RESEARCH: IMPACTS OF CULTURAL EUTROPHICATION ON LAKES

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Abstract

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 (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 should be the essential cornerstone of effective management in lakes. This approach would incorporate nutrient loading restrictions with bio manipulation to limit the levels of phosphorus and nitrogen in lakes as well as to alter the food web to control phytoplankton populations, the major contributor to eutrophication.

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). 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).

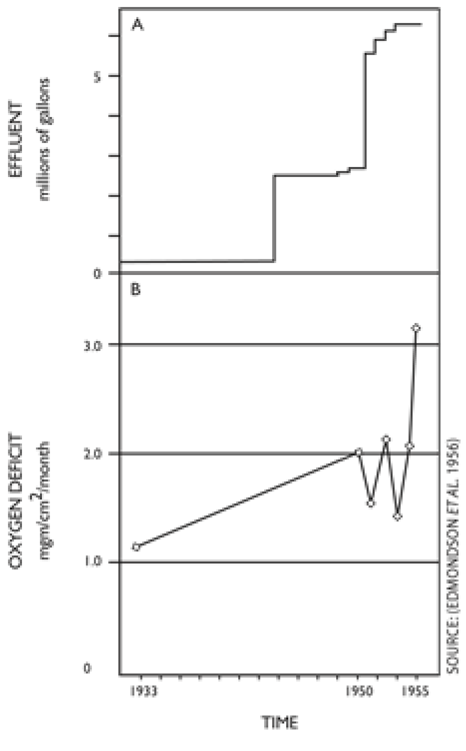

Figure 1: (A) Daily capacity of the sewage treatment plants emptying effluent into Lake Washington. (B) Oxygen deficit below 20 meters

Eutrophication also jeopardizes the re - source 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 ex - pensive and often causes taste and odour problems (Vollenweider 1968). Algae removal also increases filtration costs for industries using eutrophic waters. Furthermore, swimming in eutrophic waters causes “swimmer’s itch” (Vol - lenweider 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

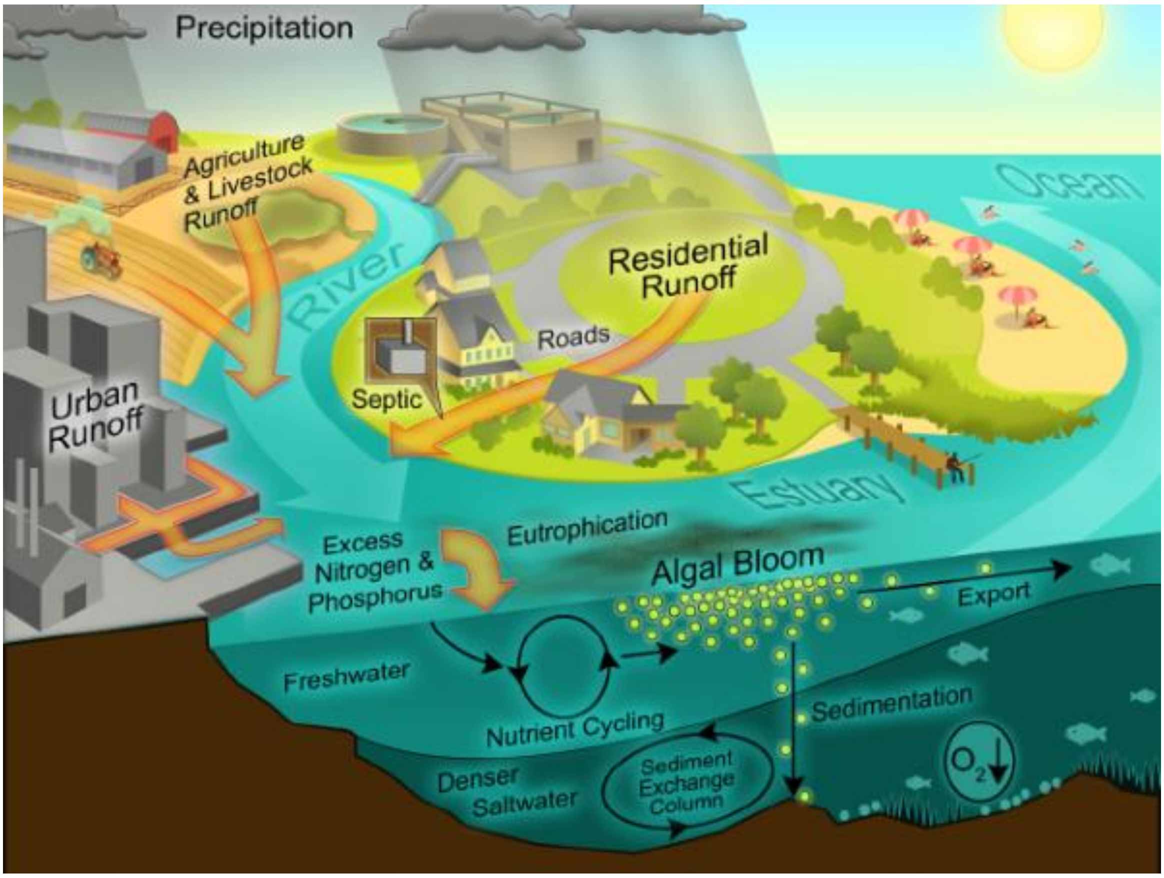

Figure 2: Numerous sources from the watershed of the lake contribute to nutrient inputs and eutrophication

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 de crease in the concentration of dissolved oxygen, harming marine organisms and making compliance with local and federal regulations more difficult to achieve (WHO 2003).

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 (Mandeville 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, which washes 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 (Ben net 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 been increasing as the use of phosphate-containing fertilizer, manure, and laundry detergent has become more common (Litke 1999). Consequently, humans re lease 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, 400 grams of phosphates could potentially induce an algal bloom to the extent of 350 tons (Sharma 1999).

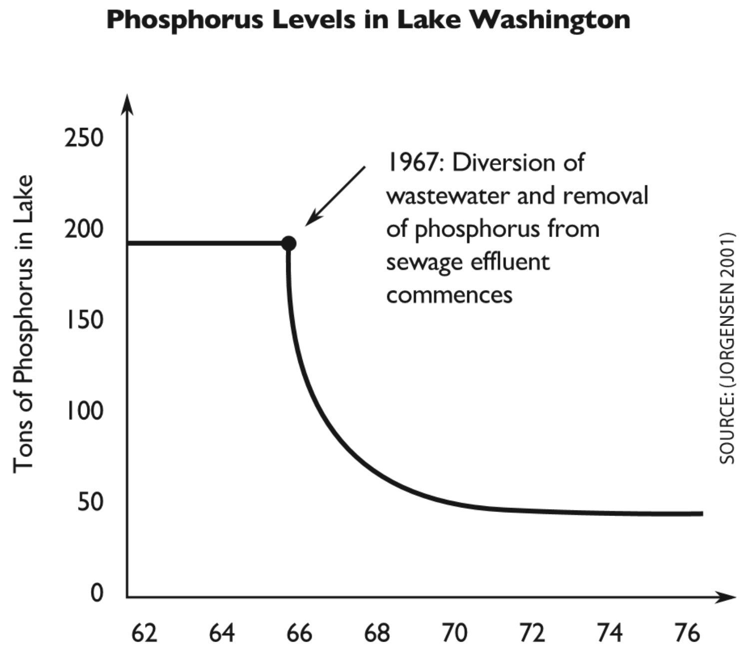

Figure 3: Diversion of wastewaters and removal of phosphorus from sewage effluent entering the lake proves to be effective in the reduction of total phosphorus levels

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 sources' higher levels persist and conditions remain favourable, algal blooms can become long-term events that have an impact on the ecosystem. Algae tend to grow very quickly under high nutrient availability, but each algae is short-lived, and the result is a high concentration of dead organic matter that starts to decay. The decay pro cess 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 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 can have negative impacts on other organisms due to the production of natural toxins, the infliction of mechanical damage, or by other means. These algae are often associated with large-scale marine mortality events and have been associated with various types of shellfish poisoning (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 the EPA set limits on nutrient loading in 1976, current 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 hypo-limnetic aeration (where water from the bottom of a lake is brought to the surface to be oxygenated then returned to the bottom), bio manipulation (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 bio manipulation is essential to future eutrophication management. While hypo-limnetic 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 hypo-limnetic aeration reduces algal biomass (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 hypo-limnetic aeration is ineffective, there is still much debate over the use of bio manipulation 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. Continuing to educate consumers so that they 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, re storing 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 of its 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 between 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 bio manipulation to target the biological factors aggravating eutrophication unaffected by nutrient controls.

Eutrophication Management Strategies: Bio Manipulation

Bio manipulation refers to procedures that alter the food web—communities of organisms where there are interrelated food chains. In one form, bio manipulation prompts organisms to favour grazing on phytoplankton. In another, bio manipulation eliminates fish species that recycle nutrients and favour those that assist algal management (Shapiro 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 (Shapiro 1990).

Bio manipulation involves eliminating certain fish species or restructuring the fish community to favour 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 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 (Shapiro et al. 1984).

While bio manipulation may not be effective on its own, particularly in larger lakes where changes in fish population have less of an impact, research has shown that bio manipulation 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 bio manipulation in conjunction to control and limit all sources of eutrophication, speeding up the recovery of a lake.

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 bio manipulation 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 multifaceted 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 and also to develop 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.

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