IMPACTS OF EUTROPHICATION ON THE SAFETY OF DRINKING AND RECREATIONAL WATER

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Summary

Eutrophication is most commonly associated with the anthropogenic pollution of water with excessive nutrients. The effect of this is the rapid increase in biomass, which can

have both positive and negative effects. Positive effects relate to the use of the waterbody as a source of fertilizer for economic benefit, such as for fish farms or rice paddies. Unfortunately, there are many more negative effects including: increased turbidity; dominance of particular species and therefore loss of biodiversity; offensive odor, taste and color; problems for drinking water treatment; and release of toxins causing human and environmental health problems.

Many cyanobacteria possess gas vesicles which allow them to migrate vertically within the water column to reach optimum growth conditions. This facility can provide them with a great advantage over other phytoplankton, particularly in stratified waters. Even in well mixed, shallow waters cyanobacteria may have an advantage, because many are capable of growth in varying levels of light and with low levels of nitrogen to phosphorus. Some species also proliferate in waters with low levels of dissolved oxygen having an affinity for phosphorus, nitrogen and carbon dioxide.

A great many of the World's recreational and drinking water sources suffer from eutrophication and outbreaks of cyanobacteria, mainly as a result of increased stream regulation. This has provided ideal conditions for concentrations of nutrients and growth of cyanobacteria. The toxins contained in cyanobacterial cells can have many acute effects on vertebrates, ranging from minor skin irritations, liver damage, impaired nervous system to death of livestock, wildlife and pets. Paralytic shellfish poisons have the potential to cause human deaths because they bioaccumulate in freshwater mussels. There are also risks of chronic illness from consumption of low doses of cyanotoxins, such as from drinking water or from bioaccumulation in crops irrigated with contaminated water. Marine cyanobacteria have been found to harbor *Vibrio cholerae* and are known to survive in ships ballast waters. Therefore conditions which favor cyanobacterial growth may increase the incidence of water-related diseases.

The problem of eutrophication can be reversed, but it needs both diffuse and point sources of nutrients reduced in order to be effective. Marine cyanobacterial outbreaks may be more difficult to control, due to the complexities created by the tides, winds, freshwater outflows and topography. Remediation of dams and lakes using these processes may still take several years until the new equilibrium between sediment and water is reached. In the meantime, the health risk must be reduced by physical removal of cells and toxin by treatment, or the issuing of warnings for recreational waters. To this end, a number of countries have developed legislation aimed at sustainable development, supported by guidelines to assist government agencies and the community to jointly combat these problems. However, further animal data is required to develop accurate guideline values and set suitable targets to control eutrophication.

1. Introduction

There is an increasing trend towards eutrophication of waterbodies world-wide. This process, when caused by human intervention, brings about rapid changes in aquatic biomass, often with losses of biodiversity and proliferation of exotic species. Additionally, eutrophication favors the growth and dominance of cyanobacteria, which contain toxins that can have detrimental effects on human and environmental health.

Eutrophication and cyanobacterial growth can become a problem in any types of water. In freshwater, the accelerated algal growth can lead to problems with odors, taste and color and cause problems for water treatment by blocking filters. The toxins can be difficult to remove during water treatment, causing additional cost and increased human health risks from drinking water. Cyanobacterial growth in fresh water has also caused losses of livestock, wildlife and pets. Recreational waters can also harbor cyanotoxins and water-related diseases, with varying health effects. The aim of this article is to explain eutrophication and look into its cause. It will provide examples of eutrophic lakes and the detrimental effects of excess nutrients. Then it will outline the growth requirements of cyanobacteria and look at the impacts of cyanotoxins on health from the various exposure pathways. Finally, the article will discuss legislation, policies and guidelines in place to assist in the management and control of eutrophication and what the future may hold.

2. What is Eutrophication?

Waterbodies can be broadly classed as ultra-oligotrophic, oligotrophic, mesotrophic, eutrophic or hypereutrophic, depending on the concentration of nutrients in the water and the productivity of the waterbody. 'Trophy' refers to the rate at which organic matter is supplied to a waterbody per unit of time. Natural eutrophication is the process, which may take thousands of years, for a waterbody to age and become more productive.

Anthropogenic or cultural eutrophication is water pollution caused by excess quantities of nutrients, such as nitrogen and phosphorus, resulting in excessive growth of plants and algae and reducing visibility. The subsequent decomposition of this organic matter by bacteria can consume all the dissolved oxygen in the water, killing other aquatic life and sometimes producing offensive odors and tastes in treated drinking water. Algae also absorb and concentrate mineral nutrients. When they die and settle to the bottom of the waterbody these nutrients are released, serving as a form of secondary pollution. Cultural eutrophication can also favor the growth of particular organisms, such as nitrogen fixing bacteria, allowing them to out-compete other species and decrease biodiversity. In contrast, oligotrophic waterbodies are characterized by a low level of nutrients, low productivity, high visibility and a diverse biota.

In the mid 1900's eutrophication was recognized as a pollution problem in many European and North American lakes and reservoirs. Since then waterbodies world-wide have shown an increasing trend towards eutrophication from anthropogenic sources. This trend is causing deterioration of the aquatic environment and creating serious problems for drinking-water treatment and human health.

In their natural state, rivers generally have a significant flushing rate, allowing sediments to accumulate, and then be carried downstream. As humans have tried to control nature by damming rivers in order to provide a constant source of water for their needs, they have altered the hydrology of the watercourses. Surface water consumption has also continued to grow with increasing population. Many rivers are often highly regulated, impacting the quality and environmental flow of the water. Slower flows allow less water for dilution and reduce the level of turbidity or mixing in the water.

Lakes and dams generally have longer water retention times than rivers and can accumulate sediments and nutrients. The increased retention times and larger surface areas associated with dams and lakes change the growth conditions of the waterbody. The sediments can act as a sink for nutrients such as phosphorus, which can later be released back into the water and, when combined with ideal growing conditions, create a rapid increase in the growth of cyanobacteria and algae.

Humans add excessive amounts of plant nutrients, such as carbon, nitrogen and phosphorus to waterbodies. This pollution has become a problem particularly in areas with high levels of industrialization and urbanization. Sewage treatment plants and intensive animal industries provide the main point sources for nutrients in waterways. Runoff from fertilized land and eroded soils as well as animal manures and plant litter are the main non-point sources. Many rivers worldwide have high phosphorus levels, with some rivers having high nitrogen levels as well. Storm water from urbanized areas can transport many nutrients and chemicals to the receiving water. Cropping and deforestation contribute to erosion and run-off of nutrients and top soils, binding some nutrients and increasing the sedimentation levels. The loss of riparian vegetation along the stream lengths, and the introduction of exotic fish pests, such as carp and gambusia have also had an impact on many rivers, adding to the rate of sedimentation and loss of native organisms in the waterways.

It was suggested that the level of phosphorus was responsible for the eutrophication in lakes, impairing the use of the waterbody as a resource for drinking water and recreation. Carbon and nitrogen undergo biochemical conversion to their gaseous forms, but phosphorus accumulates in aquatic systems, causing over production of biomass in the waterbody. Using seven, small, natural lakes as experimental systems, scientists at the University of Manitoba added various combinations of nutrients to determine the major plant nutrient that was the key to controlling eutrophication in lakes. Lakes 226 and 227 were particularly important in demonstrating that phosphorus was that key nutrient.

Studies of Lake 227 demonstrated that algae in lakes were able to obtain sufficient carbon from the carbon dioxide in the atmosphere to support eutrophic blooms. Nitrogen fixing algae were able to fix sufficient nitrogen to support algal growth. Lake 226 was divided into two portions using a plastic divider curtain. For several years, carbon and nitrogen were added to one half and carbon, nitrogen and phosphorus were added to the other half. It was found that the side receiving only carbon and nitrogen did not become eutrophic while the other half, receiving the phosphorus, developed eutrophic algal blooms each year, convincing skeptics that phosphorus was the key nutrient**.** This brought about changes in legislation to remove phosphates from laundry detergents and to control phosphates in sewage. However, this nutrient pollution is still a problem world-wide.

Although a number of elements are necessary to sustain the growth of algae, phosphorus is generally considered the limiting nutrient in temperate fresh waters. Most phosphorus goes into the bottom sediments, providing a permanent source of phosphorus. A portion of the soil particles can remain suspended for a period of time, acting as a potential reservoir of biologically available phosphorus, or the sediments can release phosphorus back into the water with changes in pH and redox potential. The microorganisms and higher plants present in waters can readily remove phosphorus from solution to fulfill their growth requirements.

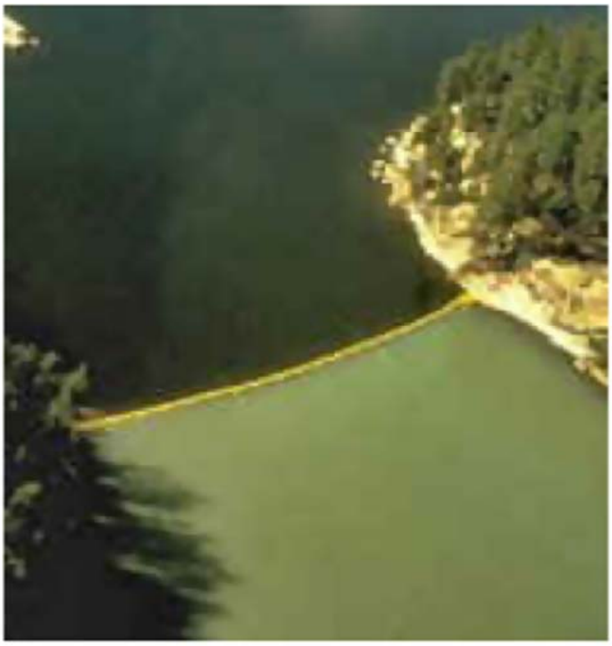

Figure 1. Lake 226 – Manitoba
(*Source:* Experimental Lakes Area, or ELA. (n.d.). University of Manitoba Viewed 6 April, 2006, available: http://www.dfo-mpo.gc.ca/regions/central/pub/ela-rle/index_e.htm.)

3. Effects of Eutrophication

3.1. Stratified Lakes

The quality of a lake and its ability to support aquatic organisms are affected by the amount of mixing the lake is subjected to, as well as other factors, such as climate, topography, inflows and the amount of vegetation. The depth, size and shape of the lake can be important factors influencing mixing. Water density peaks at 3.9°C, any warmer or colder water is lighter in density. As the surface water warms, it loses density. Wind and waves will readily mix a lake six to nine meters in depth, unless it is too small to catch the wind, or an unsuitable shape for mixing. However, deeper areas will not be mixed, dividing the lake into three zones, each with different physicochemical characteristics and biological populations.

The epilimnion is the zone of warm surface water and majority of plant growth. The thermocline is the transition area between the warm water and the colder hypolimnion zone at the bottom. Stratification traps nutrients released from the bottom sediments in the hypolimnion. During Autumn and Spring, the temperatures of the surface and the bottom even out; mixing occurs, causing an increase of nutrients flowing to the surface and the formation of blooms. Mixing also distributes oxygen throughout the lake. Many organisms cannot function efficiently unless the oxygen content of the waterbody is near saturation point. If the lake produces too much algae which then fall to the bottom to decay, the oxygen levels become depleted. This problem can preclude fish and other biota from inhabiting the deepwater regions of anoxic lakes on a seasonal or nocturnal basis.

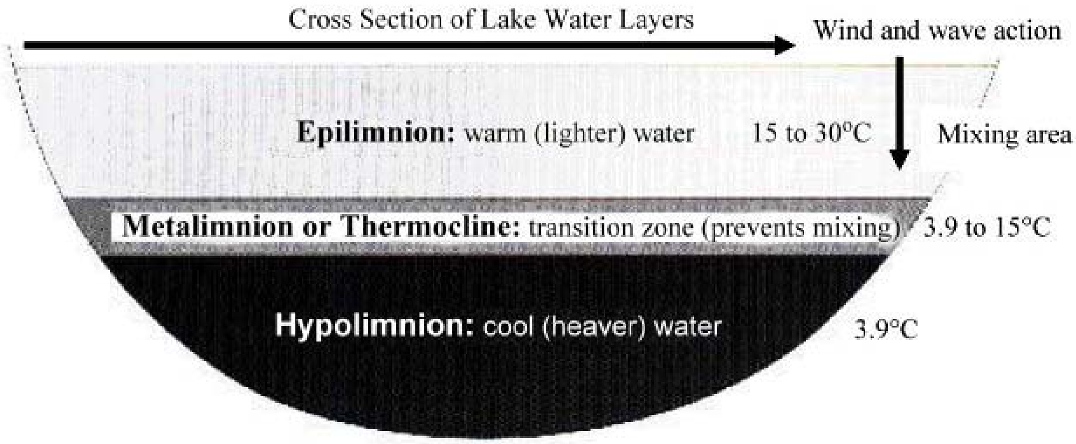

Figure 2. Diagram showing the stratified layers of a lake
(*Source:* Modified from the Washington Lake Book (n.d.) Lake Charactistics. Washington State Department of Ecology. Viewed 6 April, 2006, available: http://www.ecy.wa.gov/programs/wq/plants/lakes/characteristics.html.)

A shallow lake is considered healthy when there is a balance between large rooted plants (macrophytes) and algae. Once the situation favors micro or macro algae, it is very difficult to reverse the system. Biological processes and water quality are maintained by having a diverse range of plants. They take up nutrients and provide food and shelter for zooplankton which may graze on algal species. Vegetation not only provides oxygen to the water column during photosynthesis, but also stabilizes the sediments and reduces the release of sediment-bound nutrients during destratification or mixing.

3.2. Shallow Lakes

Shallow lakes present different challenges to the control of eutrophication than deep lakes. Sunshine normally penetrates to the bottom of the lake and nutrients from the sediments are bioavailable to all plants and organisms due to the lake's ability to be easily mixed by wind, storm or inflows. However, excessive nutrients enrich the water causing massive algal growth, and changing the natural biodiversity of the waterbody. Native fish species have been replaced by more resistant species such as carp, which can muddy the water and dislodge submerged vegetation, or there may be a complete loss of fish species. Elevated levels of algae compete with macrophytes for light and can smother submerged vegetation as is the case with sea grasses covered in the marine cyanobacterium, *Lyngbya majuscula*. Changes in water depth can reduce light penetration to submerged vegetation or cover them with sediment from silt. Beaches and lake edges can be detrimentally affected by masses of rotting, stinking algae, causing problems for tourists, beachgoers and water treatment agencies. In sub-tropical and tropical areas there is little differentiation between seasons which can create eutrophic blooms of algae almost all year round.

Ingestion of these contaminated waters has been associated with the deaths of cattle and other animals. Gastrointestinal disorders in humans have also been linked to ingesting cyanotoxin contaminated water. Recreational use of waters containing cyanobacterial blooms have caused allergic and dermalogic reactions in some people. Some green algae and cyanobacteria can cause off-flavors and odors in water and fish, as well as causing filtration difficulties in water treatment and industrial facilities.

3.3. Problems for Treatment

Green algae and cyanobacteria can produce earthy, musty or grassy odors and tastes, which are mainly attributed to the compounds geosmin and methylisoborneol. Although not considered a health concern at this stage, customer complaints about these problems can provide a useful early alert system. As they proliferate, they can look like streaks or slimy scums of blue-green paint on the surface, or they may be distributed evenly throughout the water column giving the water a visible green discoloration. Any treatment which lyses the bloom will release toxins into the water, which are difficult to remove. The blooms can also cause problems with water treatment processes by clogging filters. This causes shorter filter runs and more frequent backwashing. However, cyanobacteria with gas vesicles to give them added buoyancy may cause filter clogging even after a clarification step.

These cyanobacteria are able to regulate their buoyancy and actively seek water depths suitable for optimal growth. However, this regulation process can be slow and when the weather changes from stormy to fine, shifting the water from turbulent to stratified, buoyant cells may accumulate on the surface. Light winds may drive them to the shore forming scums. Such agglomerations are very dense, accumulating cells by a factor of 1 000 or more. Million-fold accumulations looking like pea-soup consistency, can pose a serious health risk to recreational users.

3.4. Accumulations of Scum

Accumulations of cyanobacteria are usually caused by planktonic species, in eutrophic waters. However, benthic cyanobacteria often growing in marine environments, can form mats on the lake or marine floor in oligotrophic conditions. They can only grow in clear water where sunlight penetrates to the bottom. Their photosynthesis on sunny days, may lead to high levels of oxygen production, forming bubbles under the mats which can cause parts of the mats to break away and float to the surface. Again, these situations can pose a serious health risk.

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Biographical Sketches

Jennifer L. Davis recently completed her Bachelor of Science Environmental Health receiving several awards for excellence during her studies. For the last seven months, she has worked as a research assistant at Griffith University, co-authoring with Dr. Glen Shaw three articles in peer reviewed publications. She is currently awaiting her acceptance for a Master of Philosophy, which will research the effect on aquatic organisms of chlorination disinfection byproducts in wastewater.

Dr Glen Shaw is a senior lecturer with the School of Public Health, Griffith University, Queensland, Australia. He is also Program Leader for Ecotoxicology in the Centre for Aquatic Processes and Pollution at Griffith University. Dr Shaw has been Program Leader for Toxicology in the Cooperative Research Centre for Water Quality and Treatment in Australia since 2001. His background expertise lies in the fields of environmental chemistry and environmental toxicology. His research interests relate to toxic algae and encompass their ecology, toxicology, treatment to remove toxins, toxin analysis and assays. His research in toxic algae spans the freshwater cyanobacteria, marine cyanobacteria and dinoflagellates and their toxins. Dr Shaw has also a research interest in anthropogenic chemicals in the environment including water chlorination disinfection byproducts and persistent organic pollutants.