

Biocontrol of Water Quality: Multifunctional Role of Biota in Water Self-Purification

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Abstract — The experimental data analysis, concepts, and generalizations in this article provide the fundamental elements of the qualitative theory of biocontrol of water quality in a systematized form. The theory covers water self-purification in freshwater and marine ecosystems. The theory is supported by the results of the author's experimental studies of the effects exerted by some chemical pollutants including synthetic surfactants, detergents, and other xenobiotics on aquatic organisms. The theory provides a basis for remediation of polluted aquatic ecosystems including purification of water bodies and streams, and briefly present the qualitative theory of the self-purification mechanism of aquatic ecosystems, phytoremediation and other types of technologies.

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INTRODUCTION

The benefits of aquatic resources and proper water quality are classical examples of ecosystem services. In 2000 some elements of the theory of the function of aquatic ecosystems were developed [1]. However, the role of aquatic biota in the control of water quality still needed to be covered by a scientific analysis, and enormous amount of relevant data needed to be organized. Water quality depends on the activities of many aquatic organisms [2–19].

The role of the ecological factors and processes that contribute to improving water quality (water self-purification) increases due to the deterioration of natural water quality [3, 4, 14, 20] an anthropogenic impact on water bodies and streams [3, 14, 21–41]. The self-purification of aquatic ecosystems and water quality formation is controlled by many factors [8, 15, 17, 20–33, 36–38, 42–50].

The aim of this study is to systematize some key segments of the knowledge about the polyfunctional role of

aquatic biota (aquatic organisms) in the self-purification of water bodies and streams and to present briefly the qualitative theory of the self-purification mechanism of aquatic ecosystems. The synthesis and system-based organization of the material was made at the conceptual level without detailed review of extensive literature. This paper is substantially based on the string of our previous publications including published in refs. [18, 19, 24, 32, 51] and some others. The article is not a review of extensive literature in the field, it is an opinion paper that is an outcome of a multi-year period of experimental studies and publications by the author.

COMPLEX OF PROCESSES CONTRIBUTING TO THE WATER QUALITY AND THE WATER SELF-PURIFICATION IN AQUATIC ECOSYSTEMS

The formation of water quality and its purification in the aquatic ecosystems is governed by physical, chemical [42], and biotic [1, 2, 8, 15, 17, 20, 22, 23, 25, 26, 28, 30, 31, 33, 36–38, 42, 46, 49, 50] processes.

The physical and chemical processes of water self-purification are often controlled by biological factors or strongly depend on them. Thus, the redox state of the aquatic environment, which is formed with the participation of H_2O_2 released by microalgae in the light [23, 42], is of an importance for a decrease in the toxic effect of some pollutants. The concentration of H_2O_2 in the river Volga was found to be equal up to

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10^{-6} – 10^{-5} mol l⁻¹, which was found by measurements made by Dr. E.V. Shtamm and other authors [23, 42].

An important process is gravitational sedimentation of suspended particles both of biotic and abiotic nature. The sedimentation of phytoplankton depends on water temperature. The sedimentation velocity is equal to 0.3–1.5, 0.4–1.7, and 0.4–2.0 m day⁻¹ at T = 15, 20 and 25°C, respectively. According to our data, the sedimentation velocity of the pellets of *Lymnaea stagnalis* varies from 0.6 to 1.4 cm s⁻¹ with a mean value of 0.82 cm s⁻¹ at T = 22–24°C [23].

Experiments with the traps for suspended particles showed that the suspended matter precipitates onto the bed of the river Moskva with a mean rate of 2.3 mg cm⁻² of the bed surface, that is, 23.1 g m² day⁻¹ of the bed surface. The proportion of C_{org} (where C is carbon) in these sediments is 64.5% [40].

Organic matter oxidation and water filtration by aquatic invertebrate animals (filter-feeders) are among the major biotic processes contributing to improve water quality and water purification.

The overall oxidation of organic matter by the entire community can be expressed either in absolute or in relative units, for example, as the ratio of energy expenditure to the exchange (total respiration R) by aquatic animals to their total biomass B. This ratio (R/B) is referred to as Schroedinger ratio. The subscript “e” is introduced to show that the estimation is made for the ecosystem as a whole. In the water bodies where primary production exceeds the total respiration of the community this ratio averages 3.0–6.1 [1], but it can be even greater in some water bodies. For example, the Schroedinger ratio is 17.0 in the lake Lyubevoe in the Leningrad province and 33.8 in the lake Zun-Torei east of the lake Baikal [1]. It is believed that the primary production in these lakes is much less than the total respiration, and a large amount of organic matter delivered from outside is oxidized here.

Many aquatic organisms contribute to organic matter oxidation but particular role in this oxidation belongs to bacteria [31]. The total population of heterotrophic bacterioplankton taken at a depth of 0.1–1.0 m in the Mozhaisk Reservoir in June and July amounted to (1.4–5.9) 10⁹, and the population of hydrocarbon-oxidizing bacteria was (0.4–5.0) 10⁶ cell ml⁻¹ [8].

The rate of water filtration (FR) by some aquatic animals (e.g., zooplankton, barnacles, some echinoderms, bivalves, polychaetes, sponges and many others) com-

monly amounts to 1–9 l h⁻¹ g⁻¹ of ash-free dry mass [22, 23]. The dependence of filtration rate, l h⁻¹, on the mass of the aquatic animal dry weight of soft tissues (DW, g), can be described by the power function [2, 23]:

$$FR = a DW^b$$

The values of a coefficient for some bivalve mollusk species vary from 6.8 to 11.6, and those of coefficient b are between 0.66 and 0.92 [23]. The rate of water filtration by five bivalve mollusk species converted to the area of their gills is about 1.2–1.9 ml min⁻¹ cm⁻² [23].

The total rate of water filtration by benthic (bottom-dwelling) populations of macroinvertebrates (e.g., bivalve mollusks, polychaetes) was estimated at 1–10 m³ m⁻² day⁻¹ of the bottom of the aquatic ecosystem [20, 23].

Additional data on the filtration activity of aquatic animals are given in ref. [32].

THE MAJOR COMPONENTS OF THE SELF-PURIFICATION MECHANISM OF AQUATIC ECOSYSTEMS

According to a serie of our previous publications, the biological self-purification mechanism of aquatic ecosystems incorporates three main types of major functional components [22, 23]: filtration activity of organisms (“filters”) [21]; the mechanisms of transfer of chemicals from one ecological compartment into another, from one medium into another (“pumps”); and splitting pollutant molecules (“mills”).

The processes and aquatic organisms that serve as filters [21, 22, 23]: the invertebrate filter-feeders [2, 44]; the coastal macrophytes, which retain some nutrients and pollutants delivered into water from neighboring areas; the benthos, which retains and absorbs part of nutrients and pollutants at the water-bottom sediment interface; the microorganisms adsorbed on particulates that move within water column due to sedimentation of particles under the effect of gravity; as a result, the water mass and microorganisms move relative to one another, which is equivalent to the situation when water moves through a porous substrate with microorganisms attached to the walls [21]. Precipitation of a suspended particle, that is, its movement relative to water, enhances O₂ exchange between the adsorbed bacteria and the aquatic medium [50].

The processes and aquatic organisms that serve as pumps [22, 23]: the transfer of part of the pollut-

ants from the water column to bottom sediments (e.g. sedimentation, sorption); the transfer of part of the pollutants from the water column into the atmosphere (evaporation); the transfer of part of the nutrients from water onto the territory of neighboring terrestrial ecosystems because of the emergence of imago of aquatic insects; the transfer of part of the nutrients from water onto the territory of neighboring terrestrial ecosystems through fish-eating birds, which withdraw some fish biomass from water.

The processes and aquatic organisms that serve as mills and split the molecules of many pollutants [22, 23]: the intracellular enzymatic processes; the processes catalyzed by extracellular enzymes; the decomposition of the pollutants by photolysis: the photochemical processes, sensitized by the organic matter; the destruction of pollutants in the free-radical processes with the participation of biogenic ligands [42].

ENERGY SOURCES FOR BIOTIC SELF-PURIFICATION MECHANISMS OF AQUATIC ECOSYSTEMS

As all types of machinery, the biomachinery for water self-purification needs some reliable sources of energy.

The processes of the biotic self-purification of water take energy from the following sources: photosynthesis, oxidation of autochthonous and allochthonous organic matter; of other redox reactions. Thus, practically all available energy sources are used. A part of the energy is supplied through oxidation of the components (dissolved and particulate organic matter) which the system gets rid of [34].

Water self-purification is commonly associated with organic matter oxidation by aerobic microorganisms. Equally important are anaerobic processes which receive energy from the transfer of electrons to acceptors other than oxygen. Anaerobic energetics feeds the metabolism of microorganisms of methanogenic community (decomposition of organic matter results in the production of H_2S , H_2 , and CH_4), and anoxygenic phototrophic community (with the formation of SO_4^{2-} , H_2S , H_2 , and CH_4) [50]. The products produced by organisms of these communities are used as oxidation substrates by organisms of other communities including the organisms that form the group referred to a bacterial oxidation filter. The latter filter functions under aerobic conditions and oxidizes H_2 , CH_4 (methanotrophs), NH_3 (nitrifiers), H_2S (thiobacteria), thiosulfate (thionic bacteria) [50].

For example, in the lake Mirror (USA) 19.1 g C m^{-2} of the lake surface is oxidized annually due to the phytoplankton respiration, 12.0 g C m^{-2} is oxidized due to the zooplankton respiration, 1.0 g C m^{-2} is oxidized due to the macrophytes, 1.16 g C m^{-2} is oxidized due to the attached plants, 2.8 g C m^{-2} is oxidized due to the benthic invertebrates, and 0.2 g C m^{-2} due to the fish. Oxidation by bacteria in bottom sediments and by bacterioplankton accounts for 17.3 and 4.9 g C m^{-2} of the lake surface [49].

INVOLVEMENT OF MAJOR TAXA IN THE SELF-PURIFICATION IN AQUATIC ECOSYSTEMS

Analysis of facts demonstrate how practically all major groups of organisms contribute to the self-purification of the aquatic ecosystems and to the formation of the water quality [11, 17, 20, 22, 23, 25–29, 31, 33–38, 49, 50].

A significant role belongs to the microorganisms [8, 46, 50, 44], to the phytoplankton [22, 23], to the higher plants [22, 23], to the protozoa [11], to the zooplankton [22, 23, 49], to the benthic invertebrates [22, 23, 49], and to the fish. All these groups contribute largely to the self-purification of aquatic ecosystems, each group taking part in several processes.

Additional data on the role of the aquatic plants were obtained in experiments with microcosms [12]. It was shown that the aquatic plants accelerated the decrease in concentration of a synthetic surfactant, sodium dodecyl sulphate (SDS) that was added to water. This result was of interest as synthetic surfactant belonged to an important group of chemical pollutants of aquatic environment.

Microbial processes of water self-purification are associated basically with the activity of heterotrophic aerobic bacteria. However, representatives of practically all major bacterial groups (>30) participate in the key processes of organic matter destruction and self-purification of water bodies [50].

It is worth mentioning that the microorganisms participating in the destruction of biopolymers and in water self-purification system feature wide taxonomic diversity [50]. An important role in organic matter destruction and self-purification of the aquatic ecosystems belongs also to the eucaryotic microorganisms (protists), in particular, to the euglenes, ameboflagellates, dinoflagellates, infusoria, heteroflagellates, cryptomonads, choanoflagellates, metamonads, chitrids, and other organisms [50].

An important process of water self purification is water filtration by organisms of many taxa [2, 15, 22, 23, 44]. A detailed list of taxa including planktonic and benthic filter-feeders in aquatic ecosystems is given in paper [37]. The contributions of different groups of organisms to C removal from water of eutrophic lake Esrum (Denmark) (% of the total C) withdrawn from water are as follows: 24.4% by the respiration of producers, 20.9% by the bacterial respiration, 30.7% by the respiration of consumers, 4.5% (appears to be determined not completely) by the respiration of microorganisms in sediments, 0.14% by the emergence of the aquatic insects [49].

The results of the analysis of roles of organisms in the aquatic ecosystems made us to conclude that virtually all groups of organisms belonging to the prokaryotes and the eukaryotes are involved in the water self-purification.

THE RELIABILITY OF THE WATER SELF-PURIFICATION BIOMACHINERY

The reliability of a technical system often relies on the presence of back-up components. Analysis of aquatic ecosystems shows a similar principle to govern their functioning. For example, the filtration activity of aquatic animals is doubled so that it is implemented by two large groups of organisms, i.e. plankton and benthos. Both groups filter water with a considerable rate [2, 15, 20, 44]. Additionally, benthos duplicates the activity of the planktonic organisms permanently inhabiting the pelagic zone, since the larvae of many benthic filter-feeders follow the planktonic way of life. Plankton incorporates two large groups of the multicellular invertebrate filter-feeders, i.e., crustaceans [44] and rotifers [15], and both of them implement water filtration. One more large group of the organisms (protozoa), which have somewhat different type of feeding, also duplicates the filtration activity of multicellular filter-feeders (crustaceans and rotifers).

The enzymatic decomposition of pollutants is partially duplicated by the activities of bacteria and fungi. Almost all aquatic organisms, which are capable of consuming and oxidizing dissolved organic matter perform this function.

Self-regulation of biota is an important component of the reliability of water self-purification mechanism. The organisms that take active part in the water self-purification are the subjects to control by other organisms of both lower and higher trophic levels in the food web. The regulating role of organisms

could be effectively studied with the use of the author's method of the inhibitor analysis of regulatory interactions in trophic chains [26, 27].

Various forms of signaling including the information-carrying chemicals (ecological chemoregulators and chemomediators [28, 29, 31]) play important role in the regulation of ecosystems.

Self-control of the water quality, the water purification and the permanent restoration of its quality is an important component for the ecosystem self-stabilization. The restoration of the water quality is vital for ecosystem stability because the autochthonous and allochthonous organic matter and nutrients permanently go into water from the surrounding land by water of tributaries, atmospheric precipitation, and the solid particles carried by air [49]. Therefore, the water self-purification is as important for an aquatic ecosystem as DNA repair is valuable for the heredity system. This allows us to regard the water self-purification as an ecological repair in aquatic ecosystems.

The wide range of variations in the filtration activity rates suggests the need to regulate this activity. The volume of water filtered within one hour and measured in the body volumes of the filter-feeders amounts to 5×10^6 for the nanoflagellates and 5×10^5 for ciliates [49]. Cladocerans filter up from 4–14 ml one organism⁻¹ day⁻¹ [49] to 20–130 ml one organism⁻¹ day⁻¹ [44]. Copepods and rotifers filter 2–27 ml one organism⁻¹ day⁻¹ [49] and 0.07–0.3 ml one animal⁻¹ day⁻¹, respectively [15]. All these aquatic animals and other filter-feeders remove suspensions from water.

Thus, all forms of regulation and communication of organisms within community are of importance for maintaining the reliability of ecosystem functioning. The important role in the regulation and communication in the aquatic communities belongs to dissolved substances, ecological chemoregulators and chemomediators [28, 29, 31].

THE RELATIONSHIP BETWEEN THE RELIABILITY OF WATER SELF-PURIFICATION BIOMACHINERY AND AQUATIC ECOSYSTEM STABILITY

In our opinion, filtration activity of filter-feeders is not only a part of the water self-purification process and water quality repair but also a part of processes that maintain the stability of the aquatic ecosystem. The latter is performed through the conditioning of water,

Inhibitory effect of various pollutants on suspension withdrawal from water by filter-feeders

Substances	Organisms	Concentration, mg l ⁻¹
TX-100 ^a	<i>Unio tumidus</i>	5.0
TDTMA ^b	<i>Crassostrea gigas</i>	0.5
SDS ^c	<i>Mytilus edulis</i> and <i>Mytilus galloprovincialis</i>	>1.0
SDS	<i>Crassostrea gigas</i>	0.5
Copper sulfate	<i>Mytilus galloprovincialis</i>	2.0
Lead nitrate	<i>Mytilus galloprovincialis</i>	20.0
LD ^d "E"	<i>Crassostrea gigas</i>	2.0
LD "Fairy"	<i>Crassostrea gigas</i>	2.0
TDTMA	<i>Brachionus angularis</i>	0.5
TDTMA	<i>Brachionus plicatilis</i>	0.5
TDTMA	<i>Brachionus calyciflorus</i>	0.5
SDS	<i>Daphnia magna</i> [47]	0.5–10

^a TX-100 is the non-ionic surfactant Triton X-100. ^b TDTMA is the cationic surfactant tetradecyl trimethyl ammonium bromide. ^c SDS is the anionic surfactant sodium dodecyl sulfate. ^d LD is the liquid detergent ([23] and other publications of the author).

which serves as a habitat for many other aquatic species, and "the environmental tax for the environmental stability" that filter-feeders pay in the form of pellets of organic material. They filter out these pellet form from particulate organic matter in the organisms of filter-feeders (e.g., bivalve mollusks) from water and release into the environment in the form of 'lumps'. Pellets precipitate onto the bed of water bodies or streams. The pellets are used as food by many other aquatic organisms including zoobenthos and bacteria. The "environmental tax" is surprisingly high as compared with the share of C of the organic matter included in production. In some cases it can be >100% when calculated as the ratio of the amount of C not assimilated from the food (that is, C from fecal and pseudofecal pellets) to the amount of C consumed and assimilated for production.

The formation of pseudofeces by filter-feeding bivalves (that is, the process in which part of the filtered seston does not pass through the digestive tract of the mollusk but is prepared to the release into the environment in the form of pellets) begins at rather low seston concentration. Thus, at the concentration of seston as low as 2.6 mg l⁻¹ (the concentration of seston is commonly much greater), mollusks marine mussels *Mytilus edulis* (shell size 1.7 cm) started releasing pseudofecal pellets [23]. Therefore, the formation of

pseudofeces is not the result of excessive concentration of organic matter in the aquatic environment.

The high "environmental tax" is justified because the filter-feeders will eventually benefit from the high level of stability of water quality characteristics. The entire system of water self-purification also benefits from this because it requires the wide diversity of aquatic species to maintain its stability.

The aquatic ecosystems serve as one of the most important regulators of global geochemical cycles (e.g., of water and C), the stability of which withstands the hazard of global disturbances. Therefore, the reliability of the water self-purification biomachinery is of key importance for the global stability in the biosphere [31].

RESPONSES OF THE ENTIRE BIOMACHINERY OF THE WATER SELF-PURIFICATION TO EXTERNAL (ANTHROPOGENIC) IMPACTS ON THE AQUATIC ECOSYSTEM

Is the rate of functional activity of the biomachinery of the water self-purification a certain constant?

The author has found an essential element of a lability in one of the processes involved in water self-

purification, i.e., water filtration by aquatic animals (mollusks and rotifers) [17, 20–23, 25–27, 29–31, 33–39]. In our experiments water filtration was inhibited by sublethal concentrations of many anthropogenic pollutants, such as synthetic surfactants, surfactant-containing mixed preparations, and heavy metals (Table). Other pollutants were found to have similar effect on mollusks and planktonic filter-feeders [5, 23].

Recently in the study reported in ref. [47] it was shown that the synthetic surfactant dodecyl sulphate has an inhibitory effect on the ability of the planktonic filter-feeders *Daphnia magna* to remove phytoplankton from water during their filtration activity.

The population biomass of filter-feeders in polluted aquatic ecosystems decreases, the result of which is an additional drop in the total filtration activity in such ecosystems [23].

Therefore, the biomachinery of the water self-purification processes and its quality formation is labile [22, 23, 38] and quickly rearranges to adjust to changes in the environment. The obtained data demonstrate the hazard of a decrease in the efficiency of water self-purification system in the aquatic ecosystems to anthropogenic impacts (the chemical pollution of water bodies and streams) [17, 20–23, 25–27, 29, 31, 33–36, 38, 39].

RELATIONSHIP BETWEEN THIS THEORY AND THE FUNDAMENTAL ECOLOGICAL CONCEPTS

A key principle in the organization of ecosystems is the interdependence and mutual usefulness of the organisms involved. This principle was confirmed so often that it almost became an axiom and did not attract particular attention. However, its significance manifests itself a new way in the analysis of the water self-purification processes in aquatic ecosystems. The cooperative functioning of prokaryote communities is only one example. Another example is the high activity of filter-feeders in removing suspension from water, during which the amount of suspended organic matter extracted from water is much greater than it is required for the organism of the filter-feeder [2, 22, 23]. The environmental significance of suspension removal from water and pellet formation was analyzed in detail [23]. The assimilation of food by filter-feeders in the laboratory experiments was 50–60% [15], however, it could be much lower in nature. Thus, bivalve mollusks marine mussels *Mytilus galloprovincialis* (with a biomass of about 2 g) featured the assimilation that varied within the year from 4.8 to 51% [23]. In other words, in some

cases >95% of filtered out material was finally released by the mussels in the form of pellets.

In our opinion, the synecological cooperation is one of the functional principles of the biomachinery of the water self-purification.

Biocontrol of water quality (the purification of the aquatic ecosystem) is accompanied by transfer of chemical substances and their constituents from one location within the aquatic ecosystem into another. The results of data analysis support the earlier formulated proposal that “a competitive unity of the vectorial and stochastic motion of chemical elements, and the regulation of these processes based on biological matter exist in the aquatic ecosystems” [33]. Evidence was also obtained that led to the conclusion that the following phenomena took place in aquatic ecosystems: an integration of many organisms which closely interact and influence each other in both positive and negative ways (we called that “a competitive unity”); biological-matter-controlled regulation of cyclic and noncyclic paths of the chemical elements; the regulation of the transfer of chemical elements from one phase into another (interphase transfer), and from one organism into another (organism-to-organism transfers) [33]. We mean the term “a competitive unity” as a unity that embraces the components that sometimes are not friendly to each other and they may compete to each other. The author emphasizes that the regulation of many processes of transfer of the chemical elements in the aquatic ecosystems is biologically and abiotically controlled, and the roles of both components of that control — biotic and abiotic — are equally important and integrated each other. We suggested a special term that underlines the integrity of both types (biotic and abiotic) of that control of the transfer of matter. In Russian language this term is “biokosnyj control” [33]. The adjective “biokosnyj” was previously used by V.I. Vernadsky as a part of another word combination, “biokosnoe veshchestvo”, which means a special type of the matter that was formed by a combined action of both biotic and abiotic factors (an example of this type of the matter is soil).

FROM STUDYING THE BIOMACHINERY OF WATER PURIFICATION TO COTECHNOLOGIES

We consider the elements of the theory on the biotic mechanisms of the water purification, which were present above as a scientific basis for better control of water pollution [51]. The use of aquatic plants is of special interests among new ecotechnologies. To develop phytotechnologies we conducted experiments with 5 species of aquatic plants. Some new results were reported in a

series of publications [12, 43]. Some previously unknown quantitative parameters of the tolerance of the aquatic macrophyte *Potamogeton crispus* L. to the surfactant sodium dodecyl sulphate were determined [43]. Aquatic plants *Ceratophyllum demersum* induced a removal of the heavy metals Cu, Zn, Cd, and Pb from water [52, 53]. Some other species of plants are currently studied in our laboratory.

RELEVANCE OF THE CONCEPTS OF BIOTIC SELF-PURIFICATION OF WATER TO ISSUES OF WATER QUALITY IN VARIOUS REGIONS

Some of the elements of the theory of involvement of biota in the self-purification of water that were formulated above were used in the analysis of issues of water quality in various regions of the world including Canada [6]; China [9]; Greece [16], Russia [13], Spain [7], and USA [45].

The theory of biotic self-purification of water got a positive evaluation by other experts [10].

We predict that the pressure for having good quality of water and increasing scarcity of water will lead finding new examples of relevance of the concepts of biotic and biocoenotic control of water quality. We predict that new aspects of the key role of organisms in the control and improvement of water quality both in freshwater and marine ecosystems will be found, and new methods of applying organisms and new usages of them in water decontamination (remediation) will be described.

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