Summary: Physical Limnology of Man-Made Lakes

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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; *p*H 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.

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