Current Developments in Applied Limnology

BYRON G. TORKE
Ball State University, Muncie, Indiana

Some 37 years have passed since Raymond Lindemann published his classic paper entitled "The trophic-dynamic aspect in ecology". At the time of its publication in 1942, ecology represented a number of rather independent lines of research, largely derived from systematically based field investigations and descriptive natural history studies which had developed from the traditions of the 19th century. Much concern was given to the naming and classification of ecological patterns and processes. Lindemann's contribution was two-fold. First, it stressed the role of trophic relations, that is, the transfer and flow of matter and energy and the quantification of these processes in communities, as fundamental to the understanding of ecosystem function and development. Secondly, his paper established the validity of a theoretical orientation in ecology. By formulating a theoretical model of trophic interactions, Lindemann was able to develop a number of predictions, by which the validity of the model could be tested. This established the idea that ecosystems can be studied from an experimental standpoint and has been of inestimable significance in the development of modern approaches in aquatic ecology.

The International Biological Program (IBP) was sponsored by UNESCO during this decade and several lakes around the world, including Lake Wingra in Wisconsin and Lake George in New York State, became the focus of intensive, interdisciplinary studies, which attempted to include all pertinent aspects of lake ecosystem function and productivity, with the ultimate goal of developing predictive models which would aid in protection and management of the world's lake resources. The results of many of these whole-lake ecosystem studies have been published, and although some of the original questions remain unanswered and many new questions have been proposed, a general framework of lake ecosystem function and an understanding of the effects of man's activities on the trophic relations and productivity of lakes has emerged. With the current problems of population growth and technological development and their often drastic effects on lake ecosystems, it is essential that we begin to devote efforts to protecting and managing our lakes so that they can continue to serve as resources for future generations. Therefore, in this presentation, I will attempt a brief overview of some of the most important recent concepts leading to the development of lake problem assessment and management strategies.

Lakes undergo a natural aging process, which leads to their eventual enrichment and final extinction, which has been most commonly termed "eutrophication."

A much clearer understanding of the process involved in eutrophication was gained by the advent of studies of lake development or evolution as evidenced by sediment cores. Early studies in European lakes by Lundquist (1927) and Gams (1927) showed that lake sediments very often exhibit a stratigraphic sequence in which inorganic silt or clay is overlain by more organic sediments.

Paleolimnological studies on glacial lakes in North America (Hutchinson and Wollock, 1940, Deevey, 1942) confirmed the results of these earlier studies in Europe. Typically the newly formed lakes undergo an initial oligotrophic phase during which the nutrient concentrations and phytoplankton biomass increase slowly over time. This phase may in some cases occupy a time span of several thousand years.

After some time, the input of nutrients from the watershed and recycling of nutrients from the sediments is balanced by the export of nutrients through the lake's outlet and/or by permanent loss to the sediments. This initiates a trophic equilibrium phase which is characterized by relatively stable and unchanging nutrient concentrations and biological production. This phase may be of very long duration.

Pretty Lake in Indiana was studied by Wetzel (1970) who examined the distribution of sedimentary chlorophyll degradation products per gram of organic matter in cores which were aged by a C-14 technique. The lake was formed about 14,000 B.P., and after an initial oligotrophic phase, which lasted about 4,000 years, entered a trophic equilibrium phase, which has persisted up to the present with perhaps a slight overall decrease in the concentration of nutrients and production of phytoplankton.

The trophic equilibrium phase comes to an end when sedimentation reduces the lake volume and mean depth beyond a certain point. After this point is achieved, the littoral plant community rapidly expands to the limnetic regions, and completely dominates the metabolism of the lake. Extinction may follow one of three routes, according to Wetzel and Allen (1970), depending on the amount of allochthonous input of $CaCO_3$ and nutrient inputs from both the watershed and the lake's sediments.

Cultural or man-induced eutrophication, in contrast to natural eutrophication, typically takes place over a much shorter time span.

Cultural Eutrophication is defined as the increase of productivity and sedimentation rates in lakes as a direct consequence of the activities of man. It is often difficult to make clear distinctions between the problems of eutrophication and other problems associated with man's activities such as erosion caused by poor land use activities and certain pollutant sources producing toxic effects on aquatic organisms. Often these and other conditions occur along with and are interrelated with the effects of nutrient enrichment.

In defining the problems of eutrophication, one must separate the causes and effects. Usually the effects, in cases of advanced eutrophication, are obvious even to the casual observer, whereas the causes may or may not be easily identified and eliminated. Vollenweider (1971) distinguishes the following symptoms as being typical of incipient cultural eutrophication.

1. An increase in the quantity of the biomass of either the aquatic macrophytes and periphytic algae near the shore or of the algae of the open water regions or both. Usually such increases are accompanied by a decrease in the number of species that are typical of oligotrophic waters and, concurrently, by an increase in the number of characteristically eutrophic species.

2. Changes in both the numbers and types of animal species in the littoral, benthic, and plankton communities and also in the fish populations. In the very beginning stages of culturally induced eutrophication, an initial increase in biomass of various segments of the animal community is often observed. At a more advanced stage of eutrophication there is typically a shift of oligotrophic species to eutrophic and facultative species. In lakes of north-temperate regions, Salmonid and Coregonid fishes are typically replaced by Centrarchid and Cyprinid fish which are more tolerant of the existing conditions.

3. Physical and chemical changes include a decreasing water transparency and an accompanying change in water color. There is often a development of an oxygen maximum or minimum in the metalimnion and in severe cases this condition may alternate on a diurnal basis. Because of an increased input of organic materials to the sediments, there is a gradual overall decline in the oxygen concentration of the hypolimnion during the period of summer thermal stratification. There is an increase of the average nutrient level, that is, concentrations of phosphorus and nitrogen, which can easily be detected by chemical methods.

As the process of eutrophication advances, all of these symptoms become more pronounced finally leading to almost catastrophic changes. This advanced stage is usually characterized by massive blooms of blue-green algae (*Oscillatoria*, *Anabaena*, *Aphanizomonon*, etc.), an enormous proliferation of aquatic macrophytes, periphyton, and floating algal mats along the lake shore, the total elimination of oxygen from the hypolimnion during the summer, the accumulation of considerable quantities of phosphorus and nitrogen, the appearance in the hypolimnion of hydrogen sulphide, ammonium ions, iron and manganese, non-mineralized organic substances and sometimes the formation of methane, the disappearance of the benthic fauna in the deeper regions of the lake and massive fish kills. Such changes present serious consequences for man's use of the lake. Besides the drastic losses incurred from an aesthetic standpoint, difficulties in terms of water use and human health result. Because of problems of filter clogging, precipitates of iron and manganese, pronounced corrosion, unpleasant taste and odor, etc., direct use of water for drinking and industrial purposes is severely impaired.

From the recreational standpoint, advanced eutrophication is highly detrimental and gives rise to various unpleasant situations, such as various forms of skin irritation known as swimmer's itch, more frequent insect bites, tangling of motor boat props in weeds, and poor fishing. It is obvious that such changes do have serious repercussions on the economic value of lakes and their surroundings, including local governments, industry, resorts and other recreation based businesses, fisheries, cottage owners, and local residents. Therefore, preventative and corrective measures to curb the effects of eutrophication are highly desirable to all concerned.

It is quite apparent from numerous studies that nutrient inputs are the fundamental cause of the phenomena collectively known as cultural eutrophication. The importance of phosphorus and nitrogen has been the subject of major symposia and reviews (e.g. Nat. Acad. Sci. 1969, Likens, 1962). In lakes of the north temperate zone there can be little doubt that phosphorus is most often the limiting nutrient, that is, the element in shortest supply necessary for algal growth.

Perhaps the most important contribution regarding the concentration of nutrients in relation to eutrophication is the nutrient loading concept of Vollenweider (1968). Although nutrient concentration rather than nutrient supply will control the biomass of phytoplankton and macrophytes in a lake, nutrient loading is directly responsible for nutrient concentration. Vollenweider's early model (1968) for nutrient loading involved plotting the areal total phosphorus loading against the mean depth on a log-log scale. From this plot, straight lines could be arbitrarily drawn separating the lakes into types: oligotrophic, mesotrophic, and eutrophic. This initial simple model was received by the scientific community with much enthusiasm, because, for lakes with phosphorus loading data available, the predicted trophic states in most cases closely matched the observed trophic status as described by other criteria of lake trophy: transparency (secchi disc depth), chlorophyll concentration, oxygen depletion in the hypolimnion, etc. However, Dillon (1975) criticized Vollenweider's model because it fails to consider lake flushing rates. Dillon's model includes a factor for hydraulic flushing rate and a coefficient for the retention of phosphorus in the lake. Dillon applied this phosphorus loading equation to two Ontario lakes with very different flushing rates. His calculations accurately predicted that the lake with low flushing rates would be almost identical to the lake with high flushing rates in terms of degree of eutrophy despite the fact that the lake with high flushing rates received a phosphorus load 20 times greater than that of the other lake. Vollenweider (1975) also recognized the importance of water renewal time and modified his simple loading vs. mean depth ($\overline{Z}$) relationship to include the mean residence time of water (T_w). By plotting loading against $\overline{Z}/T_w$, Vollenweider arrived at a more realistic representation of phosphorus budgets for lakes. Dillon's equation is perhaps more representative because it includes both flushing rate and retention time in its calculation. Other factors not considered in the models of either Dillon or Vollenweider include the effects of internal loading and the extent of the shoreline and the littoral area. The effects of internal loading are exemplified by the highly eutrophic Rotsee in Switzerland (Vollenweider, 1976). Input-output calculations for phosphorus budgets failed to account for the very high concentrations of phosphorus in the lake. Vollenweider concluded that the phosphorus enriched sediments serve as a long term periodic source for large inputs of phosphorus. It seems likely that many lakes which have been eutrophic for some time will contain large reserves of phosphorus in their sediments. This is of considerable importance for lake restoration because it implies that mere reduction in phosphorus input will not always result in lower phosphorus concentrations within the lake, and that the sediments may supply phosphorus to keep the lake in an advanced eutrophic state for years to come. Although phosphorus loading budgets require substantial information for their construction, they appear to be one of the most valuable techniques in the identification of the causes of and solutions to cultural eutrophication.

Approaches to lake restoration can be placed into two categories: 1. procedures to limit production and sedimentation in lakes by curbing nutrient input, and 2. procedures to remove or manage the consequences of lake aging.

The objectives of limiting fertility in lakes are to reduce the excessive and undesirable growth of algae and rooted aquatic macrophytes and hence, by reducing their production, to reduce the rate of autochthonous sedimentation. It is generally agreed that the most desirable long term lake management approach is to reduce and control the input of nutrients, especially nitrogen and phosphorus. These inputs may be diverse for a particular lake basin and therefore studies must be conducted to identify and locate nutrient sources for each lake in question.

A. Wastewater Treatment

For many lakes domestic and industrial waste waters constitute a major source of nutrients. Waste water treatment is perhaps the most widely used technique for reducing the nutrient loads of wastewater effluents to rivers and streams, although nutrient removal for lake protection and improvement is a major objective in only a minority of situations. Unfortunately, removal of nitrogen and phosphorus is at the present time usually inadequate for the alleviation of continuing eutrophic trends in lakes. Most wastewater systems currently in operation were primarily designed to reduce B.O.D. (Biological Oxygen Demand). In other words, in plant oxidation of organic matter in order to protect the oxygen resources of the recipient water body is the primary objective. Some nutrient removal does occur although the efficiency is rather low. Furthermore, housing developments and communities on many lakes do not have sewer facilities for collective wastewater treatment, but rely on septic systems which in many cases have saturated the ground water, thus causing a diffuse discharge of nutrients from the shore into the lake. Any septic system, by its very nature, must eventually saturate the soil of the septic field into which the wastewater is discharged. The time required for saturation to occur depends largely on the characteristics of the soil (Hook et al. 1978).

B. Diversion

Diversion is the rerouting of waters outside of a lake's drainage basin. This may or may not be used in conjunction with wastewater treatment. Diversion without treatment has been severely criticized because it simply displaces the problem to another location. If, however, the new location is a river or stream some benefits may be realized since rivers and streams have a higher self-cleansing potential than lakes. Some well known examples of this procedure include Lake Washington, Seattle, Washington (Edmondson 1970); the Madison Lakes (Mendota, Menona, Waubesa and Kegonsa) Madison, Wisconsin (Sonzogni and Lee 1974); and the Chicago Sanitary Canal which diverts wastewater formerly discharged into Lake Michigan to the Illinois River. In essence, diversion can be a simple and economical solution to pollution problems which otherwise are not easily dealt with. However, a decision must be made on what sort of trade off or sacrifice will incur to the receiving water body. In many instances such sacrifices would probably be unacceptable in Indiana in view of the state's efforts to improve the water quality of our streams and rivers.

C. Control of Incoming Sediments

In reservoirs, as well as some state's natural lakes, sedimentation is a major problem, restricting recreational use, and in many cases greatly shortening the lifetime of the lake. Control measures at the present time include both procedures to reduce sediment loss in the watershed, e.g. contour plowing, grade stabilization, grassed waterways, mulching and others, and procedures to prevent eroded sediments from entering the lake, e.g. sediment basins and diversion basins. Many of these procedures are applicable to problems in Indiana's lakes and may be used in conjunction with nutrient abatement and in-lake rehabilitation projects. Where allochthonous sediments are a problem, these procedures should be given serious consideration. Sediment basins may be of special importance in that they may also function in nutrient removal, if properly designed.

D. In-lake Rehabilitation Techniques

The objectives of various in-lake rehabilitation schemes are either to accelerate nutrient outflow or to prevent recycling of nutrients within the lake ecosystem (Dunst et al. 1974). It must be emphasized that these techniques by themselves will usually provide only temporary relief from the effects of high nutrient levels unless they are used in combination with programs to reduce the input of nutrients to the lake. These techniques are directed at removing residual nutrients present in the water, the sediments, or the biota. An attempt here is made to present some of the techniques and assess their usefulness for Indiana's lakes.

1. Dredging. At the present time many people regard lake rehabilitation as being synonymous with dredging. Indeed, many of the completed lake restoration projects in the U.S. have involved dredging the pond in the city park. In the past this has usually been done without any prior studies on conditions previous to dredging and often there were no follow-up studies as well.

In non-stratified shallow lakes, nutrient regeneration from the sediments by wind generated mixing can be the major source of nutrients. Thus, dredging to expose a nutrient-poor layer can result in very significant reduction in nutrient concentrations. In deeper thermally stratified lakes, however, dredging may not have this desired effect. Sedimentary phosphorus concentrations may only reflect the binding capacity of the sediments and not the nutrient concentration levels in the overlying waters. Furthermore, the dredging of lakes with large surface areas becomes impractical both from an economic and engineering standpoint.

2. Drawdown and Sediment Consolidation. The water content of organic rich sediments in eutrophic lakes frequently exceeds 90% by volume. Consolidation of flocculent sediments by dessication is largely irreversible and results in a deepening of the lake basin and an increase in lake volume (Smith et al.).

3. Chemical Treatment for Nutrient Inactivation and/or Precipitation. The intent of these procedures is to change the form of nutrients to make them unavailable to plants, remove nutrients from the photic zone and prevent release and recycling of nutrients from the sediments. Usually this is done by application of alum slurry from a boat or barge. Recent studies indicate the effects are temporary, and the process may have to be repeated every year or so. However, when used in conjunction with procedures to curb nutrient inputs, nutrient inactivation may be a very useful procedure which gives immediate results.

4. Other In-lake Techniques. Dilution/flushing requires a large and convenient source of water low in nutrients. This alone restricts its usefulness in Indiana. Aeration and circulation may be useful in some situations. Macrophyte harvesting does have some value in nutrient removal, provided the cut plants are removed from the lake. Control of algae and macrophytes by use of herbicides, however, is purely a cosmetic treatment which does nothing to solve the causes of the eutrophication problem.

Currently the federal government, under section 314 of the Clean Water Act, provides for state and local assistance in restoring publicly owned freshwater lakes. The Clean Lakes Program is administered through the US EPA and provides grants for 3 types of programs in Lake Restoration. Each state is required to prepare a report (in Indiana, the responsible agency is the Indiana State Board of Health) on the identification and classification of all publicly owned freshwater lakes in the state according to "eutrophic" condition, and procedures and methods to control pollution sources to these lakes, and methods and procedures to restore these lakes. This report has been completed for Indiana's lakes and the results of the classification and management plan for Indiana's lakes will constitute the topic of another paper in the Academy Meeting program.

Phase I grants provide 70% up to $100,000 funding for diagnostic and feasibility studies on individual lakes. The remaining 30% funding must be generated from local and in-state sources. Phase I studies must identify a lake's trophic characteristics and lake problems and nutrient sources, and must recommend feasible restorative measures. Phase II grants provide 50% federal funding for implementation of Phase I report recommendations. No limits on the amount of federal funding are specified.

The Clean Lakes Program provides a vehicle for the states to protect and restore our valuable lake resources. The future of Indiana's lakes is in our hands. If we are to preserve these valuable resources for future generations, we must act now to insure the continued well-being of Indiana's lakes.

Literature Cited

1. DEEVEY, E. S. 1942. A re-examination of Thoreau's "Walden". Quart. Rev. Biol., **17**:1-11.
2. DILLON, P. J. 1975. The phosphorus budget of Cameron Lake, Ontario: The importance of flushing rate to the degree of entrophy of lakes. Limnol. Oceanogr, **20**:28-39.
3. DUNST, R. C., S. M. BORN, P. D. UTTORMARK, S. A. SMITH, S. A. NICHOLS, J. O. PETERSON, D. R. KNAUER, S. L. SERNS, D. R. WINTER, and T. L. WIRTH. 1974. Survey of lake rehabilitation techniques and experiences. Wisconsin Dept. Nat. Resources, Tech. Bull. No. 75, 179 p.
4. EDMONDSON, W. T. 1970. Phosphorus, nitrogen, and algae in Lake Washington after diversion of sewerage. Science **169**:690-691.
5. GAMS, H. 1927. Die Geschichte der Lunzer Seen, Moore und Walder. Int. Rev. ges. Hydrobiol. u. Hydrogr., **18**:304-387.
6. HOOK, J. E., B. G. ELLIS, L. W. JACOBS and D. L. MOKMA. 1978. Nutrient Movement Through Soils From Septic Systems. Submitted to South-Central Michigan Planning Council.
7. HUTCHINSON, G. E. and A. C. WOOLOCK. 1940. Studies on Connecticut lake sediments. II. Chemical analyses of a core from Linsley Pond. Amer. J. Sci., **238**:493-517.
8. LINDEMANN, R. A. 1942. The trophic-dynamic aspect of ecology. Ecol., **23**:399-418.
9. LIKENS, G. E. ed. 1971. Nutrients and Eutrophication. Am. Soc. Limnol. Oceanogr., Special Symposia, Vol. I, 328 pp.
10. LUNDQUIST, G. 1927. Bodenablagerungen und Entwick lingstypen der Seen. Binnengewasser 2, 124 pp.
11. National Academy of Sciences. 1969. Eutrophication: causes, consequences, correctives. The Academy, Washington, D.C. 661 pp.
12. SMITH, S. A., J. O. PETERSON, S. A. NICHOLS, S. M. BORN, 1972. Lake Deepening by Sediment Consolidation-Jyme Lake.
13. SONZOGNI, W. C. and G. F. LEE. 1974. Diversion of Wastewaters from Madison lakes. Am. Soc. Civil Engrs. Trans., Jour. Environmental Engineering Div., **100**: 153-170.
14. VOLLENWEIDER, R. A. 1968. Eutrofizzazione delle acque da fosforo. La Rivirta Italiano delle Sostanzo Grasse. 45:99-107.
15. ——————. 1971. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Organization for Economic Co-operation and Development, Paris. 159 pp., 34 fig., 61 pp. bibliography.
16. ——————. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz A. Hydrol., **37**:53-84.
17. ——————. 1976. Rotsee, a source, not a sink for phosphorus? A comment to and a plea for nutrient balance studies. Hydrologie, **38**:29-34.
18. WETZEL, R. G. 1970. Recent and postglacial production rates of a marl lake. Limnol. Oceanogr., **15**:491-503.
19. WETZEL, R. G. and H. L. ALLEN. 1970. Functions and interactions of dissolved organic matter and the littoral zone in lake metabolism and eutrophication. In Z. Kajak and A. Hillbricht-Ilkowska, eds., Productivity Problems of Freshwaters. Warsaw, PWN Polish Scientific Publishers, pp. 333-347.