Limnology:
The Science Behind Lake Management

Ken Wagner

Limnology is the study of fresh waters—basically the freshwater equivalent of oceanography. It is also the basis for informed lake management, and is the foundation upon which many of our management techniques have been built. While a lot of lake and watershed management may seem like common sense, many of the principles we assume to be long-held truths are really rather recent developments. Limnology is still a young science, but it has already yielded great advances in water resource management.

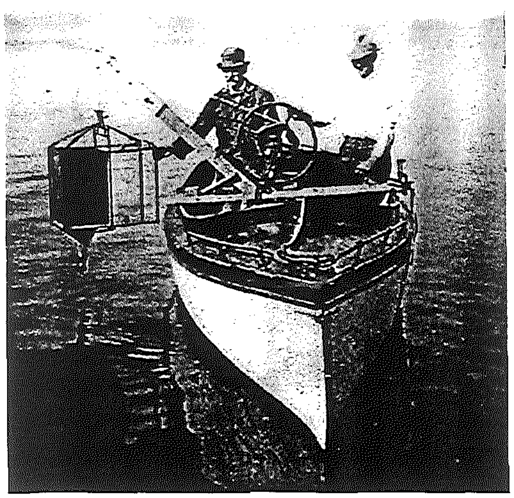
Limnology can be divided into two broad categories of effort: descriptive and experimental. Descriptive limnology is what we do in the first part of a typical diagnostic/feasibility study, in which we inventory the physical, chemical, and biological components of a lake and its watershed and assess relationships among these component parts of the ecosystem. If we can discern trends and elucidate causes and effects, these often provide keys to understanding what controls overall lake condition. Understanding can facilitate protection of desired conditions and manipulations that lead to improved conditions. Manipulations are experimental limnology, and manipulations on a whole lake scale constitute lake management.

Descriptive limnology developed tremendously between the first and second World Wars, with the pioneering work of Edward Birge and Chancey Juday in Wisconsin, a stronghold of limnological research to this day. Experimental limnology gained popularity after World War II, with the work of G.E. Hutchinson and colleagues at Yale often cited as leading the way. Many, many other scientists have contributed to this effort, and continue to do so today.

Conscious lake and watershed management is largely a post-1960 effort, although earlier examples certainly exist. Lake management accelerated greatly in the late 1970s with federal support and annual gatherings of limnologists and lake managers. NALMS was formed at the 1980 gathering of these committed scientists and practitioners, and has expanded the circle to include industrial suppliers and lake enthusiasts. As we move forward, our zeal for lake management should be tempered with recognition of the limits of our limnological knowledge and appreciation for the efforts that have laid the foundation for our successes.

When we complement management with more limnological investigation (e.g., post-treatment monitoring), we often learn more about what controls lake condition, and can fine-tune our management methods. When we extend descriptive and experimental limnology to many lakes and watersheds, we gain information that helps us adapt our management methods for varying application. Sound limnology supports sound management.

Birge and Juday sampling in Lake Mendota, Wisconsin. (State Historical Society of Wisconsin).



So what are some of the limnological developments that have shaped lake management over the last 30 years? Here I will examine a few advances that have made a difference in the way we manage lakes and watersheds.

Limiting Nutrient Concept

Leibig's "Law of the Minimum" goes way back, and basically states that it is the element that is in shortest supply relative to the needs of the plant that will limit growth. Our understanding of the importance of phosphorus as a limiting nutrient in aquatic systems is only about 50 years old. Richard Vollenweider publicized the role of phosphorus in the late 1960s and 1970s, and I felt honored to discuss his work with him over a cognac at the natal NALMS conference in 1980. He told me that it was mainly a process of elimination, based on the descriptive work of many researchers and the experimental work of others; not a stroke of brilliant thinking, but the summation of a lot of hard work. Dave Schindler, who has spoken on his whole lake fertilization experiments at several NALMS symposia, has repeatedly emphasized the "hard work" side of limnological discoveries. Other nutrients and factors such as light and temperature can play a major role in lake productivity, but phosphorus has become the successful focus of management to lower algal biomass.

Internal Phosphorus Cycling

The failure of seemingly appropriate watershed management to lead to improved lake conditions has often been traced to high internal loading of phosphorus. Just how phosphorus is cycled and especially the variability in the upward movement of phosphorus from sediment to surface waters has been the subject of a long series of investigations. We first learned that low oxygen promotes the release of phosphorus, iron and other substances from the sediment, and that under strongly anoxic ("reducing") conditions sulfide can be released. Then the importance of iron in controlling phosphorus transport and availability was ascertained, and later the critical role of sulfide in binding iron and allowing available phosphorus transport into the upper waters was determined. Recently, the means to evaluate sediment phosphorus release potential as a function of fractionation among bound forms of phosphorus was developed by a team including former NALMS president and limnologist Gene Welch. We now understand the causal agents for high internal phosphorus loading, and are applying it to gain better control of algal blooms through aluminum additions and aeration systems.

Prediction of Lake Response

Once it was determined that phosphorus loading controlled lake productivity in many cases, multiple teams of limnologists initiated efforts to model the response of lakes to phosphorus inputs. These efforts were based largely on standard engineering representations of lakes calibrated with large quantities of data for groups of lakes. These "empirical" models were generated in the mid- to late 1970s by Richard Vollenweider and NALMS members like Roger Bachmann, Jack Jones, Peter Dillon, Ken Reckhow, and Bill Walker. They became the basis for predicting lake response to management efforts intended to control loading from the watershed. These models are still in use today, and have been supplemented by additional models to cover the range of cases encountered (e.g., nitrogen limitation, anoxia, biotic influences). Development of regional values for model variables has made models more reliable for local practical application. Coupled with predictive models of algal growth, water clarity, and oxygen deficit, we can now estimate lake condition in response to potential actions in the watershed. NALMS members such as Dan Canfield and the late Rob Peters have been instrumental in this effort. Quantification of uncertainty (how likely are we to be right or wrong with our predictions, and by how much?) has facilitated better technical and economic planning.

Rooted Plant Ecology

Plants have many strategies for surviving in the aquatic environment, and understanding their diverse ecological "tricks" is essential to planning a successful plant management program. The knowledge that most rooted plants get their nutrition largely from the sediment is only about 20 years old, and we continue to study the reproductive strategies of many species, especially invasive forms. Much of this work has been conducted by researchers at the Army Corps of Engineers' Waterways Experiment Station and by NALMS members such as Stan Nichols, Sandy Engel, and John Barko. The development of herbicides that target certain species while preserving others is a function of understanding physiological differences among species, and the advancement of biological methods of plant control like the milfoil weevil has been dependent upon both descriptive and experimental limnology.

Paleolimnology

It is a common mistake to assume that lakes follow a unidirectional path at a steady pace from low to high fertility, and paleolimnology has aided our understanding of historic lake conditions greatly over the last two decades. Data generated by researchers such as NALMS Board Member John Smol and colleagues from their Canadian base have provided us with a glimpse of the variability of conditions over time in many lakes and led to the development of predictive indicators of water quality based mainly on plankton remains. The major impact of land clearing on lake condition in the 1800s has been documented, and recovery of lakes after reforestation has also be observed. Some lakes have been shown to have been eutrophic since long before white settlers arrived. Recent work by NALMS member Pete Siver in Connecticut has documented the correlation between urbanization of watersheds and declining lake water quality over the last 50 years.

Trophic Cascade

Our understanding of the relationship between phosphorus and algal biomass has always been complicated and often confounded by biological interactions that introduce significant variation into that relationship. Research that began in the late 1970s and progressed through the 1980s addressed this issue, and I enjoyed working on this topic as part of my Ph.D. research as part of the team at the Cornell Biological Field Station. In 1975 Joe Shapiro suggested biomanipulation as a means of achieving management goals without major physical or chemical alteration of lakes, and many researchers took up the challenge. NALMS members Steve Carpenter and Jim Kitchell greatly advanced our knowledge in this area through whole lake experiments in the upper Midwest.

Research in a number of locations illustrated that if enough large-bodied grazing zooplankton are present, algal biomass may not increase to the extent predicted by simple phosphorus-chlorophyll equations. When small fish that eat zooplankton become abundant, algal biomass may increase beyond the expected average based on phosphorus and other chemical features. And if large predatory fish increase to the point where they control the populations of planktivorous fish, the zooplankton may again gain some measure of control over algae.

The concept that we can enhance water clarity by altering the fish ➠

community to favor stronger grazing by zooplankton is commonly called "top down" control, a product of biomanipulation in accordance with the trophic cascade. However, as with virtually all biological mechanisms, variability in response tends to be high, and we have much more to learn to increase the reliability of this approach.

Alternative Stable States

Some lakes suffer from both algal blooms and rooted plant infestations, but most shallow eutrophic lakes have mainly one problem or the other. Research led mainly by European limnologists has illustrated the stability of both plant and algal dominated states in lakes. When we manipulate these lakes to eliminate algal blooms or rooted plant nuisances, we risk tilting the balance toward the alternative state, resulting in either an alternative set of problems or a period of instability. The need to carefully assess management methods in light of stated goals and lake uses becomes very important in such cases, and we move from limnology to social science in may cases.

Limnology provides concepts and predictive power that can be used to develop sound management approaches, and supports management of specific lakes by providing the information necessary to make technically and economically justifiable decisions. Management without supporting limnology invites unexpected results and potentially negative consequences. Although limnological investigations carry a cost, money spent on studies can be more than offset by the long-term savings in the management implementation phase, and increases the overall knowledge base that supports advances in lake management.

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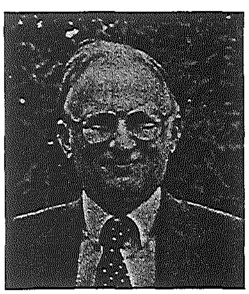
The Limiting Factor Concept

What Stops Growth?

Roger W. Bachmann



One of the earliest puzzles limnologists tried to solve was to explain why some lakes were more productive than others. Aside from academic curiosity, the answer to this question was of practical importance for fish production in lakes or ponds. In general, the more productive a lake is in terms of plant life, the higher the potential yields of fish, so there was interest in knowing how to increase the productivity of lakes in order to increase fish production. More recently, lake managers also have been interested in learning how to decrease the productivity of lakes in order to maintain or increase water clarity in lakes that have abundant growths of plankton algae.

The best explanation for productivity differences between lakes is found in the limiting factor concept first developed in the plant sciences and then applied to lakes and ponds. It says that the factor in the environment that is in shortest supply relative to the needs of the plants will determine the amount of plant material produced. For example, in order to grow, green plants need a supply of basic chemicals like carbon, hydrogen, oxygen, phosphorus, and nitrogen as well as smaller amounts of other elements such as metals like iron and magnesium. Also needed are stocks of living green plants, a source of light energy to combine the ingredients to form new organic matter, and time to accumulate the biomass. Thus, any one of these requirements—chemicals, light energy, or time—could be a limiting factor and control the amount of algae in a lake.

Nutrients as Limiting Factors

The concept of limiting factors has been applied with great success to lakes. Several lines of evidence have been used to show that the elements most often present in the smallest amounts relative to the needs of plants were either phosphorus or nitrogen. Hydrogen and oxygen are present in great abundance in water molecules and carbon dioxide is usually present in non-limiting amounts, however, every 100 grams of carbon used by plants in growth requires about 7 grams of nitrogen and 1 gram of phosphorus. Chemical analyses of lake water show that phosphorus and nitrogen are often present in smaller amounts relative to plant composition than other elements needed for plant growth.

Further proof of nutrients as limiting factors can be inferred from surveys of lakes around the world that indicate that the amount of plankton