Doklady Biological Sciences, Vol. 396, 2004, pp. 206–211. Translated from Doklady Akademii Nauk, Vol. 396, No. 1, 2004, pp. 136–141.

GENERAL BIOLOGY

On the Biotic Self-purification of Aquatic Ecosystems: Elements of the Theory

S. A. Ostroumov

Presented by Academician M.E. Vinogradov November 12, 2003

Received November 17, 2003

This paper generalizes and systematizes the basics of the theory of the multifunctional role that the biota plays in the self-purification [1–3, 7, 13, 15] and ecological remediation [11] of aquatic ecosystems using the results of previous analyses [3–12] and the theory of the function of aquatic ecosystems [2].

1. The Main Processes of Water Purification in Aquatic Ecosystems

Many physical, chemical, and biotic processes are important for the formation of water quality and water purification in aquatic ecosystems [1–3, 7, 13, 15]. Earlier I published the list of these processes; a revised list of the most important of them is shown in Table 1.

Many of these physical and chemical processes are either controlled or affected to a certain degree by biological factors. For example, the rate of the sorption of pollutants by settling particles of suspensions depends on the concentration of phytoplankton cells; photochemical decomposition of substances is only possible in transparent water, and the transparency is ensured by the filtration activity of hydrobionts. Thus, biotic processes are pivotal for the entire system of water self-purification.

2. The Main Functional Blocks of the Self-purification System of Aquatic Ecosystems

Let us distinguish the following main functional blocks covering the major part of the general hydrobiological mechanism of the self-purification of aquatic ecosystems: (1) filtration activity or “filters”; (2) mechanisms of transferring or pumping chemical substances between ecological compartments (from one medium to another); and (3) degradation of pollutant molecules.

2.1. Filters (see also [7, 14]). Filters comprise the following functional systems: (a) all invertebrate filter feeders; (b) macrophytes, which take up part of biogenic and pollutant substances entering the ecosystem from adjacent areas; (c) benthos, which takes up and consumes part of biogenic and pollutant substances migrating at the water–bottom sediment interface; and (d) microorganisms adsorbed on suspended particles moving relative to the mass of water due to the sedimentation of the particles caused by gravity; as a result, the mass of water and the microorganisms move relative to each other, which is equivalent to the situation where water is filtered through granular substrate with attached microorganisms, the latter extracting dissolved organic compounds (DOCs) and biogenic compounds from the water [7].

2.2. Mechanisms of transferring of pumping chemical substances from one ecological compartment to another (pimps). This block comprises the following functional systems: (a) the functional pump facilitating the transfer of part of pollutants from the water into sediments (sedimentation and sorption); (b) the functional pump transferring part of pollutants from the water to the atmosphere (evaporation); (c) the functional pump determining the transfer of part of biogenic substances from the water to the surrounding terrestrial ecosystems (all migrations related to the emergence of imago insects whose larval development occurs in water); and (d) a similar functional pump transferring part of biogenic substances from water to the surrounding terrestrial ecosystems because of the birds' feeding on hydrobionts: fish-eating birds remove biomass from the aquatic ecosystem, but they inhabit the area adjacent to the water body or stream.

2.3. Decomposition of pollutants (“mills”). The functional systems decomposing pollutants are (a) the “mill” of intracellular enzymatic processes; (b) the “mill” of extracellular enzymes that are present in water; (c) the “mill” of photochemical processes sensitized by substances of biological origin; and (d) the “mill” of free-radical processes involving ligands of biological origin (Yu.I. Skurlatov, cited from [7]).

Faculty of Biology, Moscow State University, Vorob’evy gory, Moscow, 119899 Russia

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Table 1. Some factors and processes of water self-purification (from [6, 7], with substantial additions). Designations: CP, chemical pollutant; DOC, dissolved organic compound; SOC, suspended organic compound

Factors and processes of environment purification	Reference and comment
1. Physical and physicochemical	
Dissolving and dilution	[7]
Washing ashore	[7]
Drifting into adjacent water bodies and waterways	The export of the carbon contained in dissolved compounds and suspended particles carried by outflowing water depends on the DOC and SOC concentrations
Sorption by suspended particles followed by sedimentation	Depends on the formation of seston and detritus by hydrobionts
Sorption by bottom sediments	Depends on the amount of organic compounds in the sediments
Evaporation	May depend on the film of organic substances on the surface of the water body
2. Chemical	
Hydrolysis	[7]
Photochemical transformations	[15]; photolysis is sensitized by organic compounds of biotic origin
Redox catalytic transformations	[7]
Free-radical transformations	Depend on biotic ligands
Decrease in CP toxicity due to their binding with DOCs	[7]
Chemical oxidation of CPs involving oxygen	Oxygen concentration depends on hydrobiont photosynthesis
3. Biotic	
The sorption and accumulation of CPs and biogenic substances by hydrobionts	[7]
Biotransformation: redox reactions, decomposition, and conjugation	In some lakes (in this case, Mirror Lake, United States), the following amounts of carbon are oxidized annually (in grams of C per 1 m^2 of water surface): due to phytoplankton respiration, 19.1; due to zooplankton respiration, 12.0; and bacterial oxidation in bottom sediments, 17.3 [15]
Extracellular enzymatic CP transformation	[3]
Removal of suspended particles and CPs from the water column as a result of water filtration by hydrobionts	Cladocerans filter as much as 40 ml (in some cases, up to 130 ml) of water per animal per day; copepods, 2–4 ml (in some cases, up to 27 ml) per animal per day [1, 13, 15]
Removal of CPs from the water column as a result of their sorption by pellets of hydrobiont excrements	[7]
Prevention or deceleration of the release of biogenic substances and CPs from bottom sediments into water; accumulation and binding of biogenic substances and CPs by benthic organisms	[7]
Removal of C, N, and P from the ecosystem as a result of the emergence of imago insects after the completion of larval development in water	The emergence of imago insects may take away from the lake 0.5 g C/m^2 water surface per year [15]
Removal of C, N, and P from the ecosystem by fish-eating and other birds feeding on aquatic organisms	Depends on the state of the biota in the adjacent area
Removal of C, N, and P from the ecosystem when the amphibians that have completed their metamorphosis in water go to land	See the previous comment
CP biotransformation and sorption in soils of farmlands supplied with polluted water	[7]
Regulation of the numbers and activity of organisms involved in water purification as a result of interactions between organisms	[14, 15]; ecological chemoregulators ecological chemotransmitters [3] are involved in the regulation

Note: Many factors are interrelated and overlap, so it is often impossible to distinguish individual factors. In the conceptual analysis, factors are regarded as individual for convenience.

3. Energy Sources of the Biotic Mechanisms of Aquatic Ecosystem Self-purification

Ecosystems receive energy for biotic self-purification from photosynthesis, oxidation of autochthonous organic compounds, and other redox reactions. Thus, almost all available sources of energy are involved. Some energy is obtained from the oxidation of the components (dissolved and suspended organic matter) that have to be removed from the ecosystem. In other words, the energetics of self-purification resembles energy-saving technologies invented by humans.

4. The Roles of the Main Large Taxa in Aquatic Ecosystem Self-purification

Microorganisms, phytoplankton, higher plants, invertebrates, and fish are involved in the self-purification of aquatic ecosystems and the formation of water quality [4, 6, 7, 9]. Note that each of these groups is involved in more than one or two process (see Table 1 in [4] for details). These groups are equally necessary for normal self-purification.

5. Reliability of Water Self-purification Systems

In technology, the reliability of a system is often ensured by doubling many components of the system. Analysis of the functions of ecosystems shows that they employ the same principle. For example, the filtration activity of hydrobionts is doubled: it is performed by two large groups of organisms: the plankton and the benthos. Both groups filter water rapidly [1, 13]. Benthos also additionally doubles the activity of planktonic organisms residing in the pelagic zone, because the larvae of many benthic filter feeders are components of plankton. In the plankton, two groups of invertebrate multicellular filter feeders, crustaceans [13] and rotifers [7, 15] double each other's filtration functions. Another large group of organisms with a different type of nutrition, protozoa, also filters water as crustaceans and rotifers do. Some other organisms also filter water (for the list of these, see Table 3 in [9]).

Enzymatic decomposition of pollutants, another component of water self-purification, is simultaneously performed by bacteria and fungi. Almost all hydrobionts that, to different extents, can take up and oxidize dissolve organic compounds also fulfil this function (although the activity of each group of organisms has certain specificity).

Thus, the reliability of water self-purification in ecosystems is ensured by the multiplicity of the processes involved, which are performed simultaneously and secure each other's function. In turn, water purification and permanent reproduction (repair) of its quality is among the most important elements of the self-sustaining stability of the entire aquatic ecosystem.

The permanent recovery of water quality is absolutely necessary for the stability of ecosystems, because it constantly withstands the constant inflow of autochthonous and allochthonous organic compounds and biogenic substances carried from the adjacent land and tributaries (by water currents), as well as by precipitation and settling waterborne particles. Therefore, water self-purification is as crucial for the stability of ecological systems as DNA repair is for heredity; therefore, water self-purification may be regarded as ecological repair of aquatic ecosystems [11]. Another important element of the reliability is biota self-regulation.

6. Regulation of Self-purification

Almost all organisms involved in intense self-purification activity are under the double control of the preceding and the next links of the food chain. Earlier [5, 14], I proposed inhibitory analysis of regulatory interactions in food chains as an effective method for studying the regulatory functions of different organisms.

Various types of signals, including chemical information carriers, play considerable roles in the regulatory mechanisms of ecosystems. It has been suggested that these chemical substances be termed ecological chemoregulators ecological chemotransmitters [3].

The influence of regulatory factors on the organisms involved in water quality self-restoration explains why the observed rates of some self-purification processes are considerably lower than the maximal rate that the hydrobionts are capable of. For example, the rate of water filtration in natural water bodies is not high enough to remove suspended organic compounds (SOCs) particles from the water. In many filter feeders, the filtration rate has been demonstrated to decrease with an increase in the concentration of sestonic particles [13 etc.].

7. The Response of the Entire Self-purification System to External Factors Affecting an Ecosystem

The system of self-purification and water-quality formation is labile [4, 6, 7] and is readily rearranged as the environmental condition change, which makes it difficult to determine its general functional patterns. My experimental studies [4, 6, 7, 14] have demonstrated the existence of an important element of the lability of one specific process, namely, water filtration by hydrobionts (mollusks and rotifers). This is exemplified by the results of experiments on the treatment of the mollusks *Mytilus edulis* and *M. galloprovincialis* and the rotifer *Brachionus calyciflorus* with tetradecyltrimethyl ammonium bromide (TDTMA) and synthetic detergents (SDs). These filtration processes were inhibited by *sublethal* concentrations of artificial pollutants,

Table 2. The substances and their concentrations that inhibit the removal of suspended matter from water by filter feeders

No.	Substance	Concentration, mg/l	(+) Presence or (–) absence of inhibition	Filter feeder	Reference and comment
1	Heptane	2–4	–	*Mytilus galloprovincialis*	The author's own data
		60	+	*M. galloprovincialis*	The same
2	TDTMA	0.05–5	+	*M. edulis* × *M. galloprovincialis* (natural hybrid population)	"
		0.5	+	*Crassostrea gigas*	[7]
		1–2	+	*Unio pictorum*	[4]
		0.5	+	*Brachionus angularis, B. plicatilis*	[7]
3	SDS	more than 1	+	*M. edulis*	[4]
		1.7	+	*M. galloprovincialis*	[4]
		0.5	+	*C. gigas*	[7]
4	Triton X-100	5	+	*Unio tumidus*	[7]
		1–5	+	*U. tumidus*	[4]
		0.5	–	*M. edulis*	[7]; after 30–60 min of incubation
		0.5	+	*M. edulis*	[7]; after 90 min of incubation
		1–4	+	*M. edulis*	[7]; after 30–90 min of incubation
5	SD1 (OMO)	50	+	*U. tumidus*	[10]
6	SD2 (Tide)	50	+	*M. galloprovincialis*	[7]
7	SD3 (Losk)	7	+	*M. galloprovincialis*	[7]
8	SD4 (IXI)	10	+	*M. galloprovincialis*	[7]
		20	+	*M. galloprovincialis*	[9, 10]
9	SD5 (Deni)	30	+	*C. gigas*	[9, 10]
10	LD1 (E)	2	+	*M. galloprovincialis*	[7]
		2	+	*C. gigas*	[7]
11	LD (Fairy)	2	+	*C. gigas*	[7]
		2	+	*M. galloprovincialis*	[8]
12	Petroleum hydrocarbons (gas oil)	4–8	+	*M. galloprovincialis*	The author's own data
13	Lindan (pesticide)	0–1.5	+	*M. edulis*	Donkin *et al.*, 1997 cited in [14]
14	Dichlorvos (pesticide)	0–1	+	*M. edulis*	Donkin *et al.*, 1997 cited in [14]
15	Trimethyl tin chloride (TMTC)	0.01–10	+	*Dreissena polymorpha*	Mitin, 1984; cited in [14]
16	Cadmium sulfate	0.5	+	*M. galloprovincialis*	The author's own data
17	Copper sulfate	2	+	*M. galloprovincialis*	The same
18	Lead nitrate	20	+	*M. galloprovincialis*	"

Note: SD, synthetic detergent; LD, liquid detergent; SDS, sodium dodecylsulfate; TDTMA, tetradecyltrimethyl ammonium bromide.

namely, surfactants and surfactant-containing mixed preparations. There are published data on similar effect of other pollutants on mollusks and zooplanktonic filter feeders [7]. These data (Table 2; see [7] for the experimental methods) demonstrate that a decrease in the effectiveness of the self-purification (ecological remediation) system of the water is hazardous under the conditions of anthropogenic impact on aquatic ecosystems [7, 11, 14].

8. An Aquatic Ecosystem as an Analog of a Bioreactor with a Water Purification Function

The specific features of the water self-purification system invite analogies with a bioreactor. Also this analogy is attractive and seems substantiated, it pertains to only one essential aspect of aquatic ecosystems. It is justified and useful in certain respects [4]; however, it by no means reflects comprehensively the essence of aquatic ecosystems, with all their diversity and variability.

Note that the regulation of many important processes involved in the transfer of chemical elements in aquatic ecosystems is bioinert, i.e., combines the effects of biotic and abiotic factors. The ascertainment of the bioinert nature of the regulation emphasizes the significance of both biotic and abiotic components. Aquatic ecosystems are characterized by considerable variability of almost all main parameters and an almost complete absence of constant quantitative characteristics. Therefore, the analogy with a technological device is not complete. Thus, we may conclude (with some reservations) that the system of processes involved in the self-purification of an aquatic ecosystem is similar to a high-technology mechanical device and may be regarded as a bioreactor fulfilling functions that are important for the ecosystem. However, this analogy pertains to only one essential aspect of an aquatic ecosystem.

9. Implications for Environmental Protection

Taking into account the theory described above, as well as the results of my earlier experimental studies [4–11, 14] and data published by other researchers [1, 13, 15], I believe that the following notions and recommendations will be useful for solving the problems related with the protection of biodiversity and environment.

(1) The conservation of the self-purification capacity of water bodies and waterways should be an essential element of environmental protection programs [10].

(2) Almost all species of hydrobionts are involved in the formation of water quality and self-purification of aquatic ecosystems or the regulation of these processes. This is one more reason for the necessity of the conservation of the entire biodiversity in aquatic ecosystems [9].

(3) Organisms living in terrestrial ecosystems adjacent to water bodies and waterways are largely involved in water purification; therefore, the conservation of biodiversity in these coastal terrestrial ecosystems is also necessary for sustaining the quality of water [10].

(4) The environmental protection measures and regulations in the protected terrestrial and aquatic areas should include not only the conservation of populations and gene pools, but also the maintenance of the functional activity of these populations (specifically, the functional activity that contributes to the maintenance of water quality and, hence, the stability of the entire ecosystem) [10].

(5) New hazards related to the chemical pollution of aquatic ecosystems have been identified [11].

(6) When solving the problem of the eutrophication of aquatic ecosystems, my earlier suggestions on the synecological approach should be taken into account [8].

(7) The assessment of the anthropogenic damage to the environment should take into account, among other factors, the damage due to the decrease in the self-purification capacity of water bodies and waterways. This brings a new element into the interpretation of environmental legislation, including both international laws and regulations and the environmental legislation of the Russian Federation.

(8) The theory offers a new approach to a more comprehensive economic assessment of the anthropogenic damage to aquatic ecosystems and organisms involved in the self-purification of aquatic ecosystems [12].

(9) According to the theory described above, we may expect new examples of chemicals hazardous for the capacity of aquatic ecosystems for self-purification.

The results of the analysis performed allows the hydrobiont community to be regarded as a device for ecosystem self-purification constituting an essential part of what V.I. Vernadsky called the "biosphere apparatus." The notions put forward in this study have further developed and detailed some of Vernadsky's concepts (on bioinert objects, the biogenic migration of chemical elements, and the biosphere apparatus).

ACKNOWLEDGMENTS

I am grateful to A.F. Alimov, M.E. Vinogradov, V.L. Kas'yanov, V.V. Malakhov, T.I. Moiseenko, and V.D. Fedorov for the discussion of and comment on the study. I thank J. Widdows, N. Walz, and G.E. Shul'man for the assistance in experiments with filter feeders.

This study was supported by the McArthur Foundation and the Open Society Institute.

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