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Eutrophication of Water Bodies – A Global Environmental Problem

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Abstract—The results of Russian and foreign studies on the process of eutrophication of water bodies are summarized. The main sources of export of nutrients in water bodies with catchment areas are discussed in the article. The toxins produced by blue-green algae and their effects on organisms are considered. Critical total phosphorus loads are estimated for some lakes of the Russian Federation and five largest lakes of China.

Keywords: eutrophication, toxins, nutrient pollution, blue-green algae, water bodies, environmental problems

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Surface waters are highly organized supraorganismal ecosystems consisting of biotic (biocenoses) and abiotic (biotopes) components that function as a unified whole. The composition and structure of aquatic biocenoses depend on the climatic, geographic, hydrologic, and physicochemical characteristics of the biotopes and are a function of water quality. On the other hand, normal functioning of biocenoses predetermines the natural composition and properties of water. Disturbed ecological balance affects the quality of water and, consequently, water management conditions. At the same time, water bodies are subject to a huge impact associated with human activities, such as drinking, household, and industrial water supply, receiving waste and drainage waters, water transport and floating; medical treatment and recreation, fishery and hunting industries, water power engineering, water engineering, mineral extraction, and others and no longer function in a normal way [1].

Water issues, primarily freshwater scarcity, occupy special place in the environmental safety system. Presently quarter of the world's population suffers from water shortages, and more than 1 bln of people have no access to clean water, and by 2015 about the same number of people are expected to live under "absolute water hunger" conditions. According to Global Water Council (GWC) data, by 2050 about two thirds of world's population will face the problem of freshwater scarcity. As a result, analysts consider that in the XXI century the struggle for natural resources will sharpen and predict specific wars ("water," "bread," and other "eco wars") in the future. "The deficit of resources will entail confrontation, conflicts, and wars... Water will become the key kind of natural resources... Something which previously could be bought for money will cost blood" — this is the estimate of the future global development of water relationships, given by a top-level staff member of the United States Joint Chiefs of Staff for intelligence matters. In parallel with this forecast, another expert states the following: "If in the XX century the definition "liquid gold" related to oil, in the XXI century this name will be given to fresh water. And, therefore, the place of oil which over the past century has brought certain prosperity to some regions and caused wars and conflicts will be occupied by fresh water" [2].

The rapid growth of population and human activity in the XX century resulted in appreciable changes in the global mass and energy exchange and chemical fluxes. In terms of geochemistry, the most substantial changes in migration fluxes should be characteristic of elements with high technophilic coefficients (the ratio of the annual output of an element to its percentage abundance), in particular, phosphorus, which is one the main elements controlling the productivity of aquatic ecosystems.

The problem of eutrophication is the central problem of aquatic ecology [3]. According to the State Standards 17.1.1.01-77, “eutrophication is the enhancement of the biological productivity of water bodies due to the accumulation of nutrient elements under the action of human-induced or natural factors.” The International Organization for Standardization (ISO) proposes another definition, specifically, the enrichment of water with nutrient substances, especially nitrogen and phosphorus, which accelerates the growth of algae and other higher plant species.

The term “trophicity of water bodies” was defined by Tinneman and Nauman at the beginning of the XX century. Thus term implies “food capacity” or “feeding power” of water bodies, specifically, availability of nutrients for aquatic species. The very word “eutrophic” is derived from the Greek word “eutrophos,” which means “richness” or “fattyness.”

For example, the daily phosphorus and nitrogen incomes to household wastewaters (and from there to rivers and lakes) are, respectively, 4 and 8 g per person. Furthermore, nutrient substances enter water bodies with waterfowl excrements, fallen leaves, or dust particles. One more source of nutrient substances in water are holiday swimmers: On the average, 75 mg of phosphorus and 700 mg of nitrogen enters water with each swimmer. Dust brings to water bodies about 10 kg/ha a year. Thus, each water body is a bowl accumulating all kinds of wastes.

It should be specially emphasized that there is an essential difference in eutrophication and pollution, namely, pollution is associated with discharges of toxic substances that inhibit the biological productivity of water bodies, while eutrophication enhances productivity to a certain extent [4–6]. According to Vinberg [7], cultural eutrophication cannot be identified with pollution until the total nitrogen and phosphorus concentration is higher than the carbon concentration on a water body. Otherwise, we can only speak about natural aging or enhanced eutrophication of the water body.

The major sources of nutrient water pollution are the runoff of nitrogen and phosphorus fertilizers from fields, water reservoirs constructed without proper cleaning of the reservoir floor, and discharge of wastewaters, including those after biological treatment.

The nutrient pollution associated with business activities in river basins and beds (construction of hydroelectric power chains and water reservoirs, recreation activities, shipping traffic, etc.) cause cultural eutrophication. The fastest eutrophication occurs in water bodies whose basins are an area of active agriculture, including arable farming (tillage, hay fields, and pastures) and stock farming (farms and various complexes). These nutrient loading sources are fully or partly uncontrolled, and, therefore, they should receive special attention. Water recreations are classed with the same type of nutrient loading sources [8].

Nutrients enter natural ecosystems via both waterways and air; for example, presently the annual global consumption of phosphate soap and detergents is more than 30 mln tons. One of Canadian chemists was awarded a prestigious national prize for the development of phosphorus-free detergents.

The eutrophication of water bodies is associated with two principal nutrients: nitrogen and phosphorus. If the mineral nitrogen-to-mineral phosphorus ratio ($N_{\mathrm{MIN}} : P_{\mathrm{MIN}}$) is lower than 10, the primary production of phytoplankton is limited by nitrogen, at $N_{\mathrm{MIN}} : P_{\mathrm{MIN}} > 17$ by phosphorus, and at $N_{\mathrm{MIN}} : P_{\mathrm{MIN}} = 10–17$ by nitrogen and phosphorus together. It was established that nitrogen controls phytoplankton productions predominantly in oligotrophic marine regions and marine ecosystems, whereas phosphorus is responsible for continental water bodies [9].

Eutrophication is a natural evolution process of a water body. From the moment of “birth” a water body passes several stages in its development: first from ultraoligotrophic to oligotrophic and then to mesotropic, and, finally, to eutrophic and hypereutrophic, i.e. aging and death to form a swamp.

However, human activities impart specific features to this natural process. The rate and intensity of the productivity enhancement of ecosystems sharply increase. Thus, if natural eutrophication of one or another lake may last 1000 or even more years, due to human activities this process may accelerate 100 or even 1000 times. Such large water bodies as the Baltic Sea and the Lakes Erie, Tahoe, and Ladoga have passed from one trophic state to another for as little as 20–25 years. This process has extended on many freshwater bodies in the USA and Canada (Great American Lakes), Japan, Europe (Geneva, Ladoga, Onega, Balaton, etc.), as well as many sea basins (Mediterranean, Black, Baltic, etc.).

According to the vivid expression of E. Odum, cultural eutrophication is cancerous growth of primary production of a water body. A progress of cultural eutrophication has a lot of unfavorable consequences for water management and consumption (bloom and quality impairment of water, development of anaerobic zones, destruction of biocenoses and disappearance of many aquatic species, including valuable food fish).

Eutrophication impairs the physicochemical properties of water, endowing it with turbidity and unpleasant odor and taste and increasing its pH, which results in the precipitation of calcium carbonate and magnesium hydroxide. Eutrophic water bodies contain dead zones. Water from such water bodies may cause outbreaks of diarrheal diseases or poisoning of cattle and poultry.

The characteristic feature of eutrophication is excessive growth of aquatic and coastal plants (reed, typha, pond grass, water weed). Accelerated development of heterotrophic filamentous algae is observed. Plant death in autumn and winter leads to logging of the coastal regions of water bodies. Eutrophication of water bodies also affects their fish population. Mass mortality of fish eggs and babies in the coastal zone results in that fish species adapted to oxygen-deficient conditions (primarily crucian carp and tench) become prevailing in the water body.

The toxic bloom in Australian freshwaters, which caused deaths of sheep, horses, pigs, and dogs, was first mentioned by G. Frensis in 1878. Since then, toxic blooms in water bodies all over the world have been well documented. Thus, evidence for the toxic blooms of blue-green algae was found in the Kiev Reservoir, Dnepr River, Couronian Lagoon of the Baltic Sea, etc. In medium latitudes they are especially favored by heating water in cooling water reservoirs, as well as by water exchange. Blue-green algae produce quite dangerous toxins (alkaloids, low-molecular peptides, etc.) which they never use. However, being released into water these toxins could pose health risks to humans and animals, specifically, liver cirrhosis and dermatitis in humans and poisoning and death in animals.

There are two types of toxins produced by blue-green algae (cyanobacteria): neurotoxins and heaptotoxins. Neurotoxins include alkaloid which affect the nervous system. Cyanobacteria producing neurotoxins are not so numerous. Hepatotoxins include cyclic hepta- or pentapeptides containing unusual amino acids. When entering an animal's body, hepatotoxins destroy liver and cause death in a few hours. Even low doses of the poison are lethal. No cases of lethal human poisoning by cyanobacterial hepatotoxins have been reported in the literature, but it is considered evident that some people died of liver cancer associated with exposure to cyanobacterial toxins. Toxins reside in cyanobacterial cells and are released to water only from destroyed cells. These toxins are quite stable and cannot be destroyed by chlorination of water. Moreover, blue-gree algal toxins can also survive in dry cells [5].

According to world statistics, toxigenic cyanobacteria are produced in 40–50% of water bloom cases. At present the proliferation of toxigenic cyanobacteria is becoming a global problem in view of the enhancing human-induced pollution of water bodies. Such countries as England, Finland, and Norway consider toxic lake blooms as a national problem. These countries set up special centers for research on and control of toxic blooms. Some observations on toxigenic cyanobacteria in Karelian lakes and the Neva Bay were published.

The problem of eutrophication is gaining in importance for aquatic ecosystems of different types. In the reports on the trophic state of lakes, submitted by 23 U.S. states to the U.S. Environmental Protection Agency (EPA), 45% of the investigated lakes were recognized eutrophic, 26% mesotrophic, and 12% oligotrophic (the state of 17% of lakes was referred to as "unknown"). The eutrophication index of water bodies of certain European countries (for example, the Netherlands), is about 300, which is much higher than the desired value of about 100 and higher that the resistance level (about 80). Eutrophication is also a serious problem for marine and estuary systems. Eutrophication aggravates the problem of water depletion [10].

An interesting example of the toxic action of plankton blue-green was observed in the South Africa. This phenomenon has attracted special attention after the construction of a large water reservoir at the Vaal River in Transvaal in 1938. Since 1940, cattle losses started to be recorded along the reservoir shores, which assumed mass character in 1942 during vigorous blue-green algal bloom on the reservoir. Thousands heads of horned cattle and sheep, as well as horses, mules, donkeys, dogs, rabbits, and domestic waterfowl died. It was noted that gentle wind drove the algae toward the shore, where they concentrated, and rapid, within a few hours, animal deaths occurred just at these sites [6, 11].

Algal toxins are the primary reason of an enigmatic Haff disease whose outbreaks, beginning in 1924, were several times took place in the vicinity of Koenigsberg (now Kaliningrad), at the shore of the Frisches Haff, a desalinated bay of the Baltic Sea. The disease affected fishermen who went fishing to the bay and did not extend to people went fishing to the Baltic Sea. The Haff disease develops unexpectedly, without premonitory symptoms; it reveals itself in acute muscle pains in response to any movement or touching, as a result of which the patients lose the ability to move and look as if they are paralyzed.

The major factor that could limit blue-green algal bloom is reduction of the discharges of nutrients (first and foremost, phosphorus) to aquatic ecosystems.

Since the eutrophication of water bodies has become a serious environmental problem, UNESCO initiated monitoring of inland waters and control of eutrophication of water bodies all over the world.

The principal criteria of the eutrophication of water bodies are as follows:

– decreasing concentration of dissolved oxygen in water column;

– increasing concentration of nutrients;

– increasing concentration of suspended particles, especially organic;

– successive alteration of algal populations with preference for blue-green and green algae;

– decreasing light penetration (self-shadowing, enhancing water turbidity);

– increasing phosphorus concentration in sediments;

– strongly increasing phytoplankton biomass (with decreasing species biodiversity), etc.

Of the great number of indicators of the trophic status of water bodies, we chose the following as the most appropriate both for direct certification of the corresponding trophicity categories and for constructing mathematical models:

(1) Income of specific nutrients.

(2) Concentration of nutrients. The critical concentrations of nitrogen and phosphorus (including phosphorus, orthophosphates, total nitrogen, and dissolved inorganic nitrogen: ammonium, nitrites, and nitrates) during intense water mixing which creates potential conditions for algal bloom, accepted at the present time, are 0.01 and 0.3 g/m^3, respectively. At lower concentrations, mild nitrogen limitation of algal growth will take place, but such concentrations are difficult to measure precisely.

(3) Rate of oxygen depletion in the hypolymnion (the bottom layer of a water body, which underlies the thermocline). Oxygen losses in the hypolymnion increase in parallel to enhancing eutrophication. The rate of oxygen depletion is used as an indicator of the trophic state, since it has a short-time variability. This indicator is only valid for stratified water bodies. The following ranges of variation of this indicator for water bodies with different trophicity are proposed, mg m^{-3} day^{-1}: oligotrophic: less than 250, mesotrophic 250–500, and eutrophic more than 550.

(4) Secchi depth. This is the most widely used (because of its simplicity) and the oldest method of the assessment of the trophic state of water bodies. The Secchi disc is a plane disk divided into quadrants painted alternately black and white and having a standard size (200 mm in diameter). The disk is lowered slowly down in the water to a depth at which it is no longer visible. This depth is recorded, and the disk is taken up back; the depth at which it becomes visible again is also recorded. The Secchi depth is an average of these two records. The Secchi depth is inversely related to the density of algal populations in water, because the suspended matter scatters the incident light and enhances its attenuation. Thus, the Secchi depth is asociated with the primary productivity of water bodies, which is an indicator of their trophicity. The Secchi depths for oligotrophic, mesotrophic, and eutrophic bodies are > 6.0, 3−6.0, and < 3 m, respectively.

The concentration of chlorophyll *a* is commonly used as a direct trophicity indicator. Chlorophyll *a* ($C_{55}H_{72}O_5N_4Mg$) is the principal photosynthetic pigment, and, therefore, its concentration in a sample of water can serve as a representative indicator of algal biomass. It is a useful and precise measure of the eutrophication of water bodies and, therefore, used on a regular basis to measure their "responses" to nutrient loading for remediation purposes. The main difficulty is that at chlorophyll *a* concentrations higher than 100 mg/m^3 this indicator tends to only slightly respond to increasing nutrient concentration, because self-shadowing prevents further growth of primary producent biomass.

Assessment of the consequences of the cultural eutrophication of water bodies is complicated by the fact that changes in the functioning of ecosystems are

Table 1. Critical total phosphorus loadings for selected lakes in Russia (arbitrary) [14]

Lake	Average depth, H, m	Lake area, km^2	L_{CP}, gP m^{-2} $year^{-1}$	Critical load, ton/year
Chudskoe	8.3	2611	0.089	232
Ladoga	51	17700	0.265	4691
Onega	29	9630	0.189	1820
Il'men'	10	1200	0.100	120
Imandra	13.4	880	0.119	105

Table 2. Critical phosphorus loadings for five largest lakes in China (arbitrary) [15]

Lake	Average depth, H_{av}, m	Lake area, km^2	L_{CP}, gP m^{-2} $year^{-1}$	Critical load, ton/year
Poyang Hu	8.4	3210	0.090	288
Dongting Hu	6.7	2740	0.078	214
Tai Hu	1.9	2428	0.037	89
Hongze Hu	1.8	1580	0.036	56
Chao Hu	4.4	820	0.061	50

not very evident at the first stage due to homeostasis. Such changes are difficult to differentiate from natural variations. The latter include seasonal and annual fluctuations of hydrodynamic processes, climate changes, biotic cycles, etc.

In this connection an optimal approach to preventing eutrophication is to reduce the nutrient loading of water bodies. The key factor capable of limiting blue-green algal bloom is nutrient reduction (first and foremost, phosphorus) to aquatic ecosystems [12].

The efficiency of direct methods of eutrophication control (aeration, removal of algae by pumping or water filtration, treatment with chemicals) is low. The pollution levels of natural waters with nitrates and phosphates should be reduced by wastewater treatment, reduction of the use of fertilizers, and discontinuation of the construction of livestock breeding complexes with manure discharges to water bodies.

Over the past years nutrient pollution of water bodies (waterways, lakes, and water reservoirs) and their eutrophication has become one of the most urgent problems of water protection. This problem is characteristic of many countries, including Russia. Much effort is undertaken to study different aspects of water eutrophication. An international commission against eutrophication of water bodies has been established and their trophicity inventory and extensive experiments and observations are being performed. Most lakes and water reservoirs in the USA, Canada, and West Europe have been explored.

Research into the relationship between the phosphorus input to a water body and the trophic level of the latter resulted in the development of the so-called nutrient loading concept which is based on the idea that there is a quantitative phosphorus input–water body's response correlation. As a result, the water body changes its position on the trophic scale. Vollenweider [13] proposed the phosphorus loading (L_{CP}, gP m^{-2} $year^{-1}$) which allows to a water body to remain in the oligotrophic state to be estimated using the average depth of the water body (H_{av}, m) as the only standard parameter:

$$L_{CP} = 0.025H_{av}^{0.6}.$$

The results of calculations by the above formula are presented in Tables 1 and 2.

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