Delib2010b_Delib9/04 9/22/10 7:20 PM Page 33

The impacts of cultural eutrophication on lakes: A review of damages and nutrient control measures

Rachel Leng

Writing 20 (Fall 2009): Freshwater Systems and Society
Professor Sandra Cooke

This essay was a research paper for my Writing 20 course, "Freshwater Systems and Society," taught by Dr. Sandra Cooke. The assignment was to explore a significant issue relating to water bodies, to study the extent to which it impacts or alters the ecosystem, and to analyze the future implications for clean water and society in general. I first encountered the phenomena of eutrophication in my high school chemistry class. As part of the class, students got to observe a severely eutrophied pond which was murky green and choked with algae, with no sign of life. The sight of such a spoiled natural environment through eutrophication shocked me, as it was so discordant from what I had learned about the chemical process. With the image of the pond in mind, I wanted to find out more about how eutrophication affected the environment and society globally. I got my opportunity to do so last year after I enrolled into Dr. Cooke's class. The more I studied the topic the more I realized how something seemingly as mundane as an excess of nutrients in water can cause widespread deterioration of water quality, severely harming the environment. But what I also found out are the numerous actions we can all take to prevent eutrophication through human activities—we can all do our part to successfully conserve this precious resource.

Cultural eutrophication is an increasingly global problem as the deterioration of water quality and excessive biological productivity in lakes inflicts significant environmental and societal damage.

Introduction

Aquatic plants need two essential nutrients for growth: Phosphorus and Nitrogen. They receive these nutrients through a process known as eutrophication, in which water bodies accumulate plant nutrients, typically from nutrient-rich land drainage (Smith 2003). In a healthy lake, both nutrients occur in limiting amounts, restricting plant growth. However, anthropogenic (or human) factors can dramatically increase the concentration of plant nutrients in water bodies, a phenomenon known as "cultural eutrophication" (Hasler 1947). Human-induced pollution through the impacts of excessive fertilizer use, untreated wastewater effluents and detergents significantly increases nutrient loading into lakes, accelerating eutrophication beyond natural levels and generating deleterious changes to the natural ecosystem (Litke 1999). Over the past 50 years, a large body of literature has been developed to identify the principle impacts and sources of increased nutrient levels on the quality of receiving waters (Smith 2003). It is now generally accepted that cultural eutrophication can stimulate the rapid growth of plants and algae, clogging waterways and potentially creating toxic algae blooms. Hypoxic (very low oxygen) conditions may result when these plants and algae die and decompose stripping water of dissolved oxygen, leading to fish kills and degrading the aesthetic and recreational value of the lake (ESA 2008). Cultural eutrophication is an increasingly global problem as the deterioration of water quality and excessive biological productivity in lakes inflicts significant environmental and societal damage.

In identifying sources of eutrophication, studies have observed a strong relationship between algal biomass and nutrient loading, with phosphorus being the primary limiting nutrient in freshwater bodies. Therefore, most efforts to control algal biomass in lakes concentrate on reducing phosphorus levels in water (Smith 1999). Of the strategies developed to mitigate eutrophication, I propose that an integrated approach focusing on nutrient loading restrictions is the essential cornerstone of effective management in lakes. This approach would incorporate nutrient loading restrictions with biomanipulation to limit the levels of phosphorus and nitrogen in lakes as well as alter the food web to control phytoplankton populations, the major contributor to eutrophication.

Delib2010b_Delib9/04 9/22/10 7:20 PM Page 34

Overview of Cultural Eutrophication

Natural eutrophication is a slow and gradual process, typically occurring over a period of many centuries as nutrient-rich soil washes into lakes. In contrast, human-induced eutrophication can occur over time frames as short as a decade (Addy and Green 1996). Although it has taken only 60 years for humans to turn many freshwater lakes eutrophic, studies suggest their recovery may take 1000 years under the best of circumstances (Carpenter and Lathrop 2008). At present, nearly 38% of US lakes are experiencing eutrophic conditions affecting aquatic life and watershed ecosystems (SAMAB 1996). Runoff, especially from urban and agricultural areas, carries fertilizers, pesticides, sediment and/or industrial effluent that accelerate eutrophication when discharged into a water body (Smith *et al*. 1999).

Eutrophication also jeopardizes the resource value of lakes as recreation, fishing and aesthetic enjoyment diminish, causing annual value losses of $2.2 billion in the US.

With severe eutrophication, hypoxic conditions often result, disrupting normal food web and ecosystem processes by creating a "dead zone" where no animal life can be sustained (Smaya 2008). In the 1960s, Lake Washington (Seattle, USA) was one of the most publicized examples of anthropogenic eutrophication. At the maximum of eutrophication, Lake Washington received 20 million gallons of wastewater effluent each day (Edmondson 1991). More than 37,000 kg of phosphates added in 1955 from developed agricultural and urban lands swamped the lake, stimulating plant and algae growth that choked out most other species (Edmondson 1970).

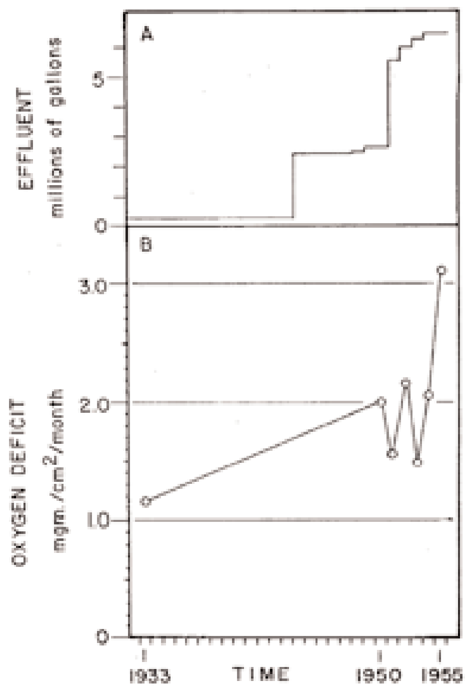

Figure 1. A. Daily capacity of the sewage treatment plants emptying effluent into Lake Washington. B. Oxygen deficit below 20 meters. *Source:* (Edmondson *et al.* 1956)

Eutrophication also jeopardizes the resource value of lakes as recreation, fishing and aesthetic enjoyment diminish, causing annual value losses of $2.2 billion in the US (Dodds *et al* 2009). As such, the impact of eutrophication on recreation and tourism is probably the most sensitive area for the public. Lakes and reservoirs deteriorate through excessive addition of plant nutrients, organic matter and silt, which combine to produce increased algae and rooted plant biomass, reduced water clarity, and usually decreased water volumes (Harper 1992). In this condition water bodies lose much of their attractiveness for recreation, as well as their usefulness and safety as industrial and domestic water supplies.

If the lake serves as a drinking water source, excessive algal growth clogs intakes, increases corrosion of pipes, makes filtration more expensive and often causes taste and odor problems (Vollenweider 1968). Algae removal also increases filtration costs for industries using eutrophic waters. Furthermore, swimming in eutrophic waters causes "swimmer's itch" (Vollenweider 1968) and people generally find clear waters more aesthetically pleasing than turbid (cloudy) waters. Both social impacts and economic losses are important and make eutrophication control necessary.

Sources of Cultural Eutrophication

As seen in Figure 2, cultural eutrophication is caused by human land use, including agriculture and residential or industrial developments. As land is developed, the natural habitat is altered and phosphorus is no longer held in the soil but is washed into lakes. More importantly, the artificial input of nutrients from run-off, along with the discharge of effluent from sources such as sewage works, agriculture and factories, result in a eutrophic lake high in nutrient levels. Although sewage, agriculture, and factories all increase nutrient input in watersheds, the amount of input varies according to the types and amounts of human activity occurring in each watershed (Smith and Schindler 2009). The combination of these effects causes a rapid growth of algae and other biomass as well as a significant decrease in the concentration of dissolved oxygen, harming marine organisms and making compliance with local and federal regulations more difficult to achieve (WHO 2008).

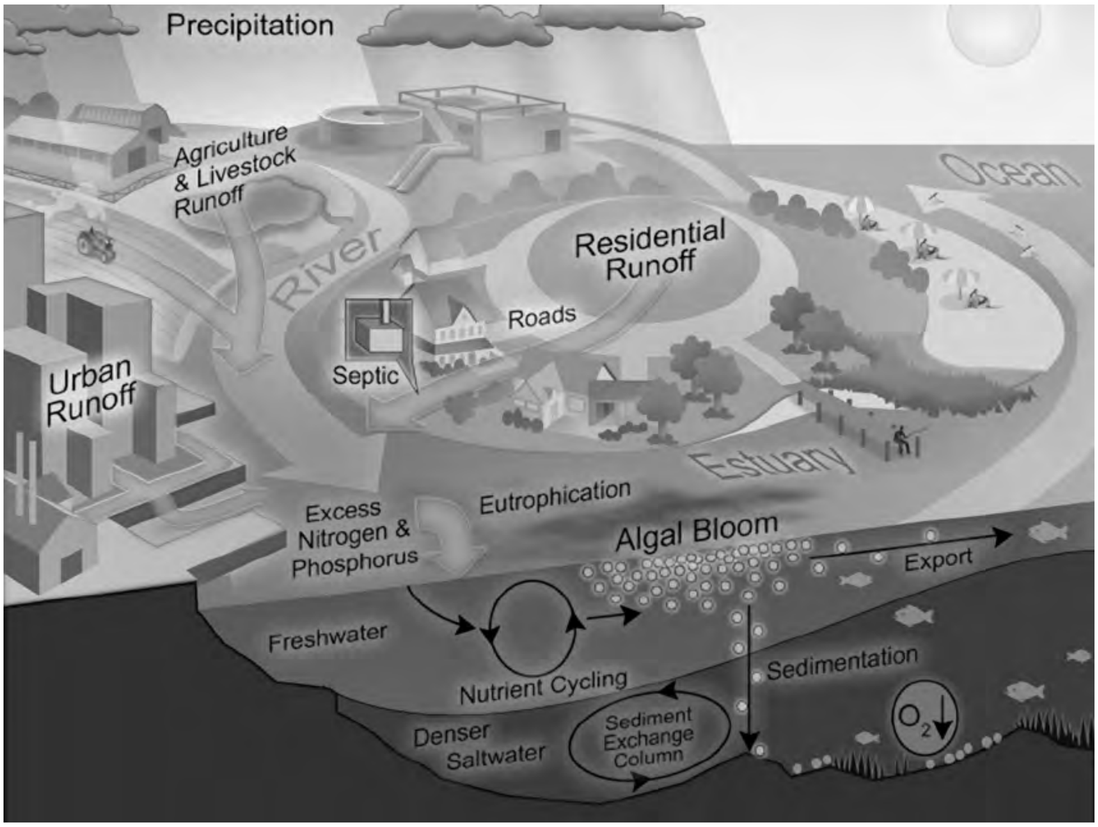

Figure 2. Numerous sources from the watershed of the lake contribute to nutrient inputs and eutrophication. *Source:* (Olli 2006)

Additionally, lowered oxygen results in the death of fish that need high levels of dissolved oxygen to survive. The consequent decrease in populations of fish such as trout, salmon and other desirable sport fish, harms the fishing industry and alters the ecosystem of the lake (Mandaville 2000).

Industrial wastes and domestic sewage are the major urban sources of nutrient overload, responsible for 50% of the total amount of phosphorus unloaded into lakes from human settlements (Smith *et al*. 2006). Approximately 15% of the US population contributes phosphorus-containing wastewater effluents to lakes, resulting in eutrophication (Hammer 1986). By 1970, nearly 10,000 public lakes had been affected by excessive human-influenced nutrient enrichment (Knud-Hansen 1994).

Other sources that contribute to cultural eutrophication include the use of fertilizers, faulty septic systems and erosion into the lake. Industrial agriculture, with its reliance on phosphate-rich fertilizers, is the primary source of excess phosphorus responsible for degrading lakes (Carpenter 2008). The routine application of chemical fertilizers and phosphorus-laden manure has resulted in the gradual accumulation of phosphorus in soil, consequently washing into lakes of the watershed where it is applied. While many states have implemented bans on chemical phosphorus, farmers still apply phosphorus fertilizers, even when soils already have a reservoir of the nutrient. This significantly intensifies the amount of phosphorus runoff to lakes (Bennet *et al*. 2001). Moreover, studies predict that fertilizer demand and use will continue to increase to 208 million tons by 2020, with greater increases in developing countries, further aggravating a trend of freshwater eutrophication worldwide (Bumb and Baanante 1996).

On a global basis, researchers have demonstrated a strong correlation between total phosphorus inputs and algal biomass in lakes (Anderson *et al*. 2002). Since 1950, phosphorus inputs to the environment have increased as the use of phosphate-containing fertilizer, manure and laundry detergent became prevalent (Litke 1999). Consequently, humans release 75% more phosphorus to the soil than would be naturally deposited by weathering of rock (Bennet *et al*. 2001). Even increases in minute amounts of the nutrient can stimulate tremendous growth and productivity (Addy and Green 1996). According to an estimate, 400g of phosphates could potentially induce an algal bloom to the extent of 350 tons (Sharma 1999).

Since 1950, phosphorus inputs to the environment have increased as the use of phosphate-containing fertilizer, manure and laundry detergent became prevalent.

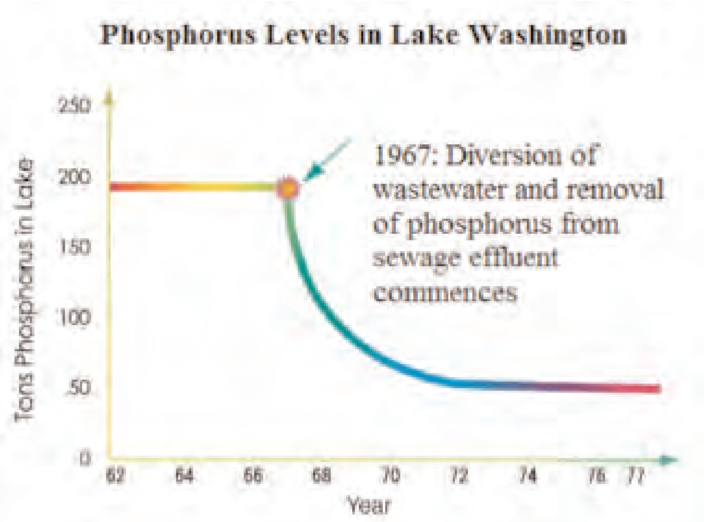

Figure 3. Diversion of wastewaters and removal of phosphorus from sewage effluent entering the lake proves to be effective in the reduction of total phosphorus levels.

Source: (Jorgensen 2001)

Algal blooms threaten ecosystems by choking off oxygen and thereby causing the deaths of plants and animals throughout that ecosystem. An algal bloom is a rapid increase or accumulation in the population of algae in an aquatic system. Freshwater algal blooms are the result of an excess of nutrients, particularly phosphorus (Diersing 2009). The excess nutrients may originate from fertilizers that are applied to land for agricultural or recreational purposes. These nutrients can then enter watersheds through water runoff (Lathrop *et al*. 1998).

When phosphates are introduced into water systems, higher concentrations cause increased growth of algae and plants. As the nutrient source becomes continuous and conditions remain favorable, algal blooms can become long-term events that impact the ecosystem. Algae tend to grow very quickly under high nutrient availability, but each alga is short-lived, and the result is a high concentration of dead organic matter that starts to decay. The decay process consumes dissolved oxygen in the water, resulting in hypoxic (low oxygen) conditions. Without sufficient dissolved oxygen in the water, animals and plants die off in large numbers. Additionally, sustained blooms can block reduce or block out sunlight penetrating the water, stressing or killing aquatic plants. In severe eutrophic conditions, harmful algal blooms (HAB) have been known to occur. HABs are algal blooms that cause negative impacts to other organisms via production of natural toxins, mechanical damage to other organisms, or by other means. These algae are often associated with large-scale marine mortality events and have been associated with various types of shellfish poisonings (Diersing 2009).

Eutrophication Management Strategies: Control of Major Eutrophication Sources

In order to control eutrophication and restore water quality, it is necessary to check and restrict phosphorus inputs, reduce soil erosion and develop new technologies to limit phosphorus content of over-enriched soils (Carpenter and Lathrop 2008).

Under natural conditions, total phosphorus concentrations in lakes range from 14-17 parts per billion (ppb). In 1976, the Environmental Protection Agency recommended phosphorus limits of 25 ppb within lakes to prevent and control eutrophication (Addy and Green 1996). However, many lakes still have nutrient levels above this limit. Lake Washington is a case in point: in the 1960s, phosphorus was found in concentrations of 70 ppb (Edmondson 1991). Although phosphorus levels have declined since EPA set limits on nutrient loading in 1976, these levels are still too high for healthy lakes. Steps that can be taken immediately include enforcing wastewater treatment and eliminating the importation of chemical phosphorus to watersheds via fertilizers (Schindler 2006).

Restoration strategies include hypolimnetic aeration (where water from the bottom of a lake is brought to the surface to be oxygenated then returned to the bottom), biomanipulation (the manipulation of food webs to lower levels of algae) and nutrient loading restrictions (restricting phosphorus levels). Of these strategies, I propose that an integrated strategy focusing on nutrient input restrictions and incorporating biomanipulation is essential to future eutrophication management. While hypolimnetic aeration is the most common approach to improve oxygen conditions of water, the effectiveness of this process is dubious and variable. For example, studies have shown that this alternative is less effective in shallow lakes. And there is little evidence that hypolimnetic aeration reduces algal biomass can be reduced (Cooke and Carlson 1989). Conversely, phosphorus loading restrictions have led to rapid recovery from eutrophication in many lakes (Smith 2009). Lake Washington is perhaps the most widely recognized success story of recovery from eutrophication through nutrient input control (Fig 3). After the city began diverting phosphorus-containing wastewater effluent from the lake, there was a profound improvement of water quality and decrease of phytoplankton growth (Schindler 2006). Thus, to mitigate eutrophication and algal biomass, nutrient control focusing on reducing phosphorus input is vital (Anderson *et al*. 2002). Nevertheless, while most scientists agree that hypolimnetic aeration is ineffective, there is still much debate over the use of biomanipulation and nutrient loading restrictions to curtail eutrophication (Cooke 2005).

Measures to curb phosphorus inputs to remedy eutrophic ecosystems have focused on detergent bans, effluent limits and soil erosion controls (Carpenter 2008). The reduction and eventual elimination of phosphates in detergents is necessary to manage eutrophication. As synthetic detergents became prevalent, phosphate consumption grew to a peak of 240,000 tons in the US. Since 1970, the detergent industry has limited the amount of phosphate in detergents, but a complete ban would remove up to 30% more of the phosphates in sewage, thus reducing future loading to lakes (Litke 1999). Additionally, the concentrations and loads of phosphorus in wastewater-treatment plant effluents fluctuate together with the consumption of phosphate in detergents. Amendments to the Federal Water Pollution Control Act in 1961 also enforced environmental technology techniques to control discharge from wastewater treatment plants and improve water quality. More plants now treat their wastewater to remove up to 99% of phosphorus, significantly decreasing the amount of the nutrient released into lakes (Litke 1999). At present, there is still a need to find a phosphate substitute in detergents and implement tertiary treatment of wastewater for more complete phosphorus removal. Continued education of consumers to choose washing products with the least amount of polluting ingredients is also vital (Knud-Hansen 1994).

Eutrophication Management Strategies: Nutrient Loading Restrictions

To curtail phosphorus runoff from fields and manure disposal sites, soil erosion rates have to be dramatically reduced. Agricultural practices that minimize runoff and reduce phosphorus applications to land surface via fertilizers should be enforced. For example, farmers can reduce erosion and sedimentation by 20-90% by applying better irrigation techniques to control the volume and flow rate of runoff water, improve water efficiency, keep soil in place and reduce soil transport (Sharpley *et al*. 1994). Soil erosion can also be prevented or reduced by ending deforestation and burning techniques in farming. Governments should impose policies that give farmers incentives to decrease phosphorus use, such as removing subsidies that promote excessive fertilizer consumption. Additionally, restoring wetlands that act as buffers between fields and lakes is necessary to decrease runoff of excess nutrients (Jorgensen 2001).

These strategies have all been applied with success to improve eutrophic conditions in a variety of lakes. However, there are several drawbacks and complications to relying on nutrient loading restrictions. First, the process of treating the impacts of eutrophication by reducing nutrient levels is expensive, incurring costs of up to millions of dollars for an individual lake (Carpenter 2008). Lake Washington's $140 million campaign to divert sewage effluent was the most costly pollution control effort at the time (Edmondson 1991). Second, similar nutrient loads do not have the same impact in different environments or at different points in time (Anderson *et al*. 2002). Removal of phosphorus entering lakes may be ineffective if there is already a large reservoir of nutrients stored in sediments previously released into the water. This shows the need to avoid nutrient loading into lakes as early as possible through proper management and planning practices. Furthermore, nutrient loading restrictions are not fool-proof. For instance, attempts to reduce nutrient inputs of erosion from agriculture have not worked as well as attempts to control point-source industrial wastewater pollution (Schindler 2006). Hence, certain restrictions that worked for a particular lake may not work for another, and optimum eutrophication control strategies will differ due to the existence of variable ecosystems (particularly the presence of agriculture). Third, while techniques to lower nutrient concentration can be effective in improving lake eutrophication, these approaches ignore the biological interactions of the lake responsible for internal nutrient recycling, poor water clarity and the slow response to nutrient diversion. Such interactions be - tween phytoplankton and algae contribute to eutrophication and cannot be mitigated by reducing nutrient inputs alone (Carpenter *et al*. 1995). Thus, it is necessary to develop an integrated approach incorporating biomanipulation to target the biological factors aggravating eutrophication unaffected by nutrient controls.

Eutrophication Management Strategies: Biomanipulation

Biomanipulation refers to procedures that alter the food web—communities of organisms where there are interrelated food chains. In one form, biomanipulation prompts organisms to favor grazing on phytoplankton. In another, biomanipulation eliminates fish species that recycle nutrients and favor those that assist algal management (Sharipo *et al*. 1984). This latter method is new to the lake management community, which has relied mostly on nutrient loading restrictions to control eutrophication. However, due to its effectiveness, lower cost and absence of machinery or toxic chemicals, it is becoming increasingly popular (Sharipo 1990).

Biomanipulation involves eliminating certain fish species or restructuring the fish community to favor the dominance of piscivorous fish instead of planktivorous fish. Food webs are controlled by resource limitation ("bottom-up") and by predation ("top-down") methods. With "bottom-up" control, sources

Delib2010b_Delib9/04 9/22/10 7:20 PM Page 38

of energy that affect the dynamics of an ecosystem, such as solar energy and nutrient inputs, are controlled to limit the amount of algal production. Nevertheless, within the limits of "bottom-up" controls, there is still a necessity for "top-down" pressures to reduce the abundance of phytoplankton by increasing the numbers of zooplankton and fish that graze on them (Sharipo *et al*. 1984).

While biomanipulation may not be effective on its own, particularly in larger lakes where changes in fish population has less of an impact, research has shown that biomanipulation used in tandem with other nutrient reduction and control mechanisms can be fully effective in a variety of lakes (Lammens 2001). Hence, it is necessary to use nutrient loading restrictions and biomanipulation in conjunction to control and limit all sources of eutrophication, speeding up the recovery of a lake.

Biomanipulation used in tandem with other nutrient reduction and control mechanisms can be fully effective in a variety of lakes.

Conclusion

Human-induced eutrophication has heavily degraded freshwater systems worldwide by reducing water quality and altering ecosystem structure and function. Population growth, industrialization and excessive use of fertilizers have resulted in disproportionate amounts of phosphorus in lakes stimulating plant and algae overgrowth. With the demand for freshwater resources expected to increase substantially (Johnson *et al*. 2001), these anthropogenic influences have severe environmental and economic repercussions. A solution to eutrophication, especially in developing countries, is urgent since nutrient accumulation renders controlling eutrophication more difficult over time (Edmondson 1991). While the first and most obvious step toward protection and restoration of a lake is to divert or treat excessive phosphorus inputs via nutrient loading restrictions, this process alone is insufficient to produce immediate and long-lasting effects. Internal recycling of nutrients can maintain the eutrophic state in a lake for some period after loading is curtailed (WDNR 2003). Thus, strategies of biomanipulation should be implemented together with nutrient loading restrictions. Studies have shown that this combination of techniques is more cost efficient and effective to obtain clear water and control eutrophication levels than if any one method were implemented alone (Schindler 2006).

Even with modern strategies, the problem of eutrophication is multi-faceted and many other aspects have to be better understood before lakes can fully recover. For example, responses of algae to phosphorus enrichment and food web structures must be considered to understand the changes that occur after alterations of nutrient loadings. An improved understanding of the interactive effects between grazers, nutrients and algal production is necessary to successful eutrophication management (Havens *et al*. 2001). Further research is also needed to clarify and manage the key physical, chemical and biological factors that determine the abilities of lakes to improve and reverse eutrophic conditions. New and innovative technologies have to be developed to limit phosphorus content in soil and runoff. At present, governments should implement more effective policies to regulate the industrial and agricultural sectors to reduce activities that contribute to eutrophication. It will be important to acquire the cooperation and understanding of these sectors to take greater measures to limit their nutrient loading. However, these dealings will take time and incur costs, which governments and the private sector may not be so willing to fund due to a loss of profit. Ultimately, it is imperative to increase public awareness and the environmental education of citizens in addition to an integrated strategy to abate eutrophication (Jorgensen 2001). Only a collective community effort can more effectively reduce nutrient inputs to lakes (e.g.: by a reduction in detergent use) and bring cultural eutrophication under control. ■

Literature Cited

Addy K, Green L. 1996. Phosphorus and Lake Aging. University of Phode Island: Natural Resources Facts; Report nr 96-2. 1 p.

Anderson DM, Gilbert PM and Burkholder JM. 2002. Harmful Algal Blooms and Eutrophication: Nutrient Sources, Composition, and Consequences. Estuaries **25**:704-726.

Bennet EM, Carpenter SR and Caraco NF. 2001. Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective. Bioscience **51**:227-232.

Bumb BL and Baanante CA. 1996. World trends in fertilizer use and projections to 2020. International Food Policy Research Institute; Report nr 38.

Carpenter SR, Christensen DL, Cole JJ, *et al*. 1995. Biological Control of Eutrophication in Lakes. Environmental Science and Technology **29**:784-786.

Carpenter SR. 2008. Phosphorus control is critical to mitigating eutrophication. Proceedings of the National Academy of Science **105**:11039-11040.

Carpenter SR and Lathrop RC. 2008. Probabilistic estimate of a threshold for eutrophication. Ecosystems **11**:601-613.

Cooke, G. Dennis. "18: Hypolimnetic Aeration and Oxygenation." *Restoration and Management of Lakes and Reservoirs*. Boca Raton, FL: CRC, 2005. 62-74. Print.

Cooke GD and Carlson RE. 1989. Reservoir Management for Water Quality and THM Precursor Control. American Water Works Association Research Foundation, Denver, CO.

Diersing, Nancy. *Phytoplankton Blooms: The Basics*. Rep. Florida Keys National Marine Sanctuary, May 2009. Web. 28 July 2010.

Dodds WK, Bouska WW, Eitzmann JL, *et al*. 2009. Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. Environmental Science and Technology **43**:12-19.

ESA (Ecological Society of America). 2008. Hypoxia. Washington DC: Ecological Society of America; 1 p.

Edmondson WT. 1991. The uses of Ecology: Lake Washington and Beyond. University of Washington Press.

Edmondson WT. 1970. Phosphorus, Nitrogen, and Algae in Lake Washington after Diversion of Sewage. Science **169**:690-691.

Edmondson WT, Anderson GC and Peterson DR. 1956. Artificial Eutrophication of Lake Washington. Limnology and Oceanography **1**:47-53.

Hammer MJ. 1986. Water and Wastewater Technology. Wiley, New York.

Harper, D (1992), "Eutrophication of Freshwaters", Chapman & Hall, Londres: 321.

Hasler AD. 1947. Eutrophication of lakes by domestic drainage. Ecology **28**:383-395.

Havens KE, Hauxwell J, Tyler AC, *et al*. 2001. Complex interactions between autotophs in shallow marine and freshwater ecosystems: implications for community responses to nutrient stress. Environmental Pollution **113**:95-107.

Johnson N, Revenga C and Echeverria J. 2001. Managing water for people and nature. Science **29**:1071-1072.

Jorgensen SE. 2001. Water Quality: The Impact of Eutrophication. Lakes and Reservoirs **3**:15-18.

Knud-Hansen C. 1994. Historical Perspective of the Phosphate Detergent Conflict. Conflict Research Consortium. Paper for the Fall 1993 Natural Resources and Environmental Policy Seminar of the University of Colorado. Boulder, CO: University of Colorado.

Lammens, Eddy. *Consequences of Biomanipulation*. FAO Fisheries Circular No. 952. FIRI/C952. Rome: Food and Agriculture Organization of the United Nations, 2001. 19 p.

Lathrop, Richard C.; Stephen R. Carpenter, John C. Panuska, Patricia A. Soranno, & Craig A. Stow (May 1, 1998). "Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota." *Canadian Journal of Fisheries and Aquatic Science*s (Toronto, Ontario, Canada: National Research Council of Canada) **55** (5): 1169–1178.

Litke DW. 1999. Review of phosphorus control measures in the US and their effects on water quality. National Water Quality Assessment Program: Water-Resources Investigations Report; Report nr 99-4007. 4 p.

Mandaville, S.M. 2000. Limnology- Eutrophication and Chemistry, Carrying Capacities, Loadings, Benthic Ecology, and Comparative Data. Project F-1, Soil & Water Conservation Society of Metro Halifax. xviii, Synopses 1, 2, 3, 13, and 14. 210p.

Schindler DW. 2006. Recent advances in the under standing and management of eutrophication. Limnology and Oceanography **5**:356-363.

Shapiro, J. and D.I. Wright. 1984. Lake Restoration by Biomanipulation: Round Lake, Minnesota, the First Two Years. Freshwater Biology. **14**: pp. 371-383.

Shapiro, J. 1990. Biomanipulation: The Next Phase Making it Stable. Hydrobiologia. **200/201**: pp. 13-27.

Sharma PD. 1999. Ecology and environment. Ecology and environment, Meerut.

Sharpley AN, Chapra SC, Wedepohl R, *et al*. 1994. Managing agricultural phosphorus for protection of surface waters: issues and options. Journal of environmental quality **23**:437-451.

Smaya TJ. 2008. Complexity in the eutrophication—harmful algal bloom relationship, with comment on the importance of grazing. Harmful Algae **8**:140-151.

Smith VH. 2003. Eutrophication of freshwater and coastal marine ecosystems: a global problem. Environmental Science and Pollution Research **10**:126-139.

Smith VH, Joye SB and Howarth RW. 2006. Eutrophication of freshwater and marine ecosystems. Limnology and Oceanography **51**:351-355.

Smith VH and Schindler DW. 2009. Eutrophication science: where do we go from here? Trends in Ecology and Evolution **24**:201-207.

Smith VH, Tilman GD and Nekola JC. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution **100**:179-196.

SAMAB (Southern Appalachian Man and the Biosphere). 1996. The Southern Appalachian Assessment Aquatics Technical Report Atlanta: USDA Forest Service, Southern Region.; Report nr 2 of 5. 166 p.

Vollenweider RA. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, With Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Paris, Rep. Organization for Economic Cooperation and Development, DAS/CSI/68.27, 192 p.

WDNR (Wisconsin Department of Natural Resources). 2003. Alum Treatments to Control Phosphorus in Lakes. Wisconsin: Fisheries and Habitat; 1 p.

WHO (World Health Organization). 2003. Emerging Issues in Water and Infectious Disease. World Health Organization; Report nr 2.

algae background art