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Sources of the Eutrophication Problems Associated with Toxic Algae: An Overview

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Abstract

Blooms of cyanobacteria (toxic blue-green algae) can produce health and environmental hazards in water, including water used for drinking or recreational purposes. How, why, and when these blooms are produced, as well as how to deal with them, are questions whose answers are vital to the safeguarding of public health in regions where the algae occur. The blooms are linked to eutrophication of water, and this paper discusses the eutrophication problems, their nature, and their relevance to the production of cyanobacteria. Nutrient limitations on algal productivity are considered, as is the involvement of the atmosphere, the storage of nutrients in soils, and the influence of anthropogenic activity.

Introduction

Eutrophication is the biological response of water to overenrichment by plant nutrients, particularly nitrogen and phosphorus. Public concern began to rise in the 1960s (although the term "eutrophication" is older), when nutrient enrichment was rapidly making many bodies of water increasingly fertile. This eutrophication was mainly caused by the addition of plant nutrients from human activities, called, in this context, artificial or anthropogenic eutrophication. The phenomenon is a consequence of society's municipal, industrial, and agricultural use of plant nutrients and their subsequent disposal.

Lakes and reservoirs have a finite life span. They may pass through periods in their existence when they become more or less fertile, according to different factors—principally their geographical position or the climatic conditions (Moss, 1988). The process of eutrophication has been used deliberately as a way to fertilize and thus to increase phytoplankton production and, indirectly, the population of fish within a lake or reservoir. What is new in the past few decades, however, is the extent of enrichment of lakes and rivers throughout the world as a result of the growing human population, more intensive agricultural and industrial activities, and the development of large sewage systems associated with large metropolitan areas. Until recently, a relative lack of control over the sources of the nutrients or over their effect upon the aquatic ecosystems has resulted in changes occurring within decades rather than over the centuries—or longer—in which such changes would appear naturally. Many studies of lakes around the world have provided evidence of human-induced changes. Good examples of such studies are those carried out on the Great Lakes (Beeton & Edmondson, 1972; Sly, 1991).

In the United Kingdom, eutrophication has been identified as an extremely widespread problem and has been blamed for damaging many aquatic sites in England known as Sites of Special Scientific Interest, despite government claims that only a few surface waters have been affected (Carvalho & Moss, 1995). In a study commissioned by English Nature, a statutory conservation agency in England, it was found that 79 Sites of Special Scientific Interest showed signs of eutrophication. As a result, English Nature has called for a large-scale investment program to deal with the eutrophication problem in aquatic wildlife sites (English Nature, 1997).

Anthropogenic eutrophication appears to be the main problem. Excessive fertility in lakes and reservoirs results in heavy growth of phytoplankton, particularly of blue-green algae (cyanobacteria), that may form thick mats at the water surface and thus spoil the appearance of the lake. Some species of cyanobacteria may produce substances that are highly toxic to fish, birds, or mammals. In some cases, dense blooms of algae have resulted in fish kills by causing the hypolimnion to become anaerobic. Increased crops of phytoplankton often clog the filters of water treatment plants and make the treatment of water more costly. Furthermore, some unwanted organic substances produced by the algae can pass through the filters at water treatment plants and cause unpleasant tastes and odors, or may even be toxic to human consumers. Eutrophication thus can not only impair aesthetic qualities of the water, but also affect the use of water for water supply, fisheries, and recreation.

The Sources

Nutrient Limitation

The essential elements required by living cells to sustain growth and reproduction are carbon, oxygen, hydrogen, other macronutrients, and trace elements. Of these, carbon is the most important, the main reservoir being atmospheric carbon dioxide. Carbon is easily soluble in water and is thus unlikely to be a limiting factor for algae growth, except during intense blooms. Oxygen and hydrogen are freely available in the water in most circumstances.

The most important macronutrients are calcium, magnesium, potassium, phosphorus, nitrogen, sulfur, iron, and silicon. Phosphorus is important because it is the only nutrient whose proportional abundance is lower in the lithosphere than in plant tissue. It is thus a prime candidate to become a limiting factor in algae growth. The main reservoir of nitrogen is atmospheric dinitrogen, which is not available to plants directly, consequently nitrogen might be a limiting factor as well.

Trace elements, including boron, chlorine, cobalt, copper, manganese, molybdenum, zinc, and, in some cases, vitamin complexes, are required in very small quantities.

The "law of the minimum," which was first formulated by Justus von Liebig, states that growth is limited by whatever is in shortest supply (Gibson, 1971; Welch, 1980). For the reasons stated above, phosphorus and nitrogen are said to be "key nutrients"; in some circumstances, they may become limiting. Therefore, they are in most cases the nutrients that control algae growth, though some diatom species may be limited by silica. Other factors, such as light, may also limit algal productivity.

Supply of Phosphorus and Nitrogen to Lakes

Phosphorus is the 11th most abundant element in the earth's crust, and it is geochemically classed as a trace element. In nature, phosphorus exists almost exclusively as phosphate, a great part of which is sorbed to soil particles or incorporated into soil organic matter. Phosphate deposits occur in the earth's crust principally as the mineral apatite: $Ca_5(F,Cl,OH,\frac{1}{2}CO_3)(PO_4)_3$. The initial natural source of phosphorus is weathering of such rocks. Weathering liberates phosphate from the mineral, and the phosphate can then enter the biosphere through uptake by plants.

The initial source of nitrogen is the atmospheric reservoir of gaseous dinitrogen. Nitrogen gas is chemically very stable. It must be converted by nitrogen fixation, by microorganisms living principally in the soil but also in aquatic environments, before it is available to most living organisms. In natural water, nitrogen is present as dissolved dinitrogen, ammonia, and salts of the nitrate and nitrite ions; in addition, there are nitrogen-containing organic compounds primarily attributable to the presence of life.

In a natural, undisturbed environment, nutrient sources are the drainage of the catchment, the direct atmospheric deposition (rainfall and dry depositions) onto the water surface, and the internal recycling from lake sediments. Ahl estimates the background phosphorus input to be in the range of 3 to 10 kilograms (kg) of phosphorus per square kilometer per year, depending on the size and the characteristics of the basin (Ahl, 1988). He also estimates the virgin atmospheric deposition in remote areas of the northern hemisphere to be less than 5 kg of phosphorus per square kilometer per year. Therefore, runoff of nutrients in natural untouched environments is very low; the main reason is that such catchments are generally almost entirely forested, the dense vegetation of these ecosystems resulting in very tight cycles of nutrients and a maximum ability of the system to resist erosion (Bormann, Eaton, Likens, Perce, & Siccama, 1974).

Because humans interfere with their environment in a complex manner, the distinction between "natural sources" and "sources that are conditioned by human activities" is not always obvious. It is more practical to distinguish between "diffuse sources" and "point sources" (Vollenweider, 1968). Point sources are easier to examine and assess than diffuse sources, for which an accurate quantitative estimation is not possible. It is important to note that all natural sources are diffuse, but that artificial sources may be either diffuse or point sources.

Atmospheric Sources

The supply of both phosphorus and nitrogen from atmospheric deposition is potentially a significant source of nutrients for aquatic ecosystems. For example, data from a watershed on Missouri Valley deep loess in southwestern Iowa showed that about two-thirds of the soluble nitrogen leaving a watershed fertilized at 168 kg nitrogen per hectare via surface runoff could be attributed directly to nitrogen in the precipitation that caused the runoff (Schuman & Burwell, 1974).

The phosphorus contribution of wet and dry deposition to lakes is highly variable. In unpolluted regions, precipitation generally contains low levels of phosphorus, but in the environs of urban-industrial aggregations, this content increases considerably. Atmospheric phosphorus fallout is mostly particles of terrestrial origin, including insect parts, whole insects, leaves, bud fragments, pollen, and so forth, that may be transported through the short-range atmospheric circulation patterns by wind and deposited onto a lake surface far from their original source. The amount of phosphorus and organic matter reaching the surface of Lake Warniak in Poland through atmospheric fallout was estimated directly for three summer months; the aerial input of phosphorus averaged 20 micromoles (µmol) per square meter per day. Comparison of this value with the one for the inflow from the drainage area yields an estimate that fallout makes up 53 percent of the total input (Kowalczewski & Rybak, 1981). Similarly, the atmospheric phosphorus input to Lake Mirror, an oligotrophic lake in New Hampshire, has been estimated to be about 12 µmol per square meter per day—that is, 50 to 60 times greater than the fluvial input of phosphorus (Cole, Caraco, & Likens, 1990). Furthermore, a study in the Montane Region of Colorado indicates transport of filterable, water-soluble phosphorus substances, probably of biogenic origin, in large amount over a short period of time, which may account for significant long-distance phosphorus transport (Lewis et al., 1985).

Nitrogen deposition is of a higher order of magnitude than that of phosphorus; it includes dissolved dinitrogen, the products of chemical fixation, and some organic compounds as well. In Lake Tahoe (California/Nevada), atmospheric deposition provides most of the dissolved inorganic nitrogen and total nitrogen in the annual nutrient load (Jassby, Axler, Goldman, Hackley, & Reuter, 1994). Atmospheric inputs of allochthonous nitrogen have increased a great deal more than those of phosphorus as a result of human activities. Gaseous nitrogen pollutants may be ammonia, from the application of aqueous fertilizers and the decomposition of animal and human wastes, and oxides of nitrogen, from the combustion of fossil fuels and the use of motor vehicles. Such compounds are released into the long-range atmospheric circulation patterns and may travel very long distances, according to atmospheric wind patterns and meteorological conditions, before they are deposited onto a lake surface.

Storage of Nutrients in Soils and the Consequences of Human Disturbance

In soil, both nitrogen and phosphorus are found principally as organic compounds, in either detritus or living tissues.

A great part of the phosphate in soil is sorbed to soil particles or incorporated into soil organic matter. The solubility of phosphates is controlled by either sorption-desorption or precipitation-dissolution reactions, depending on the environment in the soil or sediments. At a disposal site in Albany, Western Australia, estimated minimum travel times for phosphorus, based on a combination of soil parameters that resulted in the greatest mobility of phosphates, were calculated for wastewater from treated sewage. Such estimated travel times ranged from 300 to 700 years in 3.5 meters of topsoil, and from 200 to 500 years in a further 10 meters of subsoil (Gerritse, 1993). Phosphate ions are tightly bound to the molecular lattice of most soil particles and consequently are not easily leached out of most soils in soluble forms.

On the other hand, inorganic salts of nitrogen (nitrate NO_3 and nitrite NO_2), whose presence in the soil is due mainly to bacterial nitrification processes and to atmospheric deposition, are not tightly bound. Because they are very soluble in water, they are easily leached out of the upper soil layers by rainfall. These differences in chemical behavior have important consequences for losses of phosphorus and nitrogen from soils.

The release and export of nutrients from uncultivated soil is a function of the geology, the soil composition, the land form, and the type of covering vegetation, as well as air temperature, precipitation, hydrological conditions, pH, and so forth. An analysis of drainage characteristics and stream nitrate levels in the Duffin Creek area of southern Lake Ontario suggests that a number of soil and topographic variables have a significant correlation with stream nitrate levels (Hill, 1978). Ahuja, Lehman, & Sharpley (1982) show that an increase of either length or degree of slope increases the average phosphorus released per area of soil, and that the average phosphorus concentration of storm runoff decreases with an increase in storm size. Dillon & Kirchner (1975) examined the effect of geology on the export of phosphorus from watersheds; they concluded that the mean export of total phosphorus was higher from sedimentary watersheds than from igneous watersheds.

Generally, the denser the vegetation cover is, the more rapid the cycling of nutrients within the terrestrial ecosystem. In the Hubbard Brook system, clear-cutting of a forested ecosystem and inhibition of vegetation regrowth by herbicide at the beginning of the annual growing season triggered a chain of complicated interactions (Bormann et al., 1974). The more important effects were

- the elimination of transpiration and the reduction of root interception of nutrients, with the result that both the amount and the flow rates of water passing through the system increased drastically;
- higher soil moisture and temperature, which were more favorable to rapid decomposition and a major increase in the process of nitrification, with the result that concentrations of most dissolved nutrients and export of dissolved substances in stream water increased;
- increased erodibility of the ecosystem, which increased the effectiveness of water in removing both organic and inorganic particulate matter, with losses up to 10.7 times those of the forested ecosystem.

Thus, the transformation of natural ecosystems into land for man's agricultural use has a drastic effect upon nutrient losses from the soil and may contribute to eutrophication. Land use often affects water quality to a greater extent than does the geomorphology or the drainage type of the soil; studies at Lake Tahoe have demonstrated that a relatively small amount of human disturbance can significantly affect water quality, particularly when that disturbance affects the most sensitive area of the watersheds (e.g., erodible soils, steep slopes, and stream environment zones). As a result, losses of nutrients increase in proportion to intensity of land use. Harper and Stewart (1987) have studied and compared the catchments of three shallow lowland lakes, in the Tayside region of Scotland, whose land uses differ greatly. The first catchment (the Lowes, defined as mesotrophic) is mostly moorland and woodland. Most of the second catchment (Balgavies, defined as eutrophic) is given over to intensive agriculture. The third catchment (Forfar, defined as hypertrophic) has intensive agriculture but with a substantial urban proportion. Soluble inorganic nitrogen concentrations, in the main inflows to the lochs and the loch outflows, increase with greater intensity of land use, reflecting the ease with which nitrogen is lost from agricultural soils (annual mean nitrogen values ranged from 110 to 320 milligrams [mg] per cubic meter, from 1,300 to 4,000 mg per cubic meter, and from 5,630 to 10,200 mg per cubic meter for the Lowes, Balgavies, and Forfar catchments, respectively). Soluble reactive phosphorus showed only small differences between the Lowes and Balgavies catchments, because phosphorus is tightly bound to soil particles. The more intensive agriculture of Forfar's catchment however (soft fruit cultivation which leaves much of the soil surface exposed) resulted in higher concentrations of phosphorus in the rural inflows. The urban sewage effluent contained high concentrations of both nitrogen and phosphorus, particularly phosphorus (annual mean values of phosphorus concentration in the inflows and outflows ranged from 20 to 50 mg per cubic meter, 27 to 30 mg per cubic meter, and 90 to 2,200 mg per cubic meter, for the Lowes, Balgavies, and Forfar catchments respectively). Dillon & Kirchner (1975) indicate average values for the export of phosphorus from comparable watersheds; these range from 4.7 mg per square meter per year from a forested watershed, to 23.3 mg per square meter per year from a watershed with forest and pasture, to 46 mg per square meter per year from a watershed with intensive agriculture, and up to 110 to 1,660 mg per square meter per year from an urbanized watershed.

Agricultural Land Use

Catchments dominated by agricultural activities exhibit higher total nitrogen and phosphorus export and also wider export variability than do undisturbed forested catchments. The potential for soil erosion and nutrient export increases as the soil surface is increasingly disturbed and exposed to the weather. The quantities of nitrogen and phosphorus lost from agricultural land further depend on such factors as soil type, amount of fertilizer nutrient added, management practices, crop type, pasture and grazing operations, animal feedlots, and manure storage facilities; some of these factors vary according to the season and from year to year.

Soil Type

Soil characteristics have a substantial influence on the loss of chemicals from soils, and, in some cases, they may be of prime importance, even beyond land use, in determining the nutrient content of waters.

Leaching of nutrients from soils depends on the pool of nutrients already present in the soil, the adsorption capacity (i.e., the cation content), the water holding capacity, and, most important, the soil texture (i.e., the particle size distribution). From a general point of view, surface runoff is more prevalent on fine-grained clay soils than on coarse sandy soils, since the latter tend to have rapid infiltration capacity. As a result, nutrient export via surface runoff is higher with clay soils than with sandy soils. Sandy soils, however, also have a low capacity to sorb nutrients and are therefore very susceptible to leaching, whereas clay soils have a high sorption capacity and tend to retain nutrients better.

Organic soils have rather high nutrient content, and their adsorption capacity is limited; therefore losses of nitrogen and phosphorus from such soils can be high.

The Use of Fertilizers and Management Practices

Currently, the two sources of fertilization commonly used are slurry (from concentrated livestock units) and artificial compounds. Nitrogen and phosphorus losses in surface runoff from fertilized soils depend upon the quantity of transporting water and the time and rate of fertilizer application (Klausner, Ellis, & Zwerman, 1974). Of most importance is the time at which fertilizers are applied to the soil. When fertilizers are applied before a wet period or snowmelt, or on frozen ground (i.e., fall and winter fertilization), losses are higher than when fertilization is done in the spring, just before the growing season. Excessive application of fertilizer compounds and bad management practices increase nutrient loss from the soil. Lesser amounts of nitrogen and phosphorus are lost to the surface water of judiciously fertilized and well-managed soils (Cullen, Farmer, & O'Laughlin, 1988; Kilmer Eklund, Gilliam, Joyce, & Lutz, 1974; Schuman, Burwell, Piest, & Spomer, 1973). Phosphate ions are strongly held in the soil, so only a very small fraction of the fertilizer applied to the soil would be expected to reach drainage waters (Kilmer et al.). Results from a study on a rural watershed demonstrate that less than one percent of the phosphorus applied to the landscape as fertilizer and manure, in soluble form, leaves the watershed in dissolved form (Johnson, Bouldin, Goyette, & Hedges, 1976). Therefore, the application of phosphorus fertilizers is more likely to increase the phosphorus available in soil rather than that present in drainage water from agricultural lands. Fertilization may also in some cases decrease nutrient runoff by increasing plant cover and thus decreasing runoff volume and soil erosion.

Livestock Production

Nevertheless, phosphorus inputs from agricultural sources to aquatic ecosystems have also continued to increase, as a consequence of changes in animal husbandry. Animals are maintained nowadays in large, densely packed battery units. Furthermore, changes in the quality of food they are given have resulted in a more liquid slurry waste that contains very high concentrations of nutrients and organic material; the waste may be applied to the land as a method of disposal, or it may leave the feedlot in surface runoff. The consequence is that livestock units become point sources of nutrient runoff rather than diffuse sources, and under improper management practices, they may pose serious problems comparable to the discharge of untreated municipal sewage effluents. They may contribute to organic pollution of the receiving body of water as well as nutrient enrichment.

Another agricultural practice is fish farming, mainly for salmonids. The production of salmon in cages requires that feed containing nutrients be added. This addition of nutrients and of organic matter constitutes a point source of nitrogen and phosphorus to the receiving water body. It may pose problems associated with eutrophication, because such farms are located in areas of naturally low nutrient runoff and high water quality (Folke, Kautsky, & Troell, 1994).

Urban Land Use

The most intensive land use is urbanization, which concentrates people and their wastes. Urban wastes include atmospheric emission fallouts; street residues (litter, ice control chemicals, combustion residues from motor vehicles, etc.); erosion from construction sites; household wastes; detergents; and industrial effluents. A portion of the urban runoff may drain to sewage plants, while the remainder may reach surface waters by drainage channels without receiving any treatment. The impact of this waste source can be significant since the nature of the contaminants it contains is highly diverse and potentially nutrient rich.

Urban wastes are processed in sewage treatment plants whose principle is to allow the bacterial oxidation of organic matter to take place within the treatment plant rather than within the watercourse. In this way, all the major elements from the wastes (carbon, nitrogen, and phosphorus) are oxidized. These elements therefore become soluble and drain in high concentration in the effluent from the treatment plant. Such effluents are point sources of nitrogen and phosphorus.

Discussion

When eutrophication occurs, plant and algae growth in the water is enabled. The sources, as outlined previously, are intimately related to anthropogenic activity, and the results of the increased growth in these waters often affect the environment or public health adversely.

Increase in algae growth can be rapid. Where these algae produce harmful toxins, the results can be dangerous to health. Cyanobacteria can produce neurotoxins, hepatotoxins or lipopolysaccharide toxins, depending upon the species. The toxins in the first two groups can produce severe reactions in animals, including humans; the third group appears to be less virulent, although these toxins have been less intensively studied.

Any release of toxin into surrounding water can present a significant hazard to livestock and humans drinking the water. Although the possibility of an acute lethal dose reaching the consumer through the drinking-water supply can be excluded—an adult would have to ingest a huge quantity of a toxic bloom to receive such a dose—the existence of gastrointestinal disorders linked to the ingestion of cyanobacterial toxins, as well as the chronic risks posed by hepatotoxins, make the toxins of blue-green algae a serious threat to human health when they are present in drinking-water supplies.

Water used for human consumption should be regularly monitored for these toxins. Predicting where and when toxic blooms will form is difficult if not impossible. The enormous variability in the toxicity of blooms within and between years—and even within a lake on a single day—makes assessment of the potential risk a major problem. Several samples must be collected to determine whether cyanobacterial toxins are present in drinking-water supplies or lakes used for recreation. In addition, there are many variants of hepatotoxins (more than 50 microcystins have been recognized, for example), each with its own toxicity. Every lake should therefore be considered unique in terms of cyanobacterial toxin production and toxicity potential (Kotak, Lam, Prepas, Kenekick, & Hrudey, 1995). Equally important is to distinguish between cyanobacterial and other algal blooms, if public confidence in warning systems is to be maintained.

Unfortunately, the toxins produced by cyanobacteria are not removed by conventional water treatment processes such as flocculation, sedimentation, sand filtration, and chlorination. Furthermore, treatment processes that use potassium permanganate or chlorine may release the toxins from the cyanobacteria, and the toxins may therefore reach people through water supplies. Water treatment studies conducted at laboratory and pilot-plant scale have concluded that activated carbon filtration and ozonation are efficient in the removal of the toxins from drinking water to below the detection limits of the mouse bioassay and high-performance liquid chromatography (Falconer, Runnegar, Buckley, Huyn, & Bradshaw, 1989; Himberg, Keijola, Hiisvirta, Pyysalo, & Sinoven, 1989). Nevertheless, toxin levels too low to be detected by these methods can still cause chronic health problems in humans, and more sensitive analytical techniques are needed to detect and quantify the toxins in both raw and treated water. There are two such methods: The first one is an enzyme-linked immunosorbent assay (ELISA), in which the principle is to produce antibodies against, and to attach a specific enzyme to, microcystins. The enzyme can then be used with further reagents to give a color change. The second method is the protein phosphatase (PP) bioassay. It is possible to quantify microcystin at concentrations in the parts-per-million range with ELISA (Chu, Huang, Wei, & Carmichael, 1989), and as low as 0.1 microgram per liter with PP (Lambert, Boland, Holmes, & Hrudey, 1994). Microbiologists in Australia have recently found a bacterium that makes three enzymes that break down microcystin-LR. One enzyme, which the researchers called microcystinase, breaks the bond between two of the seven amino acids in the cyclic heptapeptide. The resulting linear chain of seven amino acids is said to be more than a hundred times less toxic than the ring structure. Two more enzymes cause further breakdown of the peptide to single amino acids (Anderson, 1995).

Since the first publication on toxicity from cyanobacteria (Francis, 1878), many similar incidents have been reported from all parts of the world, in cattle (Galey et al., 1987; Reynolds, 1980), sheep (Main, Berry, Peet, & Robertson, 1977), swine (Beasley et al., 1983), dogs (Edwards, Beattie, Scrimgeour, & Codd, 1992; Nehring, 1993), fish (Tencalla, Detrich, & Schlatter, 1994), and bats (Pybus & Hobson, 1985). A lot of work has also been undertaken to identify the poisonous strains of cyanobacteria, to isolate the toxins they produce, and to study their effects upon living organisms.

Although no confirmed human death has yet been attributed to the toxins produced by cyanobacteria, some cases of illness have been associated with obvious contacts with blue-green algae through household water use or water sports. The occurrences of poisoning episodes, investigation into their toxicity potential, and human exposure assessments together indicate that the toxins produced by cyanobacteria constitute a hazard to human health when present in drinking or recreational waters. Such toxins can cause not only acute responses such as allergic reactions, skin irritation, gastroenteritis, hepatoenteritis, and pneumonia-like symptoms, but also long-term chronic effects such as liver damage or tumor promotion when exposure to the toxins is prolonged.

Reports of acute toxicity fall into two main groups:

1. *Allergic reactions and skin irritations:* From bathing and showering in water containing blue-green algal blooms, skin or oral mucosal contact results in allergic reactions resembling hay fever and asthma, as well as skin, eye, and ear irritations. Cyanobacteria may also promote allergic reactions with symptoms of hay fever in susceptible persons through inhalation of airborne cells or spores (Bell & Codd, 1994; Falconer, 1989; Heise, 1951).
2. *Ingestion-related illnesses:* Gastro- or hepatoenteritis disorders may result from ingestion of the toxins in drinking water or from accidental ingestion of the toxins in recreational waters. Oral intake results in diarrhea, vomiting, nausea, muscle weakness, sore throat, respiratory difficulty, or headache (El Saadi & Cameron, 1993). Outbreaks of hepatoenteritis have been reported in towns drawing drinking water from an affected source. A severe outbreak of hepatoenteritis, which affected 148 inhabitants of Palm Island, Australia, occurred in 1979, shortly after the contaminated drinking water was treated with copper sulfate to control a heavy blue-green algae bloom. A highly toxic strain of cyanobacteria was isolated; as a result, cyanobacterial poisoning was suspected to have caused the "Palm Island mystery disease" (Bourke, Hawes, Neilson, & Stallman, 1983), although it is also possible that the illness may have resulted from the high levels of copper sulfate used to control the bloom (Prociv, 1987).

In addition to the above cases of acute poisoning, there is evidence of more long-term chronic human health hazards caused by cyanobacteria toxins; a study assessing the chronic effects associated with small amounts of cyanobacterial toxins ingested over long periods, such as might occur through drinking water, was undertaken on human lymphocytes in vitro. It found that the algal toxins produced more chromosome damage than did benzene (a known carcinogen) and sodium arsenite, while damage produced by polychlorinated biphenyls (PCBs) was similar. These results suggest that toxins produced by cyanobacteria may be a more serious environmental hazard than generally recognized (Repavich, Sonzogni, Standridge, Wedepohl, & Meisner, 1990). Cyanobacterial hepatotoxins are potent inhibitors of protein phosphatase (an enzyme that plays a role in the regulation of the number of phosphate groups on protein chains) (Carmichael, 1994). The inhibition of protein phosphatase is a general mechanism of tumor promotion in various organs. Indeed, the evidence that microcystin is a potent tumor promoter and that nodularin (another cynanobacterial hepatotoxin) is a liver carcinogen in rat liver (Ohta et al., 1994) points to the environmental hazard these toxins pose, and it is possible that microcystin might induce liver cancer in humans when present in drinking water (Nishiwaki-Matsushima et al., 1992).

It has been shown that the freshwater mussel *Anadonta cygnea* is capable of accumulating the peptide toxin from *Oscillatoria agardhii*; as a result, it is possible that other filter feeders could also accumulate this or similar peptide toxins from other strains of cyanobacteria. The accumulation of freshwater blue-green algae toxins in aquatic food chains would present a threat to human health (Eriksson, Meriluoto, & Lindholm, 1989; Humpage et al., 1993). Cyanobacterial toxins were, for example, suspected of involvement in Haff disease, which was common among fish-eating people around the Baltic coast in the 1920s and 1930s (Berlin, 1948).

Cyanobacteria from the genus *Spirulina* have been used as a food source by some populations in Chad and Mexico for hundreds of years, and no toxicity has been recorded. Some strains of *Spirulina* are protein rich and have a high nutritional quality (Jassby, 1988); they have been used as a nutritious food and as the ingredients for a safe diet pill. The production and marketing of *Spirulina* as a health food has, however, encouraged similar enterprises using potentially toxic species of cyanobacteria such as *Anabaena* and *Aphanizomenon*. This development could pose a serious threat to human health; the products give no indication of whether a proper monitoring program has been carried out to guarantee nontoxicity (Carmichael, 1994). For further discussion of public health aspects see Pitois, Jackson, & Wood (2000) and Falconer (1999).

Conclusions

Eutrophication of water bodies has always been part of the natural cycle in waters ranging from highly oligotrophic alpine lakes on land newly exposed by glacial melting to shallow, eutrophic lowland ponds. Human activities, however, have had complex effects on this process, particularly since the industrial revolution and the consequent urbanization, massive population increases, and intensification of agriculture. In general, these anthropogenic influences have been harmful, increasing nutrient inputs at rates and to levels that cannot be absorbed or regulated by the natural checks and balances available to the affected ecosystem. In the future, policies on wastewater treatment, agricultural practices, and solid waste disposal will need to be increasingly sensitive to this complex of problems.

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