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# On the Multifunctional Role of the Biota in the Self-Purification of Aquatic Ecosystems

**S. A. Ostroumov**

*Moscow State University, Vorob'evy gory, Moscow, 119992 Russia*

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**Abstract**—Principles of the theory of the ecological mechanism of water self-purification based on multiple functions of the biota in freshwater and marine ecosystems are formulated. In developing this theory, the results of the author's experiments with filtering hydrobionts have been used. These results indicate that the water self-purification mechanism is vulnerable to the impact of some pollutants and, in particular, surfactants. Conclusions drawn on the basis of the theory have practical significance for biodiversity conservation and for the sustainable use of the biological resources of aquatic ecosystems.

*Key words*: aquatic ecosystems, water quality, water self-purification, pollution, theory.

The study of water self-purification processes (Skurlatov, 1988; Ostroumov, 2000a) is essential for approaching fundamental ecological problems (Alimov, 2000; Ostroumov *et al.*, 2003) and for resolving applied issues related to the sustainable use of natural resources.

The purpose of this paper is to give a systematic account of the concepts concerning the multiple functions of the biota in the self-purification of water bodies and watercourses, without attempting to review the numerous publications in this field. A quantitative assessment of the various processes involved in the self-purification of water bodies and watercourses is also beyond the scope of this study.

An analysis of our publications over the period from 1997 to 2005 allowed me to make some generalizations concerning the main processes and factors involved in the self-purification system of aquatic ecosystems.

## MAIN PHYSICAL, CHEMICAL, AND BIOTIC PROCESSES LEADING TO WATER PURIFICATION IN AQUATIC ECOSYSTEMS

These processes are listed in Table 1. Some of them were considered in a number of publications (Alimov, 1981; Izrael' and Tsyban', 1989; Lisytsin, 2001; Matishov and Matishov, 2001).

Physical and chemical processes of water self-purification are often regulated by biotic factors or strongly depend on them (Ostroumov, 2001a, 2002c). Thus, the degree of pollutant sorption on settling suspended particles depends on the concentration of phytoplankton cells, photochemical processes depend on water transparency, and transparency depends on the filtering capacity of hydrobionts. Free-radical processes of pollutant destruction depend on the binding of metal ions to dissolved ligands, namely, organic molecules of biological origin (Skurlatov, 1988). Thus, biotic factors are at the center of the entire water self-purification system.

All processes involved in water purification are important, and none of them can be considered more significant than others. The important biotic processes leading to water purification that have been characterized in detail include organic matter oxidation (Sadchikov, 1997; Zavarzin and Kolotilova, 2001; Wetzel, 2001) and water filtration by hydrobionts (Alimov, 1981; Sushchenya, 1975; Shul'man and Finenko, 1990).

The activity of a community that oxidizes organic matter can be expressed in absolute and relative values: for instance, as the ratio of energy expended by hydrobionts for metabolism (total respiration $R$) to their total biomass ($B$). The $(R/B)_e$ ratio, referred to as the Shrödinger ratio, reflects the relationship between energy expenditures for the maintenance of life activity and, thereby, structure of the community and the amount of energy contained in its structure (Alimov, 2000).

Organic matter is oxidized by many hydrobionts, with a special role belonging to bacteria (Vinogradov and Sushkina, 1987; Zavarzin and Kolotilova, 2001; Wetzel, 2001). The total biomass of bacteria in the epipelagial zone (0–200 m) of the World Ocean is approximately $276 \times 10^6$ t C, averaging 8 g of fresh biomass (0.8 g C) per square meter of water surface (Vinogradov and Shushkina, 1987). Many specialists consider that bacteria account for 60–70% of the total heterotrophic destruction in the ocean. However, estimations of global heterotrophic destruction in the ocean are ambiguous. According to calculations based on average $O_2$ consumption by one bacterial cell, bacterial destruction in the World Ocean amounts to $100 \times 10^9$ t C per year; in this

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**Table 1.** Some factors and processes involved in water self-purification (Pl, pollutants; numbers beginning with 1, 2, and 3 indicate physical, chemical, and biological factors and processes, respectively)

| No. | Factors and processes of water purification | Biotic factors that affect the processes indicated on the left |
|---|---|---|
| 1.1 | Dissolution and dilution | Mixing depends on macrophytes |
| 1.2 | Transfer on land | The same |
| 1.3 | Transfer to adjoining water bodies | » |
| 1.4 | Sorption of Pl by suspended particles followed by their sedimentation | Seston formation |
| 1.5 | Sorption of Pl by bottom sediments | Detritus formation |
| 1.6 | Evaporation | Properties of the surface film depend on DOM |
| 2.1 | Hydrolysis | pH depends on photosynthesis |
| 2.2 | Photochemical transformation | DOM and suspended organic matter |
| 2.3 | Catalytic redox transformations | DOM |
| 2.4 | Transformations with the involvement of free radicals | DOM |
| 2.5 | Decrease in Pl toxicity resulting from binding to dissolved organic matter (DOM) | DOM |
| 2.6 | Chemical oxidation of Pl with the involvement of oxygen | Photosynthesis |
| 3.1 | Release of oxygen that oxidizes Pl | Photosynthesis |
| 3.2 | Sorption and accumulation of Pl and biogenic substances by hydrobionts | Plankton, benthos |
| 3.3 | Biotransformation of Pl | Enzymes |
| 3.4 | Extracellular enzymatic transformation of Pl | Exoenzymes |
| 3.5 | Removal of suspended particles from water by filtration | Filter feeders |
| 3.6 | Removal of Pl from water column as a result of sorption by pellets | Filter feeders |
| 3.7 | Release into water of organic substances that serve as sensitizers promoting Pl photolysis | DOM |
| 3.8 | Release into water of organic substances binding with Pl to form less toxic complexes | DOM |
| 3.9 | Release into water of substances involved in free-radical and catalytic redox mechanisms of Pl destruction | DOM |
| 3.10 | Prevention or retardation of the release of biogenic substances and Pl into water and their accumulation by benthic organisms | Benthos |
| 3.11 | Increase in organic matter content in bottom sediments, which improves Pl binding by bottom sediments | Detritus formation |
| 3.12 | Release of N and P compounds into water (element recycling), which promotes the growth of oxygen-releasing phototrophic organisms | Bacteria of bottom sediments |
| 3. 13 | Removal of C, N, and P from an aquatic ecosystem due to emergence of aquatic insects, migration of amphibians on land, and foraging of fish-eating birds | Biota of an ecosystem |
| 3.14 | Pl biotransformation and sorption in soil (when polluted water is used for irrigation) | The same |
| 3.15 | Regulation of the abundance and activity of organisms involved in water purification | » |

case, the entire heterotrophic destruction in the 0–200 m layer is $150 \times 10^9$ t C per year. In the variant based on the daily average specific production of bacteria and the coefficient characterizing the efficiency of assimilated food utilization for growth ($K_2$ = 0.33), bacterial destruction is approximately $60 \times 10^9$ t C per year, and total heterotrophic destruction is $85 \times 10^9$ t C per year. An important role in heterotrophic destruction belongs to protists (total biomass in the epipelagial $69 \times 10^6$ t C, averaging 0.2 g C/m$^2$) and metazooplankton (body size 0.2–5 mm; total biomass in the epipelagial $386 \times 10^6$ t C, averaging 1 g C/m$^2$). The ratio of daily production to biomass (*P*/*B*) in the epipelagial averages 53% for protists and 2% for metazooplankton (Vinogradov and Sushkina, 1987).

The filtration rate in some groups of hydrobionts (ascidians, cirripeds, bryozoans, echinoderms, bivalves, gastropods, polychaetes, and sponges) often ranges from 1 to 8.8 l/h per gram dry (decalcified) body weight (Dame *et al.*, 2001). The dependence of filtration rate on body weight is described by an exponential function (Alimov, 1981). The total water filtration by populations of macroinvertebrates (Mollusca, Ascidia, Polychaeta) in the water column above 1 $m^2$ of the bottom was estimated at 1–10 $m^3$ per day (Ostroumov, 2001a). A great ecological significance of filtering hydrobionts was emphasized by K.A. Voskresenskii and A.S. Konstantinov (for review, see Ostroumov, 2001a).

## MAIN FUNCTIONAL BLOCKS OF THE SELF-PURIFICATION SYSTEM IN AQUATIC ECOSYSTEMS

The main functional blocks accounting for the major part of the total hydrobiological mechanism of self-purification in aquatic ecosystems are as follows: (1) the block of filtering activity ("filters") (Ostroumov, 1998); (2) the block of mechanisms accounting for the transfer (pumping) of chemical substances from one ecological compartment (environment) to another, i.e., "pumps" operating in the self-purification mechanisms of aquatic ecosystems; and (3) the block responsible for the cleavage of pollutant molecules ("mills" that crush pollutants).

**Filters.** Four filtering systems are distinguished (Ostroumov, 1998): (a) the aggregate of invertebrate filter-feeding hydrobionts (Ostroumov, 2001a; Dame *et al.*, 2001; Ostroumov, 2005); (b) the belt of coastal macrophytes that retains a portion of the biogenic substances and pollutants coming to the ecosystem from the adjoining territory; (c) the benthos that retains and absorbs some of the biogenic substances and pollutants migrating at the water–bottom sediment interface; and (d) microorganisms sorbed on suspended particles that move relative to the water mass (settle) because of gravity; as a result, microorganisms absorb dissolved organic substances and biogenic elements from the water (Ostroumov, 1998). During the sedimentation of a water-suspended particle, oxygen exchange between the bacteria sorbed on it and the aquatic environment increases (Zavarzin and Kolotilova, 2001).

**Pumps.** The following functional systems promote substance transfer from one site to another (Ostroumov, 2001a): (a) the block of processes acting as a pump that transfers some pollutants from the water column to sediments (e.g., sedimentation and sorption); (b) the block of processes acting as a functional pump that promotes the transfer of some pollutants from the water column to the atmosphere (evaporation); (c) the block of processes acting as a functional pump that promotes the transfer of some biogenic substances from water to the surrounding terrestrial ecosystems (the sum of migration processes related to the emergence of adult insects in the species whose larvae develop in water); (d) an analogous block of processes involving the transfer of some biogenic substances from water to the surrounding terrestrial ecosystems due to the activities of birds that feed on hydrobionts, removing biomass from an aquatic ecosystem, but nest on the surrounding territory; and (e) the block of processes involving the transfer of some biogenic substances from water to the coastal ecosystems due to the emergence from a water body of amphibians whose early development proceeds in water.

**Mills** are the functional systems that destroy an excess of organic matter and cleave pollutants (Ostroumov, 1986, 2001a; Skurlatov, 1988): (a) the molecular mill of intracellular enzymatic processes, (b) the mill of extracellular enzymes present in an aquatic environment, (c) the mill of photochemical processes promoted by sensitizers of biological origin, and (d) the mill of free radical processes involving ligands of biological origin (Skurlatov, 1988). There are many examples of the quantitative study of the corresponding processes (Wetzel, 2001).

## SOURCES OF ENERGY FOR THE BIOTIC MECHANISMS OF AQUATIC ECOSYSTEM SELF-PURIFICATION

The biotic processes of self-purification receive energy from the following sources: photosynthesis, oxidation of autochthonous organic matter, oxidation of allochthonous organic matter, and other redox reactions. Thus, virtually all available energy sources are used. Some energy is received due to oxidation of the components of which the system rids itself (dissolved and suspended organic matter). In this respect, self-purification processes are comparable to energy-saving technologies (Ostroumov, 2002b).

Self-purification is often related to organic matter oxidation by aerobic organisms. Equally important are anaerobic processes, in which energy is generated due to electron transfer to acceptors other than oxygen. The anaerobic energetics determines the metabolism of many microorganisms, including the methanogenic (destruction of organic matter with the release of methane), sulfidogenic (the release of $H_2S$, $H_2$, and methane), and anoxygenic phototrophic communities (the release of $SO_4^{2-}$, $H_2S$, hydrogen, and methane) (Zavarzin and Kolotilova, 2001). The products of their activity are further used as oxidation substrates by organisms of other communities, including bacteria of the group named "the bacterial oxidative filter." This group functions under aerobic conditions and oxidizes hydrogen (hydrogen-reducing bacteria), methane (metanophores), $NH_3$ (nitrificators), $H_2S$ (sulfur bacteria), and thiosulfate (thionic bacteria). The involvement of bacteria that use metal ions or ions containing metals (Fe, Mn) as electron acceptors is also important. Quantitative characteristics of relevant processes are given in the paper by Wetzel (2001).

## INVOLVEMENT OF MAIN GROUPS OF ORGANISMS IN THE SELF-PURIFICATION OF AQUATIC ECOSYSTEMS

The involvement of microorganisms, phytoplankton, higher plants, invertebrates, and fish in the self-purification of aquatic ecosystems and the improvement of water quality was analyzed in several papers (Ostroumov, 1986, 2000c, 2001a; Zavarzin and Kolotilova, 2001). All these groups take an active part in the self-purification of aquatic ecosystems, each being involved in more than one or two processes.

Heterotrophic aerobic bacteria actively participate in self-purification processes. As noted above, representatives of many other groups of bacteria are also involved in organic matter destruction and self-purification of water bodies (Zavarzin and Kolotilova, 2001). Moreover, an important role in organic matter destruction belongs to protists, aquatic fungi, and related organisms.

The diversity of microorganisms participating in the destruction of biopolymers and in the self-purification system is the more important as the microorganisms that functionally complement each other in bacterial communities are represented by phylogenetically distant forms (Zavarzin and Kolotilova, 2001).

Water filtration, which is of primary importance for water purification, is accomplished by representatives of many taxa (Alimov, 1981; Sushchenya, 1975; Vinogradov and Shushkina, 1987; Ostroumov, 2005). In the marine plankton, for instance, the function of filter feeders consuming fine particles (nanophages) is performed by Appendiculariae, Doliolida (class Thaliacea), small Calanoida, meroplankton (larvae), and other invertebrates; the function of coarse filtration (euryphagous filter-feeders) is performed by *Oithona* sp. (Cyclopoida), Oncaea (Cyclopoida), large Calanoida, and Euphausiaceae (Vinogradov and Sushkina, 1987). For a detailed list of the main planktonic and benthic filter feeders in ecosystems, see Ostroumov (2002a).

## RELIABILITY OF THE WATER SELF-PURIFICATION SYSTEM

The reliability of the water self-purification mechanism is closely related to the fundamentally important problem of ecosystem stability (Krasnoshchekov and Rozenberg, 1992) and is often ensured by duplicating many components of the system. For instance, water filtration is performed by two different large groups of organisms, the plankton and the benthos, and at a high rate (Alimov, 1981; Sushchenya, 1975). In addition, the benthos duplicates the activity of zooplankters constantly remaining in the pelagial zone, because the larvae of many benthic filter feeders are planktonic organisms. The plankton includes two large groups of multicellular invertebrate filter feeders, crustaceans (Sushchenya, 1975), and rotifers (Monakov, 1998), which provide a backup for each other. In addition, there is yet another large group of organisms (Protozoa) with a slightly different type of feeding, which, in turn, provide a backup for multicellular filter feeders (crustaceans and rotifers).

Water filtration is performed in parallel by many representatives of the biota. The filtering activity (the amount of water filtered per hour as expressed in body volumes of the filter-feeding organism) is up to $5 \times 10^6$ in nanoflagellates and $5 \times 10^5$ in ciliates (Fenchel, 1986, 1987; cited from Wetzel, 2001). Cladocerans filter 4–40 ml (in some cases, up to 130 ml) per animal per day; copepods, up to 27 ml (Wetzel, 2001); rotifers, 0.07–0.3 ml (Monakov, 1998). These and other filter feeders provide a backup for each other in removing suspensions from the water.

Another group of important self-purification processes, the enzymatic destruction of pollutants, are accomplished by bacteria and fungi, which, therefore, provide a backup for each other. The same applies to the variety of hydrobionts participating in the oxidation of dissolved organic matter.

Yet another important component of reliability is the self-regulation of the biota. Almost all organisms involved in self-purification are under the dual control of other organisms representing the preceding and subsequent links in the trophic chain. Their role can be efficiently studied by means of the inhibitory analysis of regulatory interactions in trophic chains (Ostroumov, 2000b).

Among the mechanisms of ecosystem regulation, an important role belongs to different forms of signaling, including those by means of chemical substances that transmit information or regulatory signals. I have proposed to designate such substances ecological chemoregulators and ecological chemomediators (Ostroumov, 1986, 2003).

The reliability of the water self-purification system in an ecosystem is provided by the multiplicity of components (processes) that comprise this system and operate, to some extent, in parallel. Water purification and the improvement of its quality, in turn, are necessary for the self-maintenance of the entire aquatic ecosystem, as they provide for the remediation of the habitats of its constituent species. These processes are vitally important, since water is regularly supplemented with autochthonous and allochthonous organic matter and biogenic elements brought by precipitation, fallout, and runoff from the adjoining territory. Thus, water self-purification for an aquatic ecosystem is an important function that ensures its stability, as is DNA repair for the system of heredity systems, which gives grounds for regarding water purification as ecological repair in aquatic ecosystems.

**Table 2.** Influence of different pollutants on the removal of suspended particles from water by filter-feeding hydrobionts. The effect on the efficiency of suspension removal (EESR) was calculated as described (Ostroumov, 2001a)

| Pollutant | Hydrobiont | Concentration, mg/l | Note, reference |
|---|---|---|---|
| Trimethyl tin chloride (TMTC) | *Dreissena polymorpha* | 0.01–10 | Mitin, 1984; cited from Ostroumov, 2001a |
| Cadmium sulfate | *Mytilus galloprovincialis* | 0.5 | Original data |
| Copper sulfate | *M. galloprovincialis* | 2 | The same |
| Lead nitrate | *M. galloprovincialis* | 20 | » |
| Petroleum hydrocarbons (gas oil) | *M. galloprovincialis* | 4–8 | » |
| TDTMA | *M. edulis* × *M. galloprovincialis* (natural hybrid population) | 0.05–5 | » |
| TDTMA | *Crassostrea gigas* | 0.5 | EESR 761% |
| SDS | *M. edulis*, *M. galloprovincialis* | >1 | Ostroumov, 2001a; Ostroumov, 2002a |
| SDS | *Crassostrea gigas* | 0.5 | EESR 231% |
| Triton X-100 | *Unio tumidus* | 5 | Ostroumov, 2001a |
| Triton X-100 | *M. edulis* | ≥1 | Ostroumov, 2001a |
| SD1 (OMO) | *Unio tumidus* | 50 | EESR 187% |
| SD2 (Tide) | *M. galloprovincialis* | 50 | EESRà 207% |
| SD3 (Losk) | *M. galloprovincialis* | 7 | EESR 551% |
| SD4 (IXI) | *M. galloprovincialis* | 10 | EESR 158% |
| SD4 (IXI) | *M. galloprovincialis* | 50 | EESR 276% |
| LD1 (E) | *M. galloprovincialis* | 2 | EESR 214% |
| LD1 (E) | *Crassostrea gigas* | 2 | EESR 305% |
| LD2 (Fairy) | *Cr. gigas* | 2 | EESR 1790% |

Note: The highest EESR value over the experimental period is indicated; SD is synthetic detergent, LD is liquid detergent, SDS is sodium dodecylsulfate.

## RESPONSE OF THE SELF-PURIFICATION SYSTEM AS A WHOLE TO EXTERNAL (ANTHROPOGENIC) INFLUENCES ON A WATER BODY

The system of self-purification and water quality formation is labile (Ostroumov, 2000c) and easily transforms when environmental conditions change, which interferes with the analysis of trends in its functioning. The results of my experiments shed light on the factors responsible for the lability of a concrete process involved in self-purification, namely, water filtration by hydrobionts (mollusks and rotifers) (Ostroumov, 2000a–2000c, 2001a–2001c, 2002a–2002c, 2005). This process proved to be inhibited by sublethal concentrations of anthropogenic pollutants such as surfactants (Ostroumov *et al.*, 1997; Ostroumov, 2000a–2000c, 2001a), mixed surfactant-containing preparations (Ostroumov, 2001a; Ostroumov, 2005), cadmium, and some other substances (Table 2). A similar effect on mollusks and zooplanktonic filter-feeders was also described for other pollutants (Day and Kaushik, 1987). These data show the hazard of anthropogenic impact on aquatic ecosystems (chemical pollution of water bodies and water courses) as a factor impairing the efficiency of the water self-purification system (Ostroumov, 2000a–c; 2001a–c; 2002a–c; Braginskii and Sirenko, 2003).

## SOME GENERAL TENDENCIES AND PRINCIPLES OF FUNCTIONING OF THE WATER SELF-PURIFICATION SYSTEM

An analysis of data on specific features of the functioning of the biota as a factor of water self-purification in aquatic ecosystems provides a basis for some generalizations (note, however, that the tendencies listed below prevail but are not universal, and exceptions to the general rule may be found in some ecosystems):

(1) **The observed rates of particular self-purification processes are often lower than the maximum possible rates.** This may be evidence for the existence of regulatory mechanisms. Thus, the rate of water filtration by hydrobionts is regulated and considerably decreases when the concentration of suspension in water becomes higher (Sushchenya, 1975; Shul'man and Finenko, 1990).

(2) **There is a maximum diversification of organisms performing the main functions** in the mecha-

nism responsible for the parameters of the aquatic environment and its self-purification. Indeed, as noted above, almost every function (oxygen release, oxidation and transformation of dissolved organic matter, water filtration, etc.) in a given ecosystem is accomplished by different groups of organisms simultaneously.

(3) **The maximum possible number of stages in the pathways of biogenic migration of elements** is often characteristic of the functioning of biotic mechanisms responsible for the parameters of the aquatic environment and its purification.

(4) **Synecological cooperativity:** many processes that determine the parameters of the aquatic environment and lead to its self-purification are accomplished efficiently and at a high rate due to the joint actions of two or more species (groups of species).

(5) **Continuity of significance of the biota:** the biota remains highly important throughout the space occupied by an aquatic ecosystem and at any moment, irrespective of the time of day, season, or the stage of succession.

(6) **Balanced combination of opposite processes:** organisms simultaneously release and absorb organic molecules, oxygen, and $CO_2$; produce suspended organic matter and remove it from water in the course of their filtration (Ostroumov, 2002c); etc.

## CONCLUSIONS AND RECOMMENDATIONS FOR NATURE-CONSERVATION PRACTICE

My experiments and the theoretical considerations based on their results suggest the following conclusions, which may be important for sustainable socioeconomic development:

(1) Since almost the entire aquatic biota is involved in the processes responsible for water quality and the self-purification of aquatic ecosystems or in their regulation, it is necessary to preserve the entire biodiversity of aquatic ecosystems (Ostroumov, 2002b).

(2) Since the species of terrestrial ecosystems and habitats bordering water bodies and watercourses actively participate in water purification, it is necessary to protect the biodiversity of these coastal ecosystems in order to maintain water quality at a high level.

(3) In estimating the critical anthropogenic load on an aquatic ecosystem (Moiseenko, 1999), it is important to take into account the lability and vulnerability of self-purification processes in the ecosystem.

(4) New types of ecological hazard created by chemical substances were revealed (Ostroumov, 2001c, 2002e).

(5) New principles were proposed for eutrophication control (Ostroumov, 2001b) and nature conservation in water areas (Ostroumov, 2002b).

(6) New pollutants that reduce the capacity of aquatic ecosystems (water bodies and watercourses) for self-purification will be revealed.

The multifunctional role of the biota in water self-purification is an additional illustration of V.I. Vernadsky's thesis that "… living matter … geologically … is the greatest force in the biosphere and determines all processes occurring in it" (Vernadsky, 1991).

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