be attributed solely to the Missouri and lower Mississippi rivers, compares with an estimated 249 million metric tons, which were moved on the Mississippi River system in 1969.

TENNESSEE RIVER

Improvement of navigation on the Tennessee River is one of the fundamental objectives of the Tennessee Valley Authority Act, and after 38 years of work we feel that we have a good example of a modern improved waterway. The Tennessee River is an integral part of the Mississippi-gulf system. In 1970, about 22.9 million metric tons of freight moved on the Tennessee, 78% of which either originated or terminated outside the Tennessee Valley.

The series of high dams and man-made lakes that canalize the Tennessee River and are part of the Tennessee Valley Authority (TVA) multipurpose system (Figure 1) have advantages over a system of low-head single-purpose navigation dams. There are only nine dams in the 1040 km between Paducah and Knoxville, whereas 32 low dams would have been required in a single-purpose system. The channel is wide and deep. In dredged sections, which represent only about 8.5% of the total channel length, a minimum depth of 3.3 meters has been provided. This means 60 extra centimeters of depth for vessels drawing 2.7 meters. The minimum channel width in dredged cuts is 90 meters with some widening on bends. Depths of more than 7.5 meters prevail at normal reservoir levels for 640 km, or about 65% of the total length. Deeper water makes for better towing efficiency. The greater width and area of the lakes make the velocity of the current scarcely noticeable except for short distances downstream from the dams.

The flood control features of TVA tributary reservoirs keep fluctuations in water surface elevation to a minimum and guarantee the passage of vessels with a 2.7-meter draft throughout the year. As the magnitude and frequency of floods are reduced, the river is made safer for navigation. The high-dam reservoirs on the main river have created navigable marked feeder channels along many tributary streams and in many embayments. The large lakes also

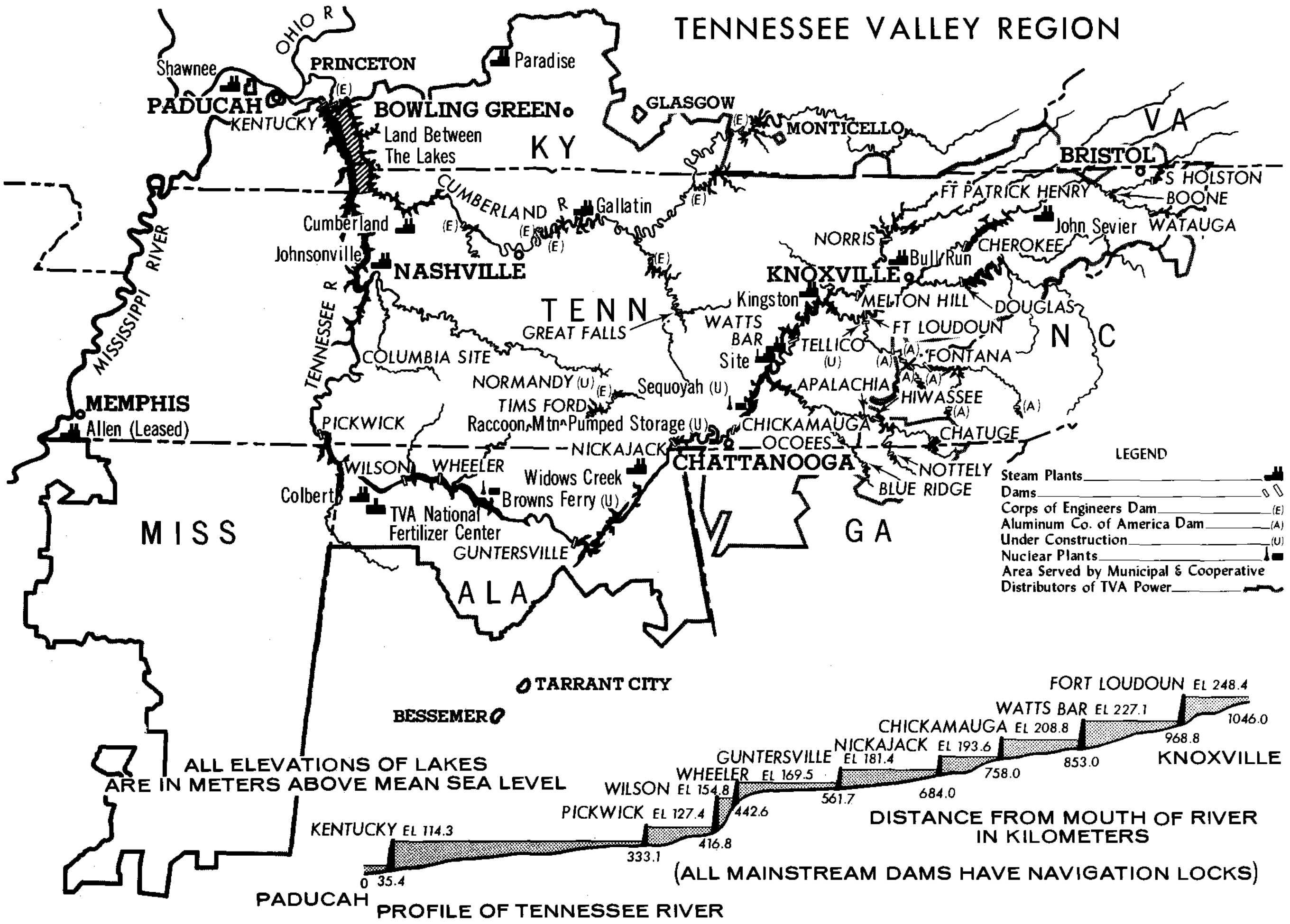


Fig. 1. Map of the Tennessee Valley region.

offer greater opportunities to improve channel alignment.

To date, traffic on the Tennessee River has been heaviest in the stretch between Paducah and Chattanooga, and all the dams in it now have 33- × 180-meter locks. In addition, they all have auxiliary locks except Pickwick Landing Dam, where a new larger lock is in the planning stages, and Nickajack Dam, where the underwater parts of a 33- × 240-meter lock have been constructed. This lock, and larger locks at Chickamauga, Watts Bar, and Fort Loudoun, will be constructed when they are needed.

On the Clinch River the Melton Hill Dam and lock extends 2.7-meter navigation 61 km up the Clinch to Clinton, Tennessee. This lock is 22.5 × 120 meters. Tellico Dam, to be located at the mouth of the Little Tennessee River, will extend 2.7-meter navigation about 48 km up the Little Tennessee and about 19 km up the Tellico River. Construction is under way on this project. A canal will connect Fort Loudoun and Tellico lakes, the need for a lock in Tellico Dam being eliminated.

INDUSTRIAL DEVELOPMENT

Multipurpose development of the Tennessee River has produced other attractions for industry besides the availability of economic barge transportation. An abundant water supply of good quality is one. Electric power is another and is also abundant and relatively low in cost. The resource development programs of the TVA have aided by improving supplies of raw materials. Its forestry development activities have helped provide an expanding source of wood for paper, timber, housing, and furniture industries. Fertilizer science and its application on farms have made agriculture more prosperous and have expanded the agribusiness sector.

The overall impact of these factors in terms of capital investment is that, from 1933 through 1970, more than $2 billion has been invested in over 200 private waterfront plants and terminals along the Tennessee River. If the investment in publicly owned waterfront plants and terminals, such as TVA steam plants, is added, the total becomes about $5.4 billion. The private firms provide direct employment for more than 38,000 people and at least an equal number of new jobs for people in trades and services.

On the Tennessee River waterfront, there is a large degree of concentration of industry within three broad groups, but there is considerable diversity within each group. A field survey made in 1969 and 1970 showed that 91% of the capital investment is in the broad industry categories of chemicals and allied products, paper and allied products, and primary metal industries. These industries have comparatively large water and power requirements and raw materials and/or products that are adaptable to barge transportation. The same would be true in varying degrees for the other waterfront industry classes: food products, wood products, machinery, transportation equipment, and stone, clay, glass, and concrete products.

Another measure of waterfront industry is the annual value of production, which we estimate to be about $1.3 billion. From this standpoint the most important industries are aluminum, synthetic fibers, and the large boilers of pressure vessels, each constituting over $100 million in annual production. The next most important industries, each with production between $40 and $100 million, are flour mills, soybean oil mills, pulp and paper mills, organic chemicals, electrometallurgical products, and motor vehicles and parts.

Significantly, 99% of the investment in these plants has occurred since the modern 2.7-meter navigable channel was completed in 1945. The completion of Kentucky lock and dam, the last mainstream project, coinciding as it did with the end of World War II, seems to have ignited the fuse on the waterfront industrial development rocket, and the trajectory is still for the most part sharply upward.

The industries that have come to the Tennessee River are not concentrated in a few places but rather are dispersed over the length of the river. We feel that this distribution of industry is one of the chief values of river improvements in this day and time, when the problems of large cities with their massed concentrations of population are of such magnitude.

On the Tennessee we have seen the rise of six industrial centers in rural or semirural areas, where industries were previously few or nonexistent. These areas are all places where major rail, highway, and water transportation routes converge and good industrial sites are available. They are Calvert City, Kentucky, on the lower reaches of the river below Kentucky Dam; New Johnsonville, Tennessee, on Kentucky Lake west of Nashville; Muscle Shoals, Alabama, near

Wilson Dam; Decatur, Alabama, on Wheeler Lake; Guntersville, Alabama, on Guntersville Lake at the southernmost tip of the river; and Charleston-Calhoun, Tennessee, near Chattanooga on the Hiwassee River arm of Chickamauga Lake. We fully expect two more similar industrial areas to rise from farmlands when the Tellico Dam and Reservoir Project on the Little Tennessee River near Knoxville and the Yellow Creek Port Project on the Yellow Creek embayment of Pickwick Lake in the northeast corner of Mississippi are completed.

TRAFFIC AND BENEFITS

The rapid industrialization that has taken place along the Tennessee River and surrounding area, coupled with the availability of an improved waterway into the center of the expanding Southeastern market, has resulted in a large volume of water-borne commerce. In 1970, according to our estimates, the Tennessee River route was used for transporting 22.9 million metric tons for an average distance of 219 km, or a total of 5 billion metric ton-kilometers. The composition of the 1970 traffic is shown in Table 1. The coal and coke category is the volume leader in terms of both metric ton-kilometers and metric tons. The important component in this category is still the steam coal shipped from mines in Tennessee, Kentucky, Illinois, and Indiana to steam electric generating plants located on the Tennessee River and to other points on the Mississippi River system, but growing foreign markets are also being served.

Ranking next with over 1.6 billion metric ton-kilometers in 1970 is the grains and products category, which includes mostly bulk wheat, corn, and soybeans. These staple cereals are highly adaptable to water transportation and began moving on the Tennessee in large quantities even before the project was completed. The Tennessee River and interconnected inland waterways provide direct routes between the grain surplus areas of the Midwest and the grain deficit areas of the Southeast, where the important broiler and livestock industries require huge amounts of grain.

TABLE 1. Tennessee River Traffic, 1970

Commodity Class	Metric Tons	Metric Ton-Kilometers
Chemicals	1,189	276,980
Coal and coke	8,852	1,758,083
Forest products	298	47,222
Grains and products	2,521	1,585,817
Iron and steel	691	175,671
Petroleum products	2,607	503,623
Stone, sand, and gravel	5,287	280,308
All others	1,393	373,154
Total	22,838	5,000,858

As is true for the inland waterways as a whole, chemicals constitute the fastest growing segment of Tennessee River traffic in recent years. The all others category includes sizable movements of such commodities as aluminum, carbon electrodes, cement, newsprint, and salt. It also includes rocket components and nuclear reactor vessels, which are too large to be transported by any other means of transportation.

Metric tons and metric ton-kilometers of water transport indicate the use of the river, but other measures must be employed to evaluate the resulting benefits. The principal measure used is the aggregate savings in freight costs to users of the Tennessee waterway. Lower freight costs are the main selling point for water transportation, which has longer transit times and larger volume requirements than those of the other modes, and these costs are a direct and measurable benefit. In essence, the costs of individual Tennessee River freight movements from first origin to final destination by the Tennessee River route are compared with the costs of the next cheapest alternate route, and the sum of the individual differences is considered the total benefit. Since our objective is to estimate the effect on shippers' freight costs due to the construction and use of the Tennessee River navigation channel, we do not consider water-competitive rate reductions by other modes in the calculation.

On this basis the estimated shipper savings in 1970 amounted to $51.4 million, which is reflected in lower prices to consumers, greater earnings for businesses, and ultimately increased income for people all across the country. These figures do not include any savings on the estimated 2.2 million metric tons of traffic using the Barkley Canal. The savings figure exceeded waterway operating costs including depreciation by $43.3 million, representing a return on net navigation investment ($244 million) of 17.8%. Since 1933, cumulative savings are almost 4 times greater than cumulative costs.

The total economic impact of a waterway cannot be measured solely by freight transportation savings on traffic that would, in the absence of a waterway, move by some more costly alternate mode. There are other factors unrelated to the explicit purpose of the program that may be even more important, particularly to the immediate region. For example, one of the major effects of a new waterway development is a general reduction of transportation costs to shippers in its trade area. With lower transportation costs the environment for economic and industrial growth is enhanced.

We have been keeping tabs on Tennessee River water-competitive rate reduction for the last 10 years, and in this period of time we have identified 463 reduced rail rates on 82 commodities. On the basis of available estimates of the volumes of material moving at these rates we believe that the savings accruing to shippers from the use of these rates exceed the aforementioned savings from the use of the waterway itself.

In the early days of the TVA we tried to look ahead to what so-called 'mature' river traffic might be, and we came up with the prediction of 6.3 million metric tons and $9 million in shipper savings in 1960. As is often true, our prediction was much too conservative, and these amounts were surpassed long before 1960 and, to repeat, stood at 22.9 million metric tons and $51.4 million in shipper savings in 1970.

These levels have been reached, I might add, in spite of two rather restrictive limitations on traffic development: the notable reluctance on the part of railroads to cooperate with water carriers on through movements by making joint rates and the great preponderance of inbound traffic on the Tennessee River, which means empty returns and higher barge costs. As progress is made in overcoming these limitations and development of the human and material resources of the Tennessee Valley region continues, traffic and savings should continue to grow. The time of economic maturity is still far in the future.

One last aspect of Tennessee River freight traffic relates to the interchange of traffic between the Tennessee River and the other segments of the inland waterway system. In 1970 the traffic that came from or was shipped to other waterways (excluding the Barkley Canal traffic) amounted to about 13 million metric tons. Of this amount, about two thirds was interchanged with rivers with locks and dams (the Ohio River and its tributaries, the Illinois Waterway, and the upper Mississippi), and about one third was interchanged with open streams (the Missouri River, the lower Mississippi, and the Gulf Intracoastal Canal). More traffic was interchanged with the Ohio River and its tributaries than was interchanged with any other waterway.

RECREATIONAL BOATING

Commercial towboats and barges are not the only kinds of craft that ply the waters of the Tennessee. Far outstripping them in numbers and variety and conferring perhaps as many or more navigation benefits are the recreational craft. The 36 lakes of the TVA in the seven Tennessee Valley states are one of the major outdoor recreation resources of the Tennessee Valley. These lakes provide more than 240,000 ha of water surface and 17,600 km of shoreline and have made the valley one of the most popular vacation areas in the country. Visits to the lakes have increased almost sevenfold in the past 20 years.

The waters of the lakes are used for almost every kind of boating: outboards, yachts, sailboats, river steamers, and canoes. Not more than 600 pleasure craft used the Tennessee River in 1933, whereas now almost 46,000 recreation boats valued at $50.7 million are actually kept on the lakes. Thousands more are transported by trailers to and from the lakes, since launching ramps are available at most boat docks and at many public parks and access areas.

Recreation boats may lock through at no charge at main river dams. These craft are locked through with commercial craft when there is room or separately at the end of each hour. In 1970, almost 18,000 recreation boats passed through Tennessee River locks. In addition to fishing, water skiing, and other individual boating activities, organized activities such as speedboat races and sailboat regattas are held regularly on the lakes.

BARGE-CARRYING SHIPS AND MINI-SHIPS

Some new vessels just coming into service have great potential for expanding the traditional role of the inland waterways. These are the small barges that are designed for use with mammoth barge-carrying ships and small ships, or mini-ships, that operate on both inland waterways and open seas. Barge-carrying ships have been called a 'dramatic, technological breakthrough' by Mrs. Helen Bentley, chairman, U.S. Federal Maritime Commission. With this equipment, goods in foreign trade can be shipped from interior origins in one continent to interior destinations in another on faster and better schedules, with less handling, and with greater overall flexibility and efficiency. Many new areas of service should be opened for both shallow- and deep-draft carriers with the growing use of these innovative techniques.

Some 25 of the small ocean-going vessels known as mini-ships are already in operation by the Mini Line on the Mississippi River, and at least 30 more are planned. Originally built to operate in Indonesia, these ships draw a maximum of 4.8 meters at a capacity of 2880 metric tons. When they operate on 2.7-meter inland channels, they can carry 900 metric tons at an average speed of 19.4 km. All vessels are equipped with a heavy-lift capacity of 27 metric tons. They transport their cargo mostly to the Caribbean and Central America or act as a feeder system for larger container ships.

Also newly in service are the Lash (lighter aboard ship) vessels, which might be referred to as maxi-ships because of their 246-meter length and 30-meter beam. Besides being very big they are very fast as well and are capable of speeds in excess of 42.6 km/hr. Although the Lash ship was designed primarily to carry preloaded barges or lighters with a capacity of 333 metric tons, it will also carry containers, and its wing tanks are capable of handling 4500 metric tons of liquid bulk cargo. The number of lighters that a Lash vessel carries varies somewhat according to individual design but generally ranges from 50 to 75. Each ship has two traveling cranes that can load or discharge the lighters and containers in less than 24 hours.

Tennessee River industries were quick to see the advantages of Lash shipments and have used the service from its inception. So far nine lighters have been consigned from Tennessee River origins to London, England, and other European destinations, and we expect the movement to grow.

Even larger than the Lash vessels are the Seabee barge-carrying ships and supporting barges now in the final stages of construction. Initial operation of the Seabee system by Lykes Brothers Steamship Company is scheduled for late 1971. These new 39-km/hr behemoths will be 263 meters long and 32 meters wide and will be capable of carrying a pay load of 32,400 metric tons. Each ship will carry on its three decks 38 loaded barges, which will be loaded and unloaded by the use of an elevator with a capacity of 1800 metric tons at the ship's stern.

The barges are 29 meters long × 10.5 meters wide and can handle up to 855 metric tons. They are the same width and exactly one half as long as the standard domestic river barge, and so they will fit neatly into almost any tow. The barges will be floated onto the elevator of the ship in pairs and will then be lifted to the proper deck, where special wheeled hydraulic transporters will position them. Loading or discharging will require only 10–12 hours.

If the barges are used to carry containers, a Seabee ship could handle over 1200 6-meter containers. If those carried on the upper deck are not in barges, the ship could carry nearly 1500. The ship can employ roll-on–roll-off loading and unloading without modification. It can also handle up to 1800 metric tons of special heavy-lift cargo, and its deep tanks can carry 13,500 metric tons of liquid cargo. All these capabilities can be adjusted quickly to meet the demand, and so the system will be extremely flexible.

A major advantage of the Lash and Seabee self-loading ships is that they will have access to more ports and need not enter crowded inner ports, delays and added costs thus being avoided. Their barges or lighters will have direct access to inland river ports without added handling of cargo. Too the overall cargo delivery time is greatly reduced because the cargo handling time is decreased to as much as one-tenth that needed for a conventional break-bulk vessel. Because of such advantages, predictions are that at least 23 such ships will be operating by 1975 and will be handling about 2500 lighters and barges.

With such new and ingenious systems as mini-ships, Lash, and Seabee the future of water transportation looks promising, and, as an essential waterway component, transportation on man-made lakes should also continue to grow in importance.

REFERENCE

International Commission on Large Dams, *World Register of Dams*, Paris, 1964.

Strategy of Archaeological Salvage

WILLIAM Y. ADAMS

Department of Anthropology, University of Kentucky, Lexington, Kentucky 40506

Archaeology can be narrowly defined as the recovery from the earth of the material remains of man and his works. From the study of those remains we hope to reconstruct something of the pattern of the past to learn things about our ancestors and predecessors which historians have not been able to tell us.

It might be argued that all archaeology is a work of salvage. Yet usually it is salvage only from temporary oblivion not from permanent destruction. The earth, properly considered, is more often a preserver than a destroyer of the record of the past. Over the centuries, far more damage to property has been wrought by man than by nature, and it has long been acknowledged that the safest place to preserve nearly anything for posterity is in the ground. Consciousness of this fact has been a great comfort to archaeologists, for it has freed them from the strictures of moral obligation. They could and did justify any choice of objectives on the ground that whatever they left uninvestigated not only was safely preserved but would provide research opportunities for future generations of archaeologists.

Only when the earth itself is threatened with destruction does it cease to be a safe repository for the remains of the past. That possibility was hardly considered by archaeologists before the twentieth century. Man's technical capacity for destruction was limited, and the supply of antiquities, as of so many natural resources, seemed inexhaustible. Today we know better. In half a century we have witnessed more man-made disruption and alteration of the face of the globe than was wrought by 10,000 generations of our ancestors.

Gradually but inevitably a sense of our responsibility for the consequences of these actions, both to man and to nature, has dawned. It has found expression in all kinds of conservationist movements, including a belated but growing concern for the preservation of archaeological remains. The heritage of the past is now regarded in most nations as a public trust, and the salvage excavation of remains which are threatened with destruction is legally sanctioned and publicly supported as a necessary measure for the preservation of that trust.

The first archaeological salvage campaign in history was carried out in Egypt between 1907 and 1911. It was made necessary by the enlargement of the original Aswan Dam, which inundated nearly 160 km of the Nile Valley, including several of its most spectacular monuments. The proposed inundation of the famous temples of Philae, in particular, caused an outcry in scholarly communities of Europe and North America, and aroused the world's attention for the first time to the threat of destruction to cultural remains which is inherent in all development projects [cf. *Emery*, 1965, pp. 35–120].

Since the original Aswan Reservoir was a seasonal rather than a permanent lake, it was ultimately decided that no effort need be made for the conservation of those monuments which could withstand periodic inundation. At the same time, however, it was decided to organize an archaeological survey devoted to the investigation and, where it was possible, the preservation of remains which would be destroyed by inundation. The survey, originally directed by George A. Reisner of the Boston Fine Arts Museum, was active in the field for four seasons and eventually excavated about 150 sites. It was by far the largest coordinated archaeological program undertaken up to that time.

After the conclusion of the first Archaeological Survey of Nubia, there was to my knowledge no further salvage activity anywhere in the world until a generation later, when a second enlargement of the Aswan Dam made necessary another salvage program in Nubia. The second archaeological survey, active between 1929 and

1934, covered an additional 145 km of the Nile Valley and investigated about 75 sites.

The 1930's witnessed also the first major efforts at archaeological salvage in Europe and the United States. In Holland the reclamation of large areas of agricultural land from the sea brought to light archaeological remains which had long been submerged, and the government assumed responsibility for the investigation of these before the reclaimed land was given over to cultivation. In North America the beginnings of salvage archaeology were associated with the Tennessee Valley Authority (TVA) project. Surveys and excavation, mostly directed by the late W. S. Webb, were carried out in each of the major TVA reservoir areas [*Brew,* 1962, pp. 7–32].

Significant as were the beginnings made in the 1930's, it was not until after World War II that salvage archaeology really came into its own. The destruction wrought by the war undoubtedly created a heightened appreciation for the value of cultural remains, and at the same time the massive reconstruction of cities in Europe, the proliferation of economic development projects in Africa and Asia, and the long building boom in America all provided expanding challenges and opportunities. One of the largest postwar salvage programs was associated with the Missouri Valley project, which ultimately included more than 100 reservoirs, but there were scores of smaller reservoir projects as well. Some measure of the scope of salvage archaeology in the United States can be gained from the fact that between 1946 and 1957 archaeological, historical, and paleontological surveys were carried out in 310 reservoirs in 42 states. Over 9000 sites were located and recorded, and over 4 million objects were recovered from excavations [*Brew,* 1962, p. 16]. Meanwhile there were other major reservoir projects on every continent, and in the 1960's the largest of all archaeological salvage programs was made necessary once again by the building of a dam on the Nile. Under the sponsorship of Unesco, more than forty different expeditions from as many countries took part in the Campaign to Save the Monuments of Nubia [*Emery,* 1965, pp. 96–100].

In addition to reservoir projects the postwar years saw also the development of right-of-way salvage programs connected with the building of highways, canals, and pipelines. These operations have thus far been confined largely to the United States. In Europe, meanwhile, the stringent antiquities laws enacted by many postwar governments have required that any threatened archaeological remains must be excavated before new buildings can be erected on top of them. Since the great majority of European cities stand upon the remains of earlier settlements, the new laws have led to a multiplication of small-scale salvage projects all over the continent. It is a rare European city which does not play host to at least one or two building salvage excavations each summer.

The past few years have witnessed a tapering off in the volume of archaeological salvage, concurrent with the worldwide building recession. Yet it is still true that salvage programs provide more research opportunities than do all other sources of support combined, and in the aggregate they have probably accounted for three fourths of all archaeology carried out since World War II. As a result of this development the parameters of the archaeological profession have been altered to an extent which is not yet fully appreciated even by many of its members. The salvage archaeologist has ceased to be a private practitioner and has become in effect a public official with a public responsibility. If his research opportunities are thereby greatly enlarged, it is at the price of surrendering his traditional discretion in the choice of research interests and objectives. To a large extent the decision not only as to how and when to dig, but even as to where to dig, is no longer his.

CRITICISMS OF SALVAGE ARCHAEOLOGY

Some archaeologists, like some other social scientists, find the mantle of public responsibility inconsistent with scientific objectivity. Their objections to salvage archaeology echo the traditional attitude of 'pure' science toward 'applied' science. They complain that the salvage archaeologist is often compelled to sacrifice methodological rigor, that he has insufficient choice in the matter of research objectives, and that as a consequence his investigations lack any problem focus or orientation [cf. *Hole and Heizer,* 1966, pp. 31–32].

The salvage archaeologist may reply that none of the supposed limitations under which he works is necessarily a disadvantage, at least when they are compared with traditional operating procedures in archaeology. Although he does indeed find it necessary at times to dispense with technical niceties, the quantitative increase in his results usually more than compensates for any qualitative shortcomings. It is also true, as *Jennings* [1966, pp. 6–7] has pointed out, that non-salvage archaeology in recent years has developed an excessive meticulousness which often results in a very low return, either in material or in information, per man-hour of excavation. To this development, salvage archaeology has initiated a useful countertrend, which will hopefully end in some sort of practical compromise between quantity and quality.

The salvage archaeologist's lack of discretion in where to dig may be viewed as a positive advantage when contrasted with the traditional selection of sites for excavation on the basis of largely nonscientific criteria. It has produced for the first time in history a certain involuntary randomness in archaeological sampling. The results are dramatically attested in such areas as the Colorado Plateau, which for two generations was regarded as the best-known archaeological province in the United States. Yet the Glen Canyon and Navajo Dam projects, along with a number of highway and pipeline salvage projects, led to the excavation of a great many inconspicuous and unprepossessing sites of the type which had been ignored by earlier generations of archaeologists. The result was a substantial enlargement and revision of our picture of prehistoric Indian life in the Southwest [*Jennings,* 1966, pp. 5–7; *Wendorf,* 1962, p. 82]. There are other areas, like the American High Plains [cf. *Jennings,* 1966, pp. 5–7] and Nubia, in which virtually all our knowledge of prehistoric cultures has come as a result of archaeological salvage programs.

It is undoubtedly true that most salvage archaeology, like most other archaeology, has been carried out without much regard for theoretical problems. Its objectives have been descriptive rather than explanatory. Yet this too is not always a practical disadvantage. Where a 100% sample is to be taken, as is usual in building and right-of-way projects, it is not necessary to have a sampling strategy. The salvage archaeologist on a highway or building project can always look for problem orientations after the fact, so to speak. His special challenge is to find problems appropriate to his data instead of following the more usual practice of seeking data appropriate to his problems. Either procedure is equally legitimate scientifically. It is only in the larger reservoir salvage programs, where the archaeologist is indeed faced with strategic choices, that problem orientation in advance of excavation becomes a practical necessity.

It must also be recognized that lack of problem orientation, even when it is relevant, is a de facto limitation rather than an inherent limitation of salvage archaeology. In salvage programs, as in most other programs, practical considerations have too often supervened over theoretical ones in the selection of sites for excavation. Yet insofar as archaeology has any potential for explanation as well as for description, it has the same potential in salvage operations as it does in any other context.

My purpose here is not to suggest that salvage archaeology is above criticism, but rather that it has usually been criticized for the wrong reasons. Some of its alleged deficiencies are in fact advantages, others are common to nearly all archaeology, and not one is specifically inherent in the context of salvage. If, nevertheless, many archaeological salvage programs have failed to achieve their full potential, I believe that their failure has been due to reasons nearly opposite to those usually cited. The most legitimate charge to which salvage archaeology is open, it seems to me, is that it has failed to develop distinctive strategies appropriate to its distinctive circumstances. In other words, salvage archaeology can be criticized not so much for its differences from conventional archaeology as for its lack of difference.

This criticism is relevant above all to reservoir salvage programs. For obvious reasons the potential contribution to knowledge of right-of-way and building projects is limited. Such as it is, however, it is usually fully achieved, thanks to a level of funding which normally permits the excavation of all remains encountered. Man-made lakes, on the other hand, present the archaeologist both with challenges and with opportunities on a far larger scale. Neither of these facts has, I believe, been fully appreciated by the archaeological profession, and therefore reservoir projects have not always lived up to their full promise.

SPECIAL CHARACTERISTICS OF RESERVOIR SALVAGE

River basin salvage stands apart from other kinds of archaeology (both salvage and non-salvage) in a number of important respects. The sheer territorial extent of many reservoirs far exceeds the areas in which systematic survey and excavation are usually carried out. Moreover, since river valleys generally are or have been desirable habitats, there is virtual assurance that a large number of archaeological sites will be found. (By contrast, right-of-way projects often avoid productive areas for the sake of lower land acquisition costs, and as a result there is no a priori probability that important remains will be encountered.) Finally, river basins are very often discrete ecosystems, within which patterns of settlement and land use can be understood without reference to larger environmental units. Thus the salvage archaeologist is presented at the outset with a meaningful unit of study; he is not sampling an undefined universe, as he often is in right-of-way and building projects.

Offsetting the scientific advantages inherent in reservoir salvage projects are certain obvious disadvantages. One, which may not be immediately apparent either to laymen or to archaeologists themselves, is the impossibility of preserving architectural remains in situ. When intrinsically valuable or important structural remains are encountered in the course of building or highway projects, it is usually sufficient reason for halting construction and, if necessary, relocating the building or highway on an alternate site. In the case of reservoirs, however, anything that is to be preserved must be either removed or protected with restraining dikes. The physical conservation of monuments for historical or esthetic reasons rather than for purely scientific ones is therefore a special challenge in reservoir archaeology. It is, properly speaking, a challenge to the engineer rather than to the archaeologist, since the expertise necessary to build levees or to dismantle, transport, and reerect buildings is not part of the archaeologist's normal equipment. Nevertheless, the money for these enormously costly operations and the money for scientific excavations usually come from the same appropriation, and whatever is devoted to the conservation of monuments is therefore in a sense diverted from the conservation of knowledge. Monetary considerations have not been a serious consideration up to now in American reservoir projects, but their importance in the case of Nubia is readily apparent. At least 95% of the funds contributed to the Campaign to Save the Monuments of Nubia were allocated to the dismantling and removal of the Nubian temples, with the result that the amount of 'dirt archaeology' which could be accomplished was necessarily diminished [cf. *Adams,* 1967, p. 1].

Even when there are no monuments to be preserved, the level of funding in reservoir salvage projects is rarely sufficient to permit the excavation of all threatened remains. The reservoir archaeologist must therefore make strategic choices among alternate possibilities. In this respect his situation is no different from that of the archaeologist in nonsalvage contexts; the latter however can make his choices with the comforting knowledge that future generations may supply his deficiencies and correct his mistakes. For the salvage archaeologist on the other hand there is no tomorrow. He alone among the members of his profession must make not only choices but final choices, in the knowledge that whatever he leaves is left forever. 'After us the deluge' must be his guiding consideration.

Because he must make hard choices, the salvage archaeologist in reservoir projects, unlike his colleagues in building and right-of-way projects, must have a coherent research strategy before he enters the field. Yet because his choices are final, he cannot operate with the kind of strategies which have been characteristic of nonsalvage excavation programs. He has to consider the public interest as well as his own interests, and to ask himself not only what he would like to know but what others might like to know, now and in the future. The strategy of reservoir archaeology is therefore a matter not merely of program but of policy; it represents the only instance in which archaeology may perhaps be regarded as a policy science.

Archaeology in man-made lakes, then, demands both a coherent and a comprehensive research strategy, designed to answer as many questions as possible in the time available and with the resources at hand. This is the unique challenge which I believe has not been fully perceived by many salvage archaeologists. Salvage expeditions have taken to the field either with no sampling strategy at all (as is usual and legitimate in right-of-way and building projects) or with a narrowly specialized and noncomprehensive strategy of the kind which is appropriate to nonsalvage projects. In these cases a sense of the importance of what they are doing may blind the archaeologists to the possibly greater significance of what they are not doing. When several expeditions are involved in the same program, as has occurred in some of the very large reservoirs, the problem is further complicated, for each institution is apt to follow its individual preferences on the assumption that its deficiencies are being supplied by others, and that somehow all the various and disparate efforts of the different groups will in the end add up to a meaningful whole. Unless there is a comprehensive strategy for the entire project, however, that hope may be a vain one, as the recent salvage program in Nubia illustrates.

NUBIAN CAMPAIGN AS A CASE STUDY

The Nubian campaign of the 1960's exemplifies both the greatest triumphs and the greatest failures which salvage archaeology has yet recorded. Not without reason, the general public accounts it an unqualified success. The dramatic and ultimately victorious efforts to save the Nubian temples from inundation excited the world's admiration, and few but the most narrow-minded specialists will quarrel with the scale of priorities which allocated the bulk of available funds and resources to the conservation of monuments rather than to the conservation of knowledge. Even in the latter area there were substantial additions to the understanding of Nubian cultures and history [cf. *Adams*, 1966*a*, 1967, 1970].

Moreover, when we compare the achievements of the 1960's with those of the 1900's we can hardly fail to be impressed by the progress which has been made in Nubian archaeology in 50 years. The work of the First Archaeological Survey was confined to the excavation of graves and the epigraphic recording of temples [*Emery*, 1965, pp. 35–45]. Even the Second Archaeological Survey, a generation later, concentrated largely on cemeteries, although excavation was also carried out in a couple of village sites and two fortresses. There was a concurrent survey of churches and other medieval buildings, but it was not supported by excavation funds [*Emery*, 1965, pp. 46–55]. The most recent Nubian campaign on the other hand involved the first comprehensive investigations of prehistoric remains and of rock drawings and inscriptions, as well as much more systematic attention to villages and industrial sites than had been given in earlier years.

None of the refinements in Nubian archaeology can, however, be recorded specifically to the credit of salvage archaeology as distinct from archaeology in general. Wherever excavations are carried out over a long period of time, each succeeding campaign will inevitably benefit by the experience of its predecessors in terms of more precise expectations and more refined methodologies. In addition, archaeology in Nubia and throughout the world has been characterized in the twentieth century by a continually broadening sense of what is worth investigating and what is worth preserving. No longer are we dominated by esthetic and museological considerations; in the words of *Daniel* [1964, p. 74] we have 'exorcised the demon of taste.' Concern for the investigation of humble as well as of monumental remains has led inevitably to the development of more precise excavation techniques and more comprehensive recording than were typical of the past. Yet these achievements belong to all archaeology, and are no more conspicuous in salvage programs than in any others.

Individually, the objectives and methods of the various expeditions which worked in Nubia in the 1960's were well up to the high standards of the times. Yet for most expeditions they would have been the same whether the region was threatened with inundation or not. What was conspicuously lacking was a set of special objectives and methods appropriate to the salvage context, and above all a master strategy to which the objectives of the individual expeditions should have been subordinate [cf. *Adams*, 1966*b*, p. 161]. Because of this strategic failure at the highest level the purely scientific work of the Nubian salvage campaign must be accounted only a partial success. As *Trigger* [1970, p. 347] has recently written:

> Because of the vast amount of archaeological work that has been accomplished in Lower Nubia, it is easy to overestimate how much we know about the cultural history of the region and to underestimate the loss of historical data that has resulted from the building of the High Dam. The reasons for this are clear and mostly understandable. Few archaeologists who worked in Lower Nubia arrived there with specific objectives in mind; their aim was to salvage as much archaeological material as possible before the region was flooded. By the time their research had led them to formulate more detailed problems of Nubian culture history, field work was no longer possible. Because of this, much of the archaeological work done in Nubia has been repetitive rather than problem-oriented and the amount of

material that has been collected greatly exceeds its significance.

POLICY FOR THE FUTURE

The failures as well as the successes of Nubia may yet serve as guideposts for the future. Simply because of its unprecedented magnitude, the Nubian campaign has underscored, far more than any earlier work, the need for a special approach in reservoir salvage archaeology which is commensurate with its special circumstances. While operating strategies must be based in part on the particular challenges and opportunities inherent in each field situation, they must also be based on considerations of public policy which are unique to the salvage context and which remain largely constant from one program to the next. It is because these considerations remain constant that the lessons of Nubia have relevance for the world of archaeology as a whole. In the remainder of this paper I shall discuss what I believe should be the broad strategy guidelines for future archaeology in man-made lake basins, based on my experience both in Nubia and in earlier programs in the United States.

Clearly the overriding need in reservoir salvage programs is for a coherent strategy in advance of fieldwork. Since in many cases not all sites, or even a majority of them, can be excavated, it is essential to have a consistent scale of priorities to determine what is to be done and what is not to be done. The archaeologist's problem may therefore be expressed in terms of classic economic theory: to allocate limited resources among alternate ends on some rational and consistent basis. Accordingly three questions must be asked at the outset of any salvage program:

1. What are the possible ends?
2. What are the available resources?
3. What shall be the basis of allocation?

Possible objectives must be defined in terms of material available for investigation. How many sites are there, how big are they, how deep are they, how well preserved are they, how are they distributed spatially, and what are their physical characteristics? These questions can be answered only by field reconnaissance. As a basis for strategy development it therefore becomes essential to begin every salvage project with an exploratory survey. Its purpose is not merely to locate sites for later investigation, but to make an accurate descriptive record of every site encountered, so far as this is possible from surface examination. Surface collections should be made of pottery, artifacts, and any other potentially informative material. The information thus gathered will not only serve as a basis for the future selection of sites for excavation; for those sites which are not selected it will be the only surviving record. In areas of heavy overburden (as in Nubia) it may be necessary to carry out a certain amount of trial excavation in the course of survey in order to obtain the minimum necessary information about each site. However, the strategy at this stage of operation should always be to keep excavation at a minimum in order to complete the preliminary survey as rapidly as possible and get on to the next and most critical stage of the program. Obviously, a basis for sampling has not been established until the preliminary inventory of sites is complete.

In a number of recent salvage campaigns the work of field reconnaissance has been aided enormously by aerial photography. Air photos may reveal the existence of sites which are not apparent from the ground, even at close range. In no case, however, do photos provide all the information which the archaeologist will need to record; they are an aid and supplement to rather than a substitute for ground exploration. Their greatest value is often in providing an accurate medium for recording site locations where detailed maps are lacking [cf. *Miller,* 1957; *Adams and Allen,* 1961].

The information recorded for each site must be categorized in terms of a set of characteristics which, taken together, will determine its suitability or unsuitability for further investigation. Gross features such as size, depth, and state of preservation will indicate whether excavation is likely to reveal anything not visible from the surface; chronological and morphological characteristics will suggest which sites show promise of answering important historical and cultural questions. Although recording in the field is often most conveniently done in the form of raw notes, the most important categories of information must eventually be transferred onto standardized recording forms which will serve as a basis for site comparison and selection. Punch cards are ideal for this purpose.

Having defined the size and complexity of his problem in terms of sites to be excavated, the archaeologist must next survey the resources which he can bring to bear on them. In salvage projects where he has been given little advance notice, the most critical resource may be time. Inundation schedules will obviously determine not only the final cutoff date for his operations, but in many cases also his sequence of operations. The lower the contour level, the earlier the deadline. Since most sites are located on or close to the banks of the river which is being flooded, those which are farthest downstream are obviously the first to be threatened. Where the period of reservoir filling is to be a protracted one, as was the case in Nubia, the variable time factor may in itself serve as a basis for the selection of one site in preference to another [cf. *Wendorf,* 1962, pp. 33–47].

Aside from time, the necessary requisites for excavation are of course trained professional personnel, equipment, and money for the maintenance of field crews and for the employment of unskilled labor. These resources are normally to be found in learned institutions; either in universities or, less commonly, in museums. Under most present-day antiquities laws, specified institutions have automatic responsibility for salvage operations in specified areas. Yet there may be times when the normal resources of an institution are inadequate to the challenge of a salvage project; in these circumstances an effort must be made to increase the available resources either through a monetary subvention from the dam-building agency or some other source, or by enlisting the cooperation of additional institutions. Reservoir projects in the United States ordinarily include a substantial appropriation for archaeological salvage, which will enable the participating institutions to purchase equipment and to employ temporary personnel above and beyond their normal operating levels. In reservoir projects abroad, and particularly in the developing nations, supplementary funds for archaeological salvage have much more often had to be raised through public or private appeals.

In sum, the salvage archaeologist must begin by measuring his available resources against the size of the job and the time allotted. If they seem inadequate to obtain even a minimum sample, he must make every effort to increase his resources through one or more of the channels suggested. When maximum possible resources have been secured, he is ready to estimate the overall sampling level which will govern his operating strategy. What percentage of the known sites in the region can he reasonably expect to excavate with the time and facilities at his disposal? His preliminary estimate will probably have to be modified continually in the light of experience, but, unless some operating figure is kept in mind, he will have no firm basis for the allocation of priorities.

Allocation of priorities, or in other words the choice of what to do and what not to do, is the critical step in strategy formulation. In the broadest terms, the goals of salvage archaeology are the conservation of material remains of the past and the conservation of historical and cultural knowledge of the past. Very often (particularly in the prehistoric periods) these go hand in hand, such that maximization of either result is more or less tantamount to maximization of the other. Yet they cannot always be reduced to a common denominator. In many parts of the Old World there are historical monuments which have long since been thoroughly examined and recorded. Their physical loss would not diminish from our scientific knowledge; yet their cultural, historical, and, if you will, symbolic value is enormous. These values cannot be weighed against scientific values on any rational basis, nor is the professional archaeologist especially competent to judge them. The choice between conservation of monuments and conservation of knowledge, where it must be made, is properly a matter of public policy rather than of archaeological strategy, and it should not be left exclusively to the archaeologist. Ideally, priorities should be established independently and on their own merits in each area, and conservation funds should be allocated accordingly.

Relieved of a policy burden which is not properly his, the salvage archaeologist can concentrate upon his familiar goal of maximizing knowledge of the past through the excavation and, when feasible, the preservation of its material remains. His main challenge is to translate that goal into a practical operating strategy. If he has decided that he can excavate, at a maximum, 40% of the remains discovered in his preliminary survey, on what basis will that 40% be selected? Obviously the archaeologist will not adopt a wholly random sampling procedure except in those rare instances where there are no indications of variability among sites. The caprices of time and nature usually assure a considerable amount of randomness in the archaeological record without the conscious intervention of man. The archaeologist will also not select automatically the largest and potentially richest sites in his inventory, though he will probably eliminate the poorest. He must not, however, run the risk of ignoring the remains of any time period or of any type of human activity about which he might reasonably hope to learn through excavation. In order to avoid that risk, his strategy must be one of categorical sampling.

An initial reduction of the 'sampling population' can usually be made on purely technical grounds. Many eroded and disturbed sites give no promise that excavation will reveal any more than is visible at the surface, and these can be eliminated from consideration at the outset. Such sites may make up as much as 50% of the total inventory; yet, because their aggregate area is usually small, their elimination may not significantly reduce the amount of work confronting the archaeologist. Usually hard choices must still be made after obviously unsuitable sites have been eliminated, and those choices must be made on other than technical grounds.

The two most common and useful bases for site classification are chronology and morphology. Since human cultures vary in time, the remains of any given era are seldom exactly the same as those of earlier and later eras. Even when houses and graves remain the same, the pottery and artifacts found in them are sure to undergo minor stylistic changes in the course of time. Periodically there are more radical changes as well, new house types or new technologies or new arts, resulting from the arrival of new peoples or the transmission of new ideas. As a result the archaeological sites in most parts of the world can be arranged in sequences of more or less well-defined time horizons, which are distinguished by such things as pottery styles, artifact assemblages, and house forms. When the sequence of 'horizon markers' is known in advance, the job of the salvage archaeologist in ordering his sites chronologically is made easy. When the sequence is not known, but cultural variation in time is suspected, it can sometimes be established in a preliminary way by trial excavations in one or more deep, stratified sites [cf. *Adams,* 1961, 1962]. Even when there are no obvious horizon markers, chronological ordering may still often be achieved through the application of such absolute time measures as radiocarbon dating and tree ring dating. Wherever a long sequence of occupation can be established, either by direct or by indirect means, chronology will certainly become one of the important bases for the allocation of priorities in reservoir salvage programs.

Aside from the factor of chronological change, the most common source of variability in archaeological sites is the fact that different types of human activity are apt to be performed at different places. Almost anywhere in the world an immediate and obvious distinction can be made between living sites and burial places. Additional categories which can often be recognized include religious sites, military sites, various kinds of manufacturing sites, and roads and trails. In the investigation of complex societies, distinctions can sometimes be made between various kinds of community sites, as for example family homesteads, villages, and market centers.

Differential activity is not the only source of morphological variation among sites. Sometimes the same environment is shared by two or more peoples, each with distinctive cultural characteristics. In these cases we may find, between contemporary sites, the same kinds of difference in house types, pottery styles, and so on which we usually find between sites of different periods. On the other hand, when the same people occupy a variety of environments, we are sure to find modifications in house form and settlement pattern in response to local resources and conditions. All of these differences will provide a basis for the classification of archaeological sites and for their categorical sampling.

Briefly, the strategy of the salvage archaeologist should be to excavate sites of all time periods, all peoples, all types of activity, and all ecological zones within the area of his operations. Other things being equal, he should attempt to sample the sites in each category at the same level, i.e., 20% or 40% or whatever his resources will allow. In practice, however, other things are rarely equal. Since his objective, properly defined, is to make a maximum addition to what is already known, the salvage archaeologist will begin from a base line of the known which will vary from period to period and from type of site to type of site.

Failure to recognize this principle has been one of the most consistent shortcomings in large-scale salvage projects, and has resulted in a great deal of work which has reinforced the known without significantly diminishing the unknown [cf. *Adams,* 1960, p. 19]. This is not rational behavior in terms of the defined goal of maximizing knowledge. The archaeologist should allocate his resources in such a way as to insure not that sites of all types and all periods will receive equal attention, but rather that at the conclusion of his efforts the level of knowledge will be about equal in each category. If certain types of sites are already better known than other types will ever be, his efforts should be concentrated entirely on the less well-known sites. The archaeologist may have strong personal opinions as to the relatively greater importance of certain periods or certain types of sites, but those opinions must be overridden by the consideration of public responsibility. Posterity may approach the same material with a very different scale of values.

Some of the largest man-made lakes, like those in Nubia and in the northern Great Plains, have flooded what can be regarded as complete environmental zones. In these areas it has been possible to develop sampling strategies without reference to what may lie beyond the limits of inundation. In most reservoir projects, however, this procedure is not scientifically valid. It is meaningless to ask how much we know and how much we can expect to learn within an area which is artificially and arbitrarily delimited. As a basis for sampling in the smaller reservoir projects, therefore, it is necessary first to delimit some culturally or naturally meaningful unit of territory of which the river basin forms a part, and then to ask how much is known and how much can be learned with respect to the territory as a whole. In the small-area projects an additional variable may affect the allocation of priorities, for the sites within the reservoir area must be seen as parts of a larger universe of sites within the surrounding region. The archaeologist must ask himself, with respect to each time period and each type of site, 'how much can I still hope to learn beyond the limits of the reservoir area?' If certain types of sites are widely distributed both within and beyond the river basin, while others are largely confined to the river littoral, the danger of a permanent loss of knowledge is obviously much greater in the case of those which are confined to the littoral. In Glen Canyon, for example, there were small farming sites of a type which is found all over the Colorado Plateau, and there were also lithic workshops, which are unique to the gravel terraces of the major rivers. These workshops received far more attention than is usual in the course of the Glen Canyon salvage project simply because of the absence of comparable sites outside the threatened area.

I do not suggest that the theoretical guidelines proposed here can ever be fully operationalized. The salvage archaeologist in the field is confronted by many problems I have not touched on in this discussion: problems of logistics, of interinstitutional cooperation, and even of international relations [cf. *Adams,* 1968]. On the basis of firsthand experience both in Glen Canyon and in Nubia I can testify to the limiting influence which these factors may set upon the development of scientific research strategies. I feel safe in asserting, nevertheless, that any reservoir salvage project will come closest to realizing its full scientific potential by following the general policy guidelines I have suggested, as far as operating circumstances will permit. In the campaign which I directed in Sudanese Nubia on behalf of the Sudan Antiquities Service, for example, we were obliged by lack of time and resources to combine the survey and excavation stages of operation, and therefore to make strategic decisions on the basis of very incomplete information. Yet, merely by keeping in mind the overall objective of a maximum increase in existing knowledge, we were able to concentrate our efforts on sites of the least-known periods and types, and to revise our strategy on a day-to-day basis as knowledge increased in some areas faster than it did in others [cf. *Adams,* 1966*b,* p. 162]. Our reward has been, I believe, a much more balanced picture of Nubian culture and history than that which emerged from the earlier salvage campaigns in the same region [*Adams,* 1966*a,* 1967, 1970].

CRITICAL RESOURCE: ORGANIZATION

Lack of funds and lack of time will often be cited as sufficient reasons for the failure to develop systematic research strategies in many reservoir salvage projects. Yet it should be apparent that another resource is at least equally critical in large-scale salvage operations. That resource is organization. It too has often been lacking or insufficiently developed in river basin programs. Within the archaeological profession there is no standing organizational structure above the level of local institutions, nor is there any national or international organization which has overall responsibility for archaeological salvage. In the United States there has existed since 1945 the Committee for the Recovery of Archaeological Remains, which has acted as an advisory body to various governmental agencies involved in dam building and other construction activities [*Brew,* 1962, pp. 14–16]. Rather similar committees, composed of archaeologists and other interested scholars, were set up to advise the Egyptian and Sudanese governments in the course of the recent Nubian salvage campaigns [*Brew,* 1962, pp. 21–22]. These committees, however, have generally contented themselves with insuring that necessary salvage operations were in fact carried out, without suggesting what their strategic objectives and procedures should be.

To the extent that overall strategic coordination has existed in large-scale reservoir projects, it has developed informally on an ad hoc, and too often on a post hoc, basis. In both the Glen Canyon and the Nubian campaigns, for example, there were no formal overall strategies because no individuals or institutions were specifically empowered to develop them [*Jennings,* 1966, pp. 3–4]; moreover, both programs were well advanced before informal patterns of communication and coordination among the participating institutions began to emerge.

As a final policy guideline for salvage archaeology I would suggest that strategy without organization is an empty advantage, and that the essential first step in any reservoir salvage project should be to set up a 'high command' responsible for strategy development and resource allocation for the project as a whole. This suggestion runs counter to the cherished individualism of the professional scholar, but it is one of the many sacrifices which the salvage archaeologist should be prepared to make in the public interest. It is the only way to insure an efficient use of all available resources in preserving the heritage of the past.

REFERENCES

Adams, W. Y., *Ninety Years of Glen Canyon Archaeology, 1869-959, Mus. N. Ariz. Bul,* vol. 33, Museum of Northern Arizona, Flagstaff, 1960.

Adams, W. Y., The Christian potteries at Faras, *Kush, 9,* 30–43, 1961.

Adams, W. Y., An introductory classification of Christian Nubian pottery, *Kush, 10,* 245–288, 1962.

Adams, W. Y., The Nubian campaign: Retrospect and prospect, in *Mélanges Offerts à Kazimierz Michalowski,* pp. 13–30, Akademie Nauk, Warsaw, 1966*a*.

Adams, W. Y., Post-Pharaonic Nubia in the light of archaeology, 3, *J. Egypt. Archaeol., 52,* 147–162, 1966*b*.

Adams, W. Y., Continuity and change in Nubian cultural history, *Sudan Notes Rec., 48,* 1–32, 1967.

Adams, W. Y., Organizational problems in international salvage archaeology, *Anthropol. Quart., 41,* 110–121, 1968.

Adams, W. Y., A re-appraisal of Nubian culture history, *Orientalia, 39,* 269–277, 1970.

Adams, W. Y., and P. E. T. Allen, The aerial survey of Sudanese Nubia, *Kush, 9,* 11–14, 1961.

Brew, J. O., Introduction, in *A Guide for Salvage Archaeology,* pp. 7–32, Museum of New Mexico Press, Santa Fe, 1962.

Daniel, G., *The Idea of Prehistory,* Pelican Books, Harmondsworth, England, 1964.

Emery, W. B., *Egypt in Nubia,* Hutchinson, London, 1965.

Hole, F., and R. F. Heizer, *An Introduction to Prehistoric Archaeology,* Holt, Rinehart, and Winston, New York, 1966.

Jennings, J. D., Glen Canyon: A summary, *Anthropol. Pap. 81,* Univ. of Utah, Salt Lake City, 1966.

Miller, W. C., Uses of aerial photographs in archaeological field work, *Amer. Antiquity, 23,* 46–62, 1957.

Trigger, B. G., The cultural ecology of Christian Nubia, in *Kunst und Geschichte Nubiens in Christlicher Zeit,* edited by Erich Dinkler, pp. 347–386, Aurel Bongers Verlag, Recklinghausen, West Ger., 1970.

Wendorf, F., *A Guide for Salvage Archaeology,* Museum of New Mexico Press, Santa Fe, 1962.

Summary: Engineering Management Techniques for Beneficial Use

JAMES M. SYMONS AND GORDON G. ROBECK

Water Supply Research Laboratory, National Environmental Research Center
U.S. Environmental Protection Agency, Cincinnati, Ohio 45268

Engineering works are often accused of causing water quality deterioration and environmental damage, but carefully engineered projects are able to improve water quality without serious environmental effects. This paper will summarize three projects that show how engineers can provide wider uses for water without significant environmental damage.

MORECAMBE BAY, UNITED KINGDOM STUDY

The paper by *Gibb and Corlett* [this volume] deals with efforts to create a freshwater reservoir at the mouths of the Leven and Kent rivers, where they flow into Morecambe Bay. Three schemes of dams across various parts of the bay were proposed and examined from several points of view. These were storage volume, geology, closing velocities, stored water quality, cost, impact on the fisheries, impact on wading birds, and influence on salmon, invertebrates, algae, salt marshes, navigation, sediment transport, transportation, agriculture, and recreation. These studies were in progress, and a report was expected in midsummer 1971.

IMPACT ON WATER QUALITY OF OPENING WATERSHEDS FOR RECREATION

For many years, professionals have argued over the wisdom of permitting recreation on drinking water reservoirs and on the watersheds surrounding these reservoirs [*Carswell et al.*, 1969; *Baumann*, this volume]. In 1966 the U.S. Public Health Service Water Supply and Sea Resources Program (now the Water Supply Research Laboratory, National Environmental Research Center, U.S. Environmental Protection Agency) initiated a study to determine the quality of water coming off three watersheds in the northwestern part of the United States, one well protected, one with some recreation and human use activity, and one with unlimited recreation and human use activity.

The results of this study [*Lee et al.*, 1970] showed that, within the limits of the human use studied, no impact on water quality could be found. Studies on total coliform, fecal coliform, and fecal streptococci densities in the water flowing from all these watersheds showed statistically similar patterns. Two reasons were advanced. First, the maximum human use densities only varied between 0.7 and 2.2 man-days/km^2 (0.7 and 5.7 man-days/mi^2) among the watersheds. Second, the animal population per unit area was much higher than the human use level, was quite similar (17.3–22 animals/km^2 or 45–57 animals/mi^2) among the three watersheds, and therefore was the dominant influence on water quality.

A second finding of importance was the isolation of pathogenic *Enterobacteriaceae* from 28% of the samples examined from the well-protected watershed. This finding, coupled with the occurrence of periodic high turbidities in the water flowing from the well-protected watershed, indicated the need for turbidity control of all surface waters, even those flowing from well-protected watersheds, to permit effective disinfection.

ARTIFICIAL DESTRATIFICATION FOR WATER QUALITY CONTROL

Thermal stratification often causes a severe deterioration in water quality in the hypolimnion of lakes and reservoirs. If these bodies of water are used to supply municipal drinking water, this deterioration in quality places a burden on water purveyors, since additional treatment must be provided to remove these reduced materials if the finished water quality is not to deteriorate. In an effort to provide one engineering technique to relieve this burden, a study was begun to determine whether sufficient mixing energy could be added to a lake or reservoir to overcome the density differences caused by thermal stratification and thereby avoid any water quality deterioration. The results of this study have been reported in detail by *Symons* [1969] and summarized by *Symons et al.* [1970].

During the summers of 1964, 1965, and 1966, three small lakes near Cincinnati, Ohio, were mixed to determine whether water quality could be improved and whether any detrimental effect would occur when this technique was employed. Many water quality parameters were monitored at various depths and various times throughout the summer and compared with similar measurements taken in a nearby unmixed lake, but the parameters of most importance were temperature; the concentrations of dissolved oxygen (DO), sulfides, iron, and manganese; and the densities of plankton. Tests were made with both a mechanical pump, which drew water from near the bottom and discharged it at the surface, and a compressed air system, which released air through diffuser stones laid on the bottom of the lake.

Results indicated that the lakes could be made isothermal, DO could be maintained at all levels, and reduced materials could be either oxidized or prevented from forming depending on when the mixing operation began. The results also indicated that plankton populations could be reduced and their dominant species could be altered. No detrimental effects could be determined. *Malueg et al.* [this volume] and *Oskam* [this volume] confirm this reduction in plankton density and change in species.

In 1970 the committee on Quality Control in Reservoirs of the Water Quality Division of the American Water Works Association polled 33 water utility managers who were using artificial destratification for raw water quality improvement. Of the 26 who responded, 86% said that they considered the project successful and reported some combination of improved water treatment, improved raw water quality, improved finished water quality, and/or improved esthetics in the lakes and reservoirs. A summary of all the answers to the eight-page questionnaire completed by these water purveyors, including some details on cost, has been published [*American Water Works Association Committee*, 1971].

In summary, the studies reviewed in this paper show that man can mold nature for his benefit and that, if the molding is done carefully enough and with due consideration for secondary effects, beneficial uses can be obtained without significant damage to the ecology.

REFERENCES

American Water Works Association Committee, Artificial destratification in reservoirs, *J. Amer. Water Works Ass.*, *63*(9), 597–604, 1971.

Baumann, D. D., Perception, attitude change, and the multiple use of domestic water supply reservoirs, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Carswell, J. K., J. M. Symons, and G. G. Robeck, Research on recreational use of watersheds and reservoirs, *J. Amer. Water Works Ass.*, *61*(6), 297–304, 1969.

Gibb, O., and J. Corlett, Estuarial storage in the United Kingdom: Morecambe Bay, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Lee, R. D., J. M. Symons, and G. G. Robeck, Watershed human-use level and water quality, *J. Amer. Water Works Ass.*, *62*(7), 412–422, 1970.

Malueg, K. W., J. R. Tilstra, D. W. Schults, and C. F. Powers, Effect of induced aeration on stratification and eutrophication processes in an Oregon farm pond, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Oskam, G., A kinetic model of phytoplankton growth and its use in algal control by reservoir mixing, in *Man-Made Lakes: Their Problems and Environmental Effects, Geophys. Monogr. Ser.*, vol. 17, edited by W. C. Ackermann, G. F. White, and E. B. Worthington, this volume, AGU, Washington, D. C., 1973.

Symons, J. M., Water quality behavior in reservoirs—A compilation of published research papers, *Publ. 1930*, Public Health Serv., Cincinnati, Ohio, 1969.

Symons, J. M., J. K. Carswell, and G. G. Robeck, Mixing of water supply reservoirs for quality control, *J. Amer. Water Works Ass.*, *62*(5), 322–334, 1970.

Estuarial Storage in the United Kingdom: Morecambe Bay

O. Gibb

Water Resources Board, Reading, England

J. Corlett

Natural Environment Research Council, London, England

The legislation governing the control of water conservation in England and Wales was changed radically in 1963 by the passing of the Water Resources Act, which created 29 river basin authorities with responsibility for controlling and securing the proper development of all water resources in their areas and established the Water Resources Board to guide and assist the river authorities in their new functions and to advise the government on a national policy of water conservation. The board has now completed three major regional surveys covering the whole of England and Wales (with the exception of the southwest peninsula, whose needs and geographic location isolate it from any impact on national policies) and has produced alternative regional strategies designed to meet the needs of each region independently up to the turn of the century. They are now engaged in integrating these three regional surveys into an overall national strategy that will seek to optimize the development of water resources over the whole country up to the year 2001.

Residual rainfall over the whole of England and Wales amounts on the average to about 4 m^3 (850 Imperial gal.) per person per day. Storage reservoirs totaling about 1.6 10^9 m^3 (350,000 million Imperial gal.) of capacity, together with storage generated underground, have sufficed to match the variation in natural runoff to the daily needs of nearly 50 million people. It seems likely that the addition of another 1.8 10^9 m^3 (400,000 million Imperial gal.) of artificial storage (10 days of average residual rainfall) will suffice to meet our needs up to the end of the century.

This future storage requirement is modest in comparison with that of other countries; for example, in the United States, existing storage amounts to the equivalent of about 100 days of residual rainfall. Although sites for really massive storage are extremely limited, the board's surveys have indicated that about 4 times the present volume of storage could be provided, without destroying whole villages or hamlets, at costs comparing reasonably with those of the past. Nevertheless, the social problems of acquiring inland sites are likely to be considerable, and water resource planning has perforce included consideration of less conventional, although probably more expensive, forms of developments so that the economic consequences can be weighed against the less easily quantified disadvantages of social disturbance at inland sites.

In a small island with a long indented coastline it is not surprising that attention has focused on the possibility of using river estuaries for the storage of freshwater that may ultimately be transported directly into supply or may be used to regulate the flows of other rivers.

The immediate attractions of estuarial storage are that very large volumes of storage can usually be made available with little or no interference with existing land use and that all the runoff from the river basin that drains to the estuary can be used. The disadvantages arise from the problems of constructing reservoir embankments within tidal waters and expelling the sea, maintaining a reasonable water quality at the downstream end of a river basin, and minimizing interference with land drainage on the shores of the estuary, with fisheries, and with navigation in nearby coastal waters or the rivers feeding the estuary.

Four major estuaries, the Solway, Morecambe, Dee, and Wash, have been subjected to preliminary desk studies, which indicated that they would provide supplies of about 9000 10^3 m^3

(2000 million Imperial gal.) per day between them. No further studies of Solway are proposed at present because of its remoteness from the centers of water demand, and authority is still awaited for a full feasibility study of the Wash. But full feasibility studies are in hand at Dee and Morecambe and should be completed in 1971.

The original motivation for the study of the Dee estuary was the need for an additional road across the estuary to provide improved access from the densely populated industrial conurbations on Merseyside to north Wales, which already provides recreational facilities for the Merseyside population along the north Welsh coast and could provide land on the Welsh side of the Dee estuary for housing and industrial development. The opportunities for water conservation were realized and incorporated shortly after the transport-planning study was begun. The preferred form of water storage that has evolved from the study is the construction of a series of bunded reservoirs within the estuary filled by water pumped from upstream of a tidal barrier constructed across the reshaped estuary. The shape and location of the water storage structures can be varied to suit almost any road-crossing location without greatly increased costs, and substantial savings can be effected by combining the road crossing with the embankments of the water storage impoundments. However, the final choice of scheme is likely to be affected as much by other planning considerations as by optimization of the costs and benefits of water supply and transport.

The primary purpose of the Morecambe Bay feasibility studies was water conservation. Nevertheless, because of the scale of the project and the potential consequences, detrimental as well as beneficial, in other spheres, the study was designed from the outset to cover all aspects of possible multipurpose schemes. The successful integration of the main objective of water conservation with the complementary or conflicting requirements of the natural or economic environment means that there must be a continuing dialogue between the engineers, scientists, planners, and economists throughout all stages of the study. Interchange of information and preliminary design ideals leads to acceptable modifications to design that may ameliorate unavoidable losses or enhance potential gains in the evolution of a multipurpose scheme.

The government departments, professional organizations, and consultants involved in the study are too numerous to detail in this brief description, but the principal contributors of engineering studies were Sir Alexander Gibb and Partners, Consulting Engineers, and the Hydraulics Research Station, Ministry of Technology, who supplied the hydraulic models; the principal contributor of natural environment studies was the Natural Environment Research Council; and the principal contributor of economic environment studies was the Morecambe Bay Economic Study Group, Department of the Environment. For the purposes of this paper the studies are described under these separate headings, although all were integrated into a common program by a steering committee set up by the Water Resources Board, who had overall responsibility.

ENGINEERING STUDIES

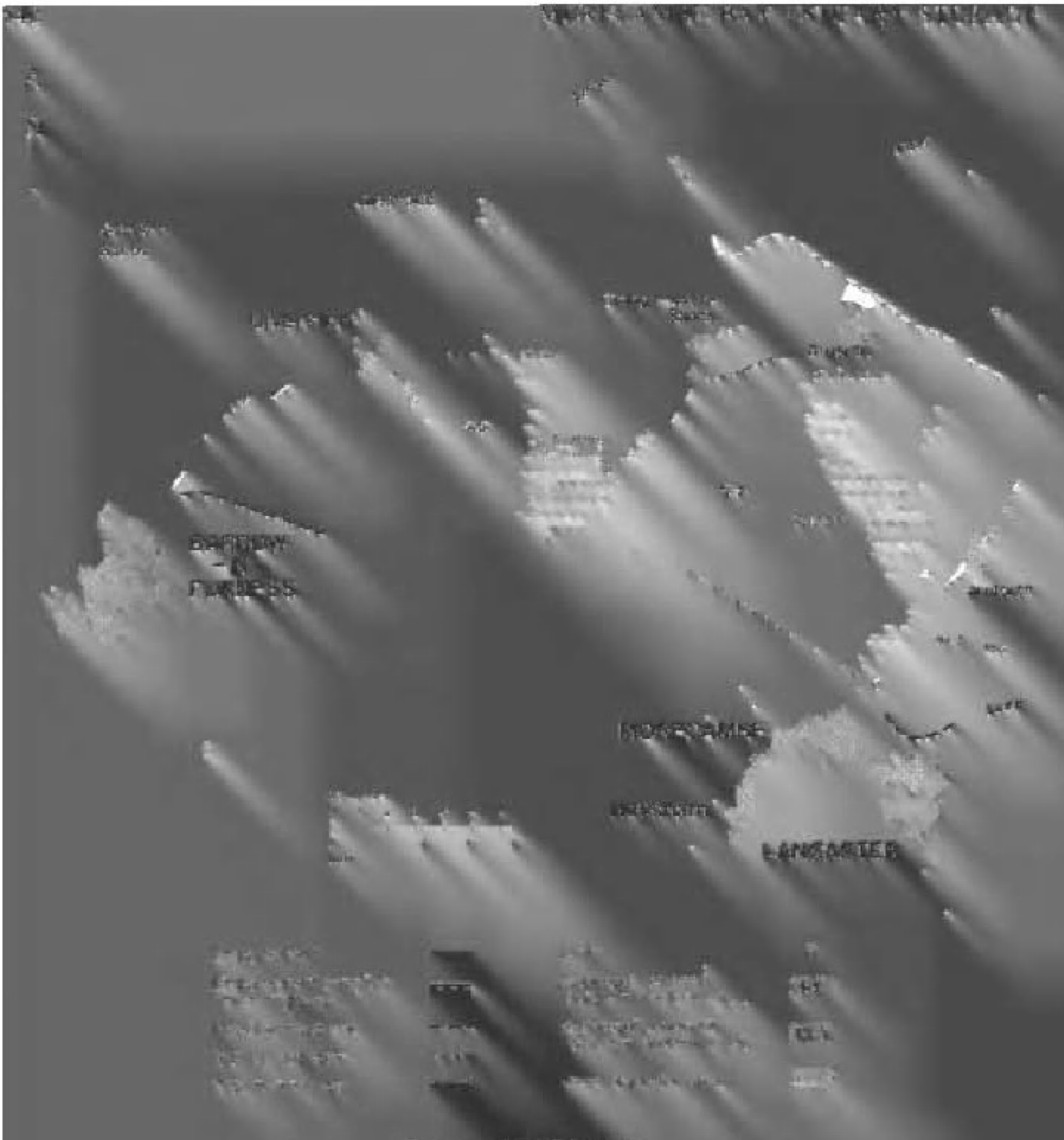
The desk study report suggested that estuary schemes at Morecambe could provide safe yields to supply of about 2050 10^3 m^3/day (450 mgd). Studies of the hydrology of the rivers discharging into the bay indicated that storage of between 286,000 10^3 m^3 (63 billion Imperial gal.) and 322,000 10^3 m^3 (71 billion Imperial gal.) would be required to provide this yield, together with residual flows into the estuary to maintain runs of migratory fish. The storage requirements vary with the location of the tidal barriers, the catchment upstream, and the method of replenishment of storage, i.e., direct impoundment or abstraction by pumping from upstream of a tidal barrier.

From the data obtained from the topographic and hydrographic surveys it was concluded that the storage could be provided by any one of three basically alternative schemes.

In scheme 1 a full barrage 18.6 km long would enclose about a third of the area of the bay (Figure 1), 103 km^2 out of a total of approximately 340 km^2.

In scheme 2, smaller separate barrages (total length 11.4 km) across the estuaries of the main rivers, the Kent and Leven, would connect the east and west shores of the estuary with the central Cartmel peninsula, additional storage being provided in a bunded reservoir located either off the Cartmel peninsula (Figure 2) or on the east shore (Figure 3).

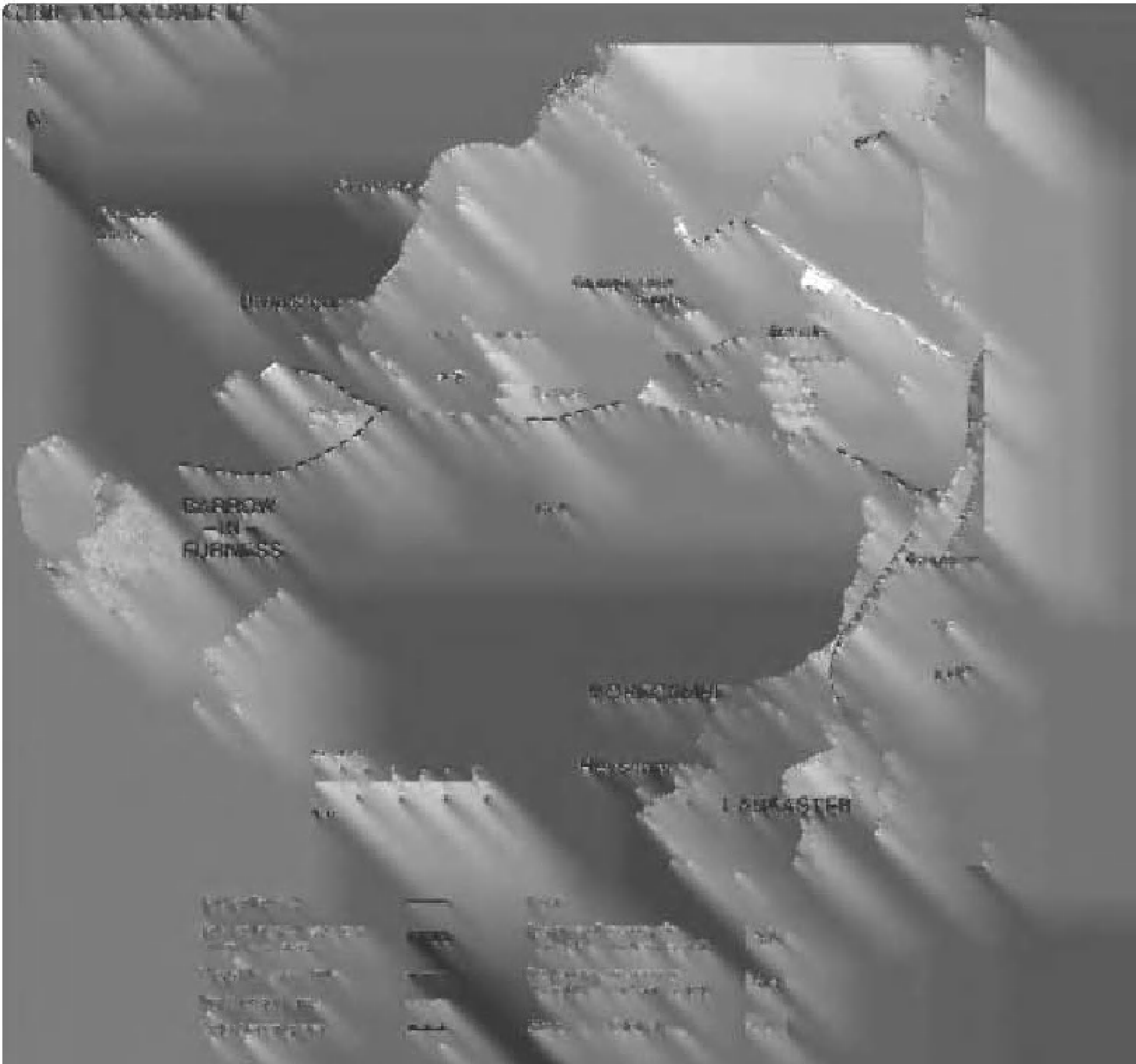
In scheme 3, tidal barriers would be built high up the estuaries of the Kent and Leven to provide intakes from which water would be abstracted



[illegible]

[illegible]

[illegible]


BARROW
-IN-
FURNESS
MORECAMBE
LANCASTER

[illegible]

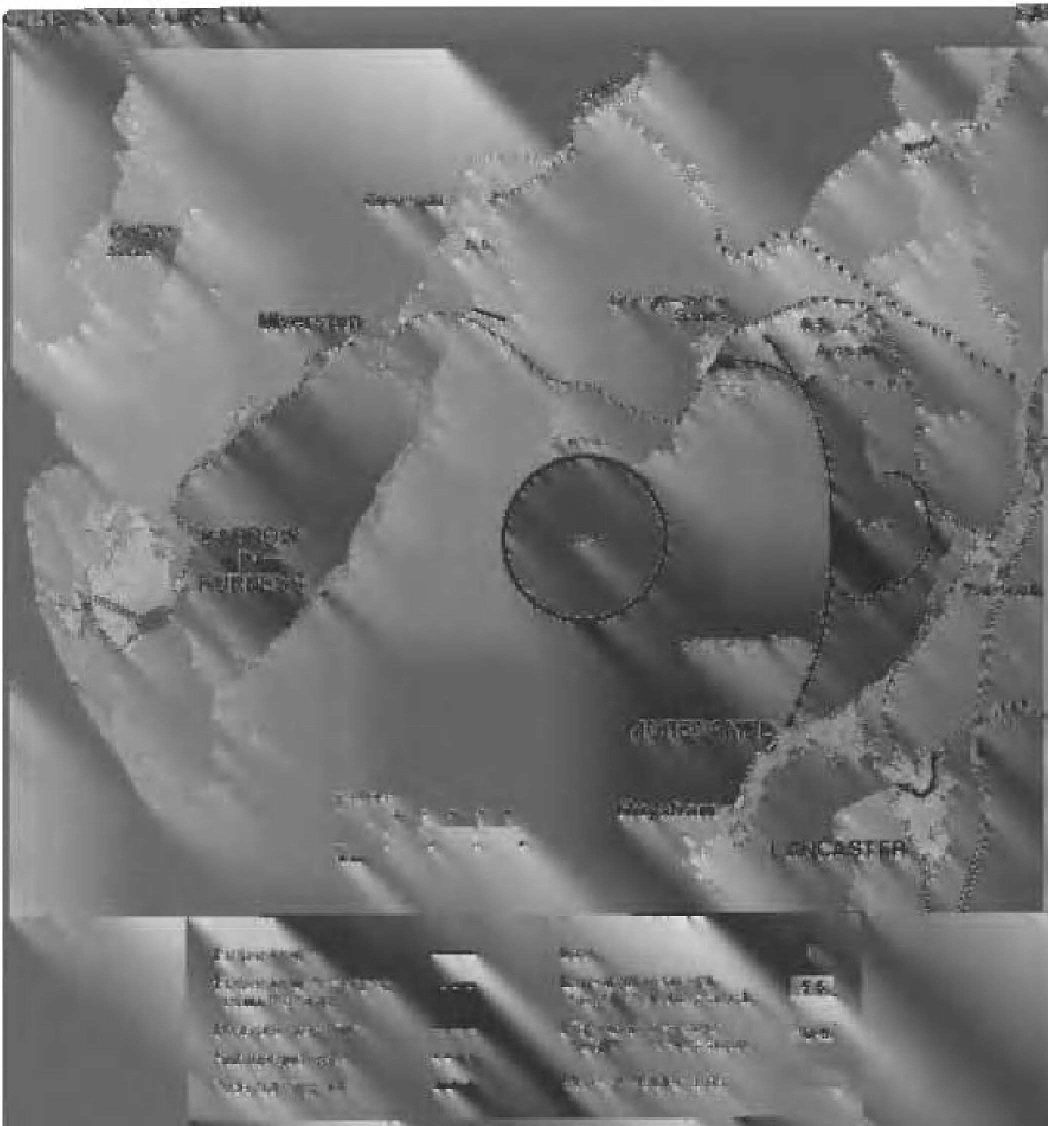
[illegible]

[illegible]

[illegible]


BARROW-IN-FURNESS
LANCASTER

[illegible]


LANCASTER

[illegible]

[illegible]

[illegible]

The intertidal sandbanks support a rich fauna of invertebrates, which forms the food for fish and for the large flocks of wading birds that winter in the area. As is usual in estuaries, the fauna consists of large numbers of animals of a few species. During the feasibility study, one large and three smaller surveys were made of the sand fauna, and the animals from about 2000 sand samples were identified and counted. These showed that the area with the densest fauna is between mid-tide level and high water of neap tides. Much of this area would be inside a reservoir in scheme 1, but accretion outside a barrage would provide new areas for colonization.

Morecambe Bay is an important wintering area for many species of wading birds that breed in northern Europe and Greenland. Regular censuses have been carried out monthly for 2½ years, and studies have been made on the food and feeding behavior. About 165,000 waders are present each winter, and three species, knot, dunlin, and oystercatcher, make up about 90% of the numbers. The birds have regular high-tide roosts, and each species has its own preference for feeding and roosting areas. Two extremes are represented by dunlin, which is commonest in the inner part of the bay and of which 75% might be disturbed by a barrage scheme, and by the bar-tailed godwit, which is in the outer part of the bay and would not be disturbed.

Many species of duck and two species of geese are found on the bay in winter, and regular censuses have been carried out for 2 years. The dabbling ducks are the commonest group; they would lose some feeding areas on the marshes but should gain new areas around the reservoirs. Diving ducks should find new areas to colonize, and sea ducks should not be affected. The duck affected most by the loss of habitat would be the estuarine shelduck, which depends on the foreshore for feeding and roosting in winter.

The Leven and Kent are salmon rivers. Salmon and sea trout also enter some of the smaller rivers, and there is commercial salmon fishing in the estuaries. To maintain the 'runs' of fish, suitable fish passes must be built in each barrage, and problems of attracting fish to the passes from the sea must be solved. The main problems are having sufficient water from the 'home' rivers discharging into the bay and maintaining adequate channels through the sandbanks. The volume of water required cannot be estimated with accuracy, and experiments in management will be needed once the passes are put in operation.

Any reservoir in Morecambe Bay will be colonized naturally by trout and coarse fish from the catchment. The first colonizers are likely to be trout, perch, minnow, and pike. Roach and rudd are likely to come later, and bream and tench later still. There may be a reasonable trout fishery during the first few years, but the reservoirs will develop naturally into coarse fish waters. Eels are common in the area, and the reservoir habitat should suit them, so that an eel fishery could eventually be developed.

A reservoir in Morecambe Bay is likely to be colonized rapidly by zooplankton and insect larvae carried down the rivers from lakes Windermere and Coniston. A study was carried out on the drift of invertebrates out of Windermere and down the 4 km of the River Leven to the estuary. The first insect colonizers will probably be nonbiting midges, which may be a nuisance until a balanced community of animals, including fish, is established.

The water from all the rivers entering the bay was sampled at frequent intervals over 3 years, and chemical analyses were carried out. A comprehensive program of bioassay tests was carried out on the river waters singly and in mixtures; the algae used were those likely to cause a nuisance as 'blooms' or in the treatment works. The results of the tests and the analyses of the waters suggest that any mixture containing water from the River Kent would be potentially rich and would support algal blooms. However, as was mentioned previously, the potentiality might be reduced by removing the phosphorus from the sewage discharged into the Kent.

One of the dominant features of the fringes of the bay consists of extensive areas of salt marshes. Around the inner part of the bay, there are 1500 ha of marsh, of which about 1200 ha are characteristic sheep-grazed saltings, dominated by three species of grass. With a change to a freshwater regime, there would be a change in the species composition, and the species that will become dominant will depend on many factors, the most important of which are the level of the water table, the nutrient status, the timing of barrage construction, and wind effects.

ENGINEERING-ECONOMIC ENVIRONMENT STUDIES

Navigation. The effects of the water conservation schemes on the tidal regime of the bay and adjoining coastline were studied in a large physical model of the whole bay. (Model scales were 1 in 1000 horizontal and 1 in 100 vertical, the total area of the model was 49 × 36 meters, the velocity scale was 1/10, and the time scale was 1/100.) Initially, the model was constructed and operated as a fixed bed model to indicate the probable changes in tide levels and velocity distributions when the water conservation structures were imposed. As was expected, the full barrage (scheme 1) had the most marked effect, the duration of the flood being shortened and the duration of the ebb tides being extended with consequent velocity changes, which would be detrimental from the point of view of siltation seaward of the barrage. These effects are most significant on the east coast of the estuary, where some siltation of the approaches to the port of Heysham is almost certain to result. Surprisingly, the smaller separate barrages in scheme 2, despite the smaller reduction in tidal volume, caused effects almost as severe as those of scheme 1. Scheme 3, on the other hand, had much less effect and, with the shaped storage and training wall on the east shore determined as a result of model testing, caused almost insignificant changes in the tidal regime elsewhere in the bay.

Fixed bed model tests cannot of course reproduce the complete sequential effects of siltation seaward of the proposed works. To study these effects, the model was converted to mobile bed operation, the movement of sand, the predominant bed material, being simulated in the model by wood grains. These tests are still continuing, and it is hoped, by correlating radioactive tracer studies in the model with similar studies carried out previously in the prototype, to obtain some quantification of the extent of siltation likely to occur. Until these tests are completed, schemes 1 and 2 pose a threat to navigation at Heysham, the cost of which, in terms of additional dredging, cannot be ascertained.

Transport. On the transport credit side the barrage structures of schemes 1 and 2 would be capable of carrying dual two-lane highways, which would generate considerable net transport benefits. A traffic prediction model was developed to simulate traffic movements on a section of the national road network. Population, employment, car ownership, and traffic data for 1966 were used to 'tune' the model to give the best simulation of known conditions. The model was then used to simulate traffic on the various networks that could be developed in 1981, following the introduction of cross-estuary links, by using forecasts of population employment and increasing car ownership. The best networks were identified, and the maximum net benefit, the total benefit in social cost-benefit terms less transport specific costs, was determined by comparison with the base 1981 network. The analyses took into account a current proposal to construct a new road across the Kent estuary at Arnside, which, if it were constructed in advance of the barrage, would reduce the benefits of a barrage road. To obtain net present values of total benefits in time, the calculated single-year benefits at 1966 and 1981 were interpolated and extrapolated in the light of national forecasts of future numbers of vehicles modified subjectively to take account of trends in vehicle usage and local variations indicated by the 1966 and 1981 analyses. The estimated 1981 net present values of the transport benefit lie between £5 million and £20 million depending on the staging and assumptions about the new road at Arnside.

Agriculture. Bordering the Kent and Leven estuaries below the 8-meter (25-foot) contour are low-lying agricultural lands whose drainage is effected by gravity outfalls that at present discharge only at low tides. All the proposed schemes will affect these lands to different extents by the substitution for the present tidal conditions of stable water levels upstream of the tidal barriers, gravity discharge from the drainage outfalls thus being inhibited. The maintenance of existing land drainage under these new conditions will require the installation of land drainage pumps. At little additional cost the pumping installations could be designed and operated to provide an overall improvement in drainage conditions, which in turn would justify the improvement of underdrainage to the land involved and a consequent improvement in productivity.

The calculated net benefits resulting from the improvement in agricultural output, after allowing for the costs of underdrainage of the land affected by each scheme, amount to about £0.5 million. The net benefits are expressed here as a capitalized net increase in annual output at 10 years' purchase, which is roughly equivalent to the net present value of benefits at the discount rate of 10% adopted elsewhere in the study.

All schemes would involve the enclosure of areas of shallow water around the edge of the bay, which would be detrimental to water quality. Therefore these areas should be excluded from water storage by the construction of polder embankments. (In scheme 1 this area amounts to 15 km^2.) It was first thought that these polder areas might be reclaimed and brought into agricultural use. However, studies of soil samples taken on a 1-km grid over all the polder areas indicated that the organic content was low, the nutrient-retaining capacity was poor, and the fine sand and silt content was so high that the provision of effective drainage would be either impracticable or uneconomic. Agricultural use has therefore been discounted, and consideration has been given to the use of polder areas for amenity and recreational purposes and nature conservation.

Fisheries. The creation of a barrage lake in scheme 1 would produce both losses and gains to fisheries. So far as commercial fisheries are concerned, some losses would be certain. Although these might be of considerable significance locally in terms of losses at first sale and their effects on local processing and packaging industries, they would be small in relation to overall costs and benefits in other spheres and might well be outweighed by the possible gains from an eel fishery in the lake. Schemes 2 and 3 would have much smaller effects.

Amenity and recreation. The ecological studies have provided an assessment of the probable effects of the schemes on the wildlife of the bay. Other studies have provided subjective assessments of the overall effects on nature conservation in the surrounding area, of the impact of the scheme on the landscape of the bay, and of the effects of changes from tidal to controlled water levels. All schemes will have effects considered detrimental to some interests, but these cannot at present be valued satisfactorily in monetary terms, and in the final choice their importance can be judged only by the weight of informed opinion. Nature conservationists may well contend that the provision of water storage at inland sites is preferable to the loss of wildlife habitats, which have international as well as national significance.

On the other hand, all schemes, to some degree, provide opportunities for the provision of recreational facilities and the creation of new freshwater conservation areas. Scheme 1 has the greatest potential and could provide facilities for 100,000 day visitors within 2 hours traveling time of a population of about 8 million. These new facilities would be created in an area adjoining the existing Lake District National Park, and an attempt has been made to assess the net benefit that would be generated in social cost-benefit terms on the assumption that scheme 1 would extend the Lake District recreational area and would provide similar attractions nearer the centers of population in the south and southeast.

The assessment was based on a 'Clawson' approach using travel costs as a proxy for price and origin-demand curves based on data available for the Lake District for 1966. Forecasts for 1981, based on projections of population, car ownership, travel time, and costs, provided the basic data from which assessments of net benefit (consumer surplus less specific costs) were derived.

For scheme 2 the results obtained by analogy with the Lake District were modified subjectively to take account of differences in travel time and reduced capacity. The facilities offered by scheme 3 would be more limited and possibly more local in appeal, and the analogy with the Lake District was not considered valid. Crude assessments were made based on comparisons with similar facilities elsewhere in the country.

For all schemes the net benefits in time were calculated for a number of assumptions on length of holiday period and growth of future demand by extrapolation of the basic data for 1966 and 1981. The present-value sum of net benefits discounted at 10% to 1981 lay between a maximum of £5 million for scheme 1 and a minimum of £0.5 million for scheme 3. None of these assessments of recreational benefits can be regarded as being as meaningful as the assessments in the transport and agricultural sectors. In addition to the tenuous nature of the basic philosophy of the method, about which there is still room for debate, these particular assessments have necessitated many assumptions and subjective judgments because of the lack of 'real' data. They are probably most useful as an indicator of the order of comparison between alternative schemes.

Wider economic aspects. The possibility that freshwater reservoirs might be used as sources of surface cooling for power stations was investigated by the Central Electricity Generating Board. Their conclusion was that any possible benefit that might be derived in this way was likely to be more than offset by unusually difficult foundation conditions at sites around the bay and by additional transmission costs, since the location is remote from the main centers of demand for electrical power. The main effect of any of the proposed schemes on the nearby ports of Heysham and Barrow would lie in any changes in the costs of dredging the approaches to these ports that might result from the construction of works in the bay. This apart, none of the proposed schemes, including those that incorporate a cross-estuary road link, would have any significant effect on the present or future trading potential of these ports. It is also unlikely that industries sited in the vicinity of the bay would enjoy price advantages for water supplies in comparison with industries located in other areas nearby.

Thus the effects of any estuary scheme on the general economy of the area would be limited to the growth in employment that the scheme itself would generate, together with the incidental effects of the improvement in communications for schemes that incorporate a new road link. The impacts of the alternative schemes were studied under the general headings of: (1) temporary employment during the construction period and attendant short-term benefits to local trade and services, (2) new permanent employment that would be provided following the development of the major recreational centers and associated service industries, and (3) improvement in employment opportunities, mainly for areas in the west of the bay, that would follow the provision of a new road link. The studies have provided an indication of the most probable changes in employment levels. More precise evaluation was not considered possible not only because the time scale is long and forecasting employment levels more than 5 years ahead is almost impossible but also because the processes involved in the impact of such radical developments is complex and techniques for forecasting their effects are still in their infancy.

The authors regret that this account of the studies that have been undertaken at Morecambe is presented without conclusions and in many instances without specific data, but the individual elements of the studies are only now approaching completion, and they have yet to be appraised by the Water Resources Board, who hope to present their conclusions to the government in a report in midsummer of 1971. However, it will be obvious that only certain features of the full impact of the schemes can be quantified. The final report must endeavor to strike the right balance between the weight to be attached to those factors whose costs and benefits have been measured and to those that owing to their intangible nature can only be identified.