EUTROPHICATION AND ALGAL BLOOMS

Glendon R. Shaw, David P. Moore and **Corinne Garnett**
National Research Centre for Environmental Toxicology, The University of Queensland and Cooperative Research Centre for Water Quality and Treatment, Brisbane, Queensland, Australia

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Summary

Eutrophication is the process of increase of plant nutrients in water with the consequent increase in the growth of algae and higher plants. This process is facilitated by external and internal (such as nitrogen fixation) sources of nutrients. Input of nutrients may be from point or diffuse sources. With phosphorus in particular, released from sediments can be a major source of this nutrient in water. In freshwater environments, anthropogenic inputs of nutrients (cultural eutrophication) have been demonstrated to be a major contributing factor to eutrophication and consequent algal blooms. In marine and estuarine systems, cultural eutrophication tends to enhance the input of nitrogen and phosphorus but not silica. This results in dominance by cyanobacteria and dinoflagellates rather than diatoms or chrysophytes. The formation of algal blooms in freshwater and marine ecosystems can result in the production of toxins depending on

the species of algae present. A number of toxins can be produced that have ecological and human health impacts. Freshwater cyanobacteria produce hepatotoxins that can be present in drinking water. These include the microcystins, nodularin and cylindrospermopsin. The neurotoxins, anatoxin-a and the saxitoxins, may also be produced by freshwater cyanobacterial species. Marine dinoflagellates can produce various toxins including paralytic shellfish toxins, diarrheic shellfish toxins, amnesic shellfish toxins and ciguatoxins. In addition to toxin producing algae, a number of freshwater and marine species can be regarded as nuisance algae. These cause problems in water treatment and deleteriously affect the aesthetics of marine waters. A number of strategies can be employed to control or remediate eutrophication and algal blooms. Integrated catchment management is now commonly being applied to reduce nutrient input into aquatic ecosystems both freshwater and marine, while in-water control measures tend to be applied to freshwater reservoirs and include such techniques as destratification and reducing the bioavailability of nutrients especially phosphorus.

1. Introduction

Eutrophication, in the strict sense is a phenomenon that has been occurring for millennia. It is the process of addition of nutrients to water bodies, including lakes, rivers, estuaries and oceans resulting in changes to the primary production and species composition of the community. This natural eutrophication process occurs over extended periods of time that are typically geological time scales. Since the industrial revolution however, eutrophication of many water bodies has escalated as a result of anthropogenic nutrient input. This is termed cultural eutrophication and in many parts of the world has resulted in a number of deleterious effects to ecosystems. In addition, cultural eutrophication has produced adverse effects on human society resulting in loss of recreation potential, reduced seafood production, drinking water problems, and the presence of phytoplankton toxins in drinking water and seafood. Many of the problems of eutrophication arise as a direct result of the production of algal blooms that can be toxic or cause serious changes in the ecology of water bodies. This chapter discusses the physical and chemical factors responsible for eutrophication, the resultant biological consequences and the impacts on human society.

Generally, the classification of water bodies according to their trophic status varies. It has been shown that algal blooms for instance occur with different nutrient levels depending on location. For instance, in Australia, total phosphorus (TP) can range from below 10 $\mu g\ L^{-1}$ to above 1000 $\mu g\ L^{-1}$ and total nitrogen (TN) can vary from 100 $\mu g\ L^{-1}$ to levels in excess of 10 000 $\mu g\ L^{-1}$. Algal blooms of considerable magnitude can occur at the lower concentration ranges, whereas in European water bodies, algal blooms tend to occur at higher nutrient levels.

Eutrophication and its consequent effects on algal blooms have been a problem for a long time. It is possible that the following passage from the Bible actually refers to a phytoplankton bloom:

> …*and all the waters that were in the river were turned to blood and the fish that was in the river died; and the river stank, and the Egyptians could not drink of the water in the river.* (Exodus 7:20-21.)

In a recent report, it was identified that 54 percent of Asia-Pacific, 53 percent of European, 28 percent of African, 48 percent of North American and 41 percent of South American lakes are eutrophic.

2. Eutrophication

2.1. Definition and Features of Eutrophication

Eutrophication is a process, both natural and anthropogenic of origin, which causes an increase in the supply of plant nutrients to natural waters and results in the growth of nuisance algae and higher aquatic plants. The term eutrophication has been defined in various ways, ranging from “the natural aging of a water body to a eutrophic state, which occurs over very long (geological) time”, to “the rapid rise in trophic status of a water body as a result of industrialization”, which is sometimes termed “cultural eutrophication”. Figure 1 represents the eutrophication process and defines the terminology of the trophic status of the water body. The water body starts from a nutritionally poor status (oligotrophic), through a mesotrophic state with addition of nutrients, to a final state (eutrophic) where water quality declines and nutrient build-up is observed in both water and sediments.

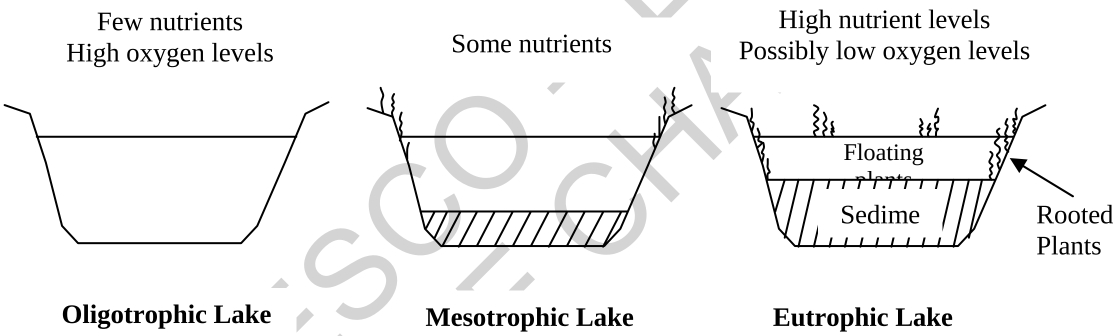

Figure 1: The eutrophication process – progression from oligotrophic to eutrophic. Adapted from Henderson-Sellers B. and Markland H.R. (1987). *Decaying Lakes. The Origins and Control of Cultural Eutrophication*, p. 2, Chichester, New York, Brisbane, Toronto, Singapore: John Wiley and Sons.

Eutrophication is induced by nutrient contributions, which arise from both external and internal inputs. The latter includes contributions from nitrogen fixation, releases from sediments, recycling from heterotrophs, and the release of soluble nutrients from the mineralization of organic matter. The two major elements controlling algal growth in temperate waters are phosphorus and nitrogen in the form of ortho-phosphate, and nitrate or ammonium salts respectively. The increased availability of these nutrients can disrupt the aquatic biological equilibrium to favour the enhanced growth of aquatic plant life. However, a process known as de-eutrophication or oligotrophication can reverse the equilibrium shift by reducing nutrient inputs. In some systems oligotrophication may be achieved through the physical removal of aquatic macrophytes that utilize nutrients. However, this is not a suitable mechanism for eutrophication control of planktonic algae which continue cycling nutrients in the system.

Eutrophic water bodies are characterized by a number of different conditions. These include:

- Decreasing dissolved oxygen concentrations in deeper waters;
- Increasing nutrient concentrations in the water;
- Increasing organic suspended solids;
- Decreasing light penetration;
- Increasing phosphorus concentrations in the sediments; and
- Progression from an algal population that is predominately diatom-based to one that is predominately cyanobacteria.

A comparison of the physical and biological characteristics of oligotrophic and eutrophic systems is presented in Table 1.

Characteristic	**Oligotrophic**	**Eutrophic**
Physical or Chemical Parameters		
Dissolved oxygen levels at bottom	High	Low
Water column nutrient concentrations	Low	High
Sediment nutrient concentrations	Low	High
Depth	Deep	Shallow
BIOLOGICAL PARAMETERS		
Primary productivity	Low	High
Species diversity	High	Low
Algal biomass	Low	High
Phytoplankton diversity	High	Low to monoculture
Bloom frequency	Rare	Common
Dominant phytoplankton	Diatoms/Green Algae	Cyanobacteria

Table 1: Characteristics of eutrophic water bodies compared with oligotrophic systems

Algae and aquatic macrophytes which may bloom as a result of eutrophication, oxygenate the water during the assimilation of available nutrients. However these oxygen supplies are consumed as the algal blooms senesce or macrophytes die. The large quantities of dying algal and macrophyte material are oxidized by aerobic bacteria, which deplete the oxygen in the water and can cause the death of fish and other aquatic organisms. The consumption of oxygen during the decomposition phase is referred to as biochemical oxygen demand (BOD) (see *Biochemical Oxygen Demand*). The establishment of anaerobic bacteria in bottom layers produces gases such as hydrogen sulfide and methane which reduce the water quality.

As well as nutrient contributions, the input of contaminants into eutrophic water bodies can also have a detrimental effect on the natural processes operating within. For instance herbicides and other pollutants can inhibit self-purification processes involving aquatic macrophytes. There are suggestions of differential susceptibility of micro-algae and aquatic macrophytes to anthropogenic pollutants and there is some evidence that toxic cyanobacteria may be more resistant to some herbicides than macrophytes. If this is the case, then the enhancement of toxic cyanobacterial blooms may be initiated by the impact of herbicides on aquatic systems.

2.2. Contributing Factors

Eutrophic environments can exist naturally, but in most cases result from major anthropogenic changes including catchment disturbance and nutrients entering waterways via overland runoff, stormwater and sewage works. In many parts of the world, as the population increases, water usage rises and agricultural practices intensify eutrophication of surface waters can be expected to increase. For example, in recent times Australia has identified eutrophication as a major water quality problem that can promote excessive algal growth and seriously degrade the quality of waterways. Due to the much lower population density in Australia, nutrient contributions from anthropogenic sources are lower than in many European countries. The concentrations of nutrients in Australian waters can however, still result in eutrophication.

Nutrients enter waterways both from point source discharges and from diffuse sources (see Table 2). Furthermore, water bodies often hold significant internal reserves of nutrients that can be released under certain conditions.

Point Sources	Diffuse Sources	In-stream sources
• Sewage treatment plants • Piggeries • Feedlots • Dairies • Industrial effluents • Irrigation drains	• Storm runoff from rural land • Urban runoff • Groundwater discharge • Atmospheric fall-out • Grazing	• Release of nutrients from bottom sediments • Stream bank collapses • The seasonal mixing with surface waters, of phosphorus-enriched water from deeper layers in lakes or reservoirs

Table 2: Examples of point, diffuse and in-stream sources of nutrients

Rivers, lakes and reservoirs are fed by waters which have traveled over or percolated through rocks, surface soils, sub-soils and organic matter. These waters carry with them nutrients and other chemicals dissolved from the rocks etc., with which they come into contact. Consequentially, water quality in the natural environment varies with locality and time. Nutrient contributions include many macronutrients and micronutrients. For phytoplankton to survive it has been shown that they require approximately 16 chemical elements and can utilize these in a variety of forms. Two major macronutrients linked to eutrophic conditions are phosphorus and nitrogen. The most bioavailable forms of these elements are orthophosphate (PO_4^{3-}), ammonium (NH_4^+) and nitrate (NO_3^-).

Phosphorus is very dynamic in aquatic systems and is usually transported to water bodies associated with particulates. This phosphorous may be released to solution either as orthophosphate or organic phosphates which may be subsequently hydrolyzed to orthophosphate. Particulates may also be deposited to become part of the bottom sediments which ultimately release phosphorus back to the water column. Figure 2 conceptually presents phosphorus dynamics in an enclosed water body. The concentrations of phosphorous that are associated with eutrophication vary, but orthophosphate levels of as low as 5 μg L^{-1} have been associated with cyanobacterial blooms in eutrophic waters.

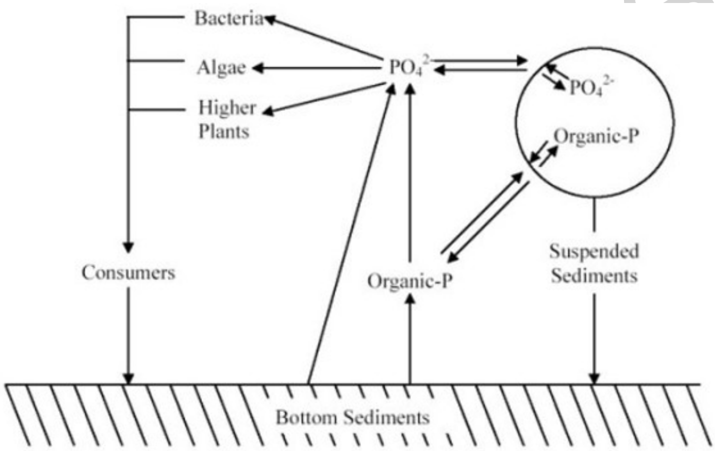

Figure 2: Phosphorus dynamics in lakes

If hypoxia occurs in the hypolimnion (denser, cooler water at bottom of water column) especially at the sediment/water interface, phosphorus release from the sediments may occur increasing the amount available to the algae. This release of phosphorus from sediments occurs because phosphorus is often bound to ferric hydroxides and under anoxic conditions the ferric ions are reduced to ferrous ions and binding is weakened thereby releasing phosphate to the water. This in turn fertilizes the algae and is referred to as “creeping eutrophication”. The processes involved in and environmental factors controlling phosphorous release from the sediments are represented diagrammatically in Figure 3.

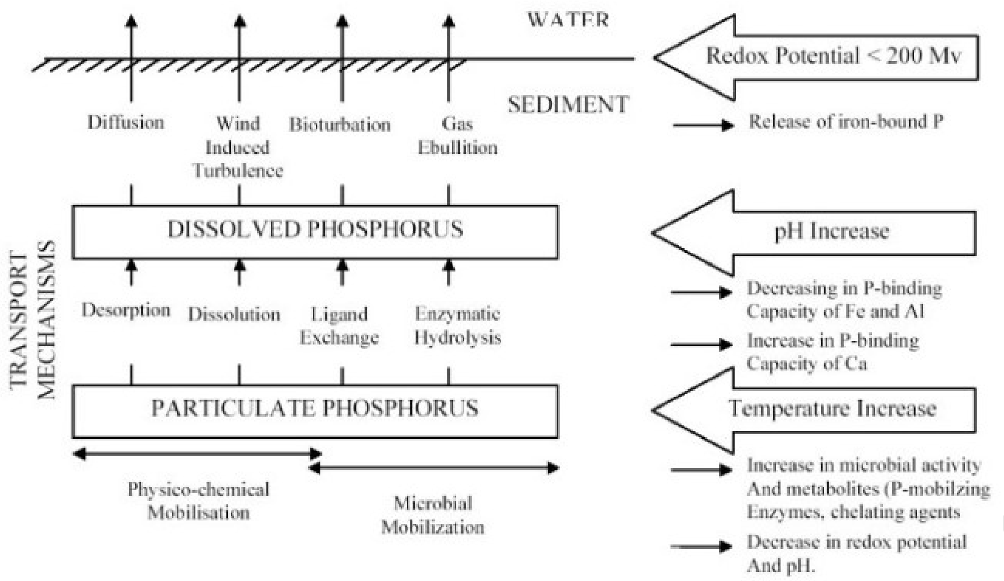

Figure 3: Representation of processes and environmental factors affecting phosphorous release from lake sediment

Many years of research on the influence of phosphorus on algal blooms in lakes and reservoirs has shown that phosphorus is the nutrient that is most often limiting. Other physical factors such as light penetration and temperature however can also be the main limiting factor even at low phosphorus concentrations. Tropical freshwater systems in contrast, usually demonstrate nitrogen limitation. Similarly, in coastal waters it is often concluded that nitrogen limitation occurs before phosphorus limitation. In estuarine systems, nitrogen is perceived as the nutrient most likely to limit primary production and this has been supported by several small-scale bioassay experiments. However larger spatial or temporal scale experiments show that estuaries do not clearly demonstrate nitrogen limitation as opposed to phosphate limitation.

A series of studies have shown that in some natural systems, the ratio of nitrogen to phosphorus (Redfield ratio) is important in terms of algal growth. The average cellular ratio of carbon/nitrogen/phosphorus in phytoplankton cells has been shown to be approximately 106:16:1. In general, aquatic systems that have a nitrogen to phosphorus ratio of greater than about 15 to 16:1, have been described as phosphorus limited. Cellular composition of phytoplankton however, is not constant and optimum cellular nitrogen/phosphorus ratios have been shown to vary from 7 to 87. This limiting nutrient concept assumes that the ratio at which the nutrients are taken up and used by algae, reflect the relative composition of these elements in the cell. This is true for “steady state” situations, but is less true for “transient” situations, (e.g. water bodies which receive substantial but intermittent nutrient input) therefore caution must be used when using this limiting nutrient approach.

Nitrogen is an essential part of the cell protoplasm in all organisms, and is an integral part of all proteins and DNA. After phosphorus it is the next most important macronutrient. Low bioavailable nitrogen (NO_3- and NH_4^+) has the potential to limit algal growth, however some cyanobacteria (both heterocystous and non-heterocystous) can fix atmospheric nitrogen and overcome this. Also following the senescence of the cyanobacterial cells, nitrogen compounds can be released and provide new opportunities for non-nitrogen fixers. Prior to assimilation, nitrate is reduced via nitrite to ammonia, and then can be incorporated in proteins and other cellular compounds in a process closely linked to photosynthesis. It has been shown that ammonium is preferentially absorbed relative to nitrate for a range of marine and freshwater algae. Some algae also have demonstrated the ability to utilize organic nitrogen compounds such as urea, amino acids and purines as a nitrogen source, and this may become significant in highly polluted environments. Processes involved in the nitrogen cycle at the sediment-water interface are illustrated in Figure 4. The biochemical transformations are carried out by either aerobic or anaerobic microorganisms in the sediments.

It is common management practice to limit loads of nitrogen and phosphorus entering a water body on the assumption that there is a direct causal relationship between these nutrients and phytoplankton biomass. There is considerable debate regarding whether nutrients limit the rate of growth, the total phytoplankton biomass or both. In real systems it is important to know both rate of uptake from the soluble pool and rate of regeneration of the nutrient from the algal pool. A very low nutrient concentration could indicate that the nutrient is depleted from the water column (and potentially limiting phytoplankton growth) or that the release and subsequent uptake of the nutrient is very rapid.

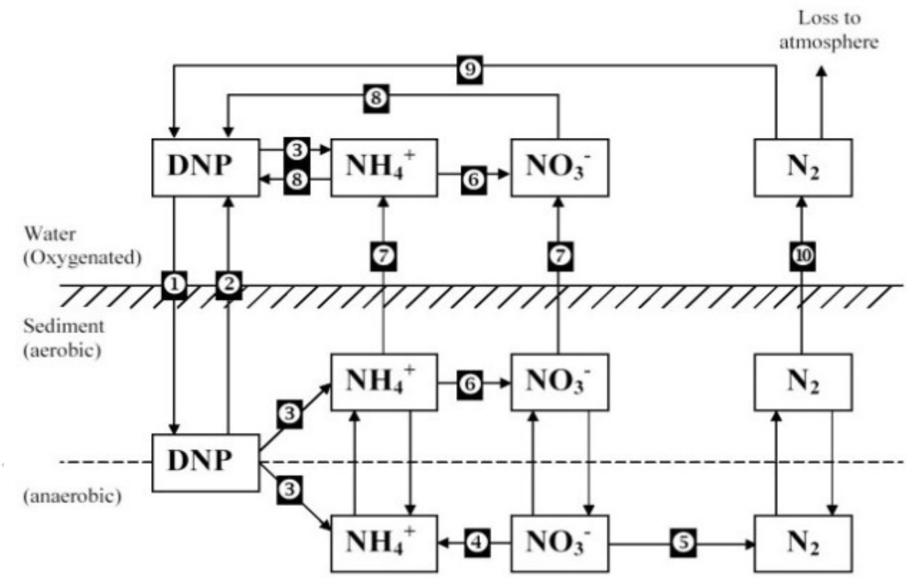

Figure 4: Chief processes forming part of the nitrogen cycle in the sediment–water system. 1-sedimentation, 2-resuspension, 3-ammonification, 4-reduction, 5-denitrification, 6-nitrification, 7-diffusion, 8-assimilation, 9-gas convection, 10-nitrogen fixation. DNP denotes nitrogen bound as organic forms such as nucleotides.

If the uptake and regeneration of nutrients is not balanced (without external inputs) the soluble pool may become depleted or enriched in a particular nutrient. Turnover rates for dissolved inorganic phosphorus and dissolved inorganic nitrogen are generally much more rapid in oligotrophic than eutrophic waters, as would be expected with the larger pool of soluble nutrients in the eutrophic waters. Oligotrophic systems are much more dependent on internal nutrient recycling.

Thermal stratification of water bodies is a physical process that can assist in producing a biologically eutrophic system at lower dissolved nutrient concentrations than otherwise expected. Based on temperature and resulting density changes, stratification occurs when two distinct layers of water exist within the one water body. During spring as the surface water heats up, a thermocline is formed and produces an upper warm layer, termed the epilimnion and a cold, denser, anoxic bottom layer, termed the hypolimnion. An inversion of these water layers occurs during autumn as the surface water cools, resulting in a mixed water body, which persists through winter.

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Biographical Sketches

Dr. Glendon (Glen) Shaw is a senior research fellow with the National Research Centre for Environmental Toxicology in Brisbane, Australia. He is also program leader for toxicology in the Cooperative Research Centre for Water Quality and Treatment where he manages research projects related to health aspects of toxins in drinking water. His background expertise includes various aspects of environmental chemistry and environmental toxicology. His interests include studies on the effects of eutrophication on the proliferation of and toxin production in freshwater cyanobacteria. He has undertaken studies of the environmental properties of anthropogenic organics including polychlorinated biphenyls and polycyclic aromatic hydrocarbons. Additionally he has interests in determination and prediction of the genotoxic and carcinogenic potential of both anthropogenic chemicals and natural toxins. Currently his areas of research include determination of the mechanisms of toxicity and genotoxicity of cyanobacterial toxins, human health risk assessment of algal toxins, development of assays for cyanobacterial and dinoflagellate toxins and studies of the ecological requirements of toxic cyanobacteria, and studies of treatment techniques to remove cyanobacterial toxins from drinking waters.

David Moore (B.App.Sc. (Env. Sc.) Hon) graduated from the University of Queensland, Australia in 1998. He is interested in freshwater ecosystems and he has gained experience in a number of private, public and research positions. His postgraduate education is focused on the ecology of freshwater cyanobacteria, in particular on *Cylindrospermopsis raciborskii*.

Corinne Garnett has been involved with research on the effects of global climate change on freshwater cyanobacteria and production of toxins by these organisms. This has included both laboratory and field determination of the effects of eutrophication and physical/chemical parameters associated with climate change on proliferation of the toxic cyanobacteria. She has background expertise in identification of a wide range of phytoplankton species and in instrumental analytical techniques. Corinne has also been part of a research team undertaking toxicological research on arsenic.