International Journal of Oceans and Oceanography
ISSN 0973-2667 Vol.1, No.1 (2006), pp. 111-118

http://www.ripublication.com/ijoo.htm

Biomachinery for maintaining water quality and natural water self-purification in marine and estuarine systems: elements of a qualitative theory

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Abstract

Basic elements are formulated for a qualitative theory of the polyfunctional role of the biota in maintaining self-purification and water quality in aquatic ecosystems. The elements of the theory covers the following: (1) sources of energy for the mechanisms of self-purification; (2) the main functional blocks of the system of self-purification; (3) the list of the main processes that are involved; (4) analysis of the degree of participation of the main large taxons; (5) degree of reliability and the main mechanisms providing the reliability; (6) regulation of the processes; (7) the response of the system towards the external influences (man-made impacts); (8) the analogy between ecosystems and a bioreactor; and (9) conclusions relevant to the practice of biodiversity conservation. In support of the theory, results are given of the author's experiments which demonstrated the ability of some pollutants (surfactants, detergents, and some others) to inhibit the water filtration activity of marine filter-feeders (namely, the bivalve mollusks *Mytilus galloprovincialis, Mytilus edulis,* and *Crassostrea gigas*).

Key words: Ecosystems, pollution, water quality, water self-purification, filter-feeders.

Abbreviations: LD – liquid detergent; SD- synthetic detergent; SDS - sodium dodecylsulphate; TDTMA - tetradecyltrimethyl ammonium bromide.

Introduction

Aquatic organisms participate in various processes leading to water purification. Not only microorganisms, but also invertebrates [1, 2] and many other groups of organisms are involved [3-8], which was discussed and analyzed in [9-12].

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, 14, 15] and ecological remediation [11] of aquatic ecosystems using the results of previous analyses [3–12, 15, 16, 17]. When using the expression 'water self-purification', we mean a system of natural processes that lead to improving water quality as a result of the interplay of natural factors without any man-made attempts to treat or purify water.

The analysis is made at the qualitative level. Some details of the methods, experiment and additional references were given in [7, 15]. This paper is based on the presentations that the author made at the recent conference 'Aquatic Ecosystems and Organisms-6' (the 6th international conference that was run in Moscow in 2004, at Moscow University; organized by the Department of Hydrobiology), and recent American Society of Limnology and Oceanography (ASLO) Meetings.

Table 1: Some processes and factors playing a role in purification, remediation and upgrading the quality of water in marine and estuarine ecosystems.

Types	Processes and factors
1. Physical	1.1 Dilution 1.2 Adsorption 1.3 Sedimentation 1.4 Evaporation 1.5. Advection and mixing
2. Chemical	2.1 Hydrolysis 2.2 Photochemical reactions, photolysis 2.3 Oxidation and reduction 2.4 Free radical-dependent destruction 2.5 Complexation by and binding to other molecules
3. Biological	3.1 Microorganism-dependent oxidations, reductions and other biotransformations 3.2 Transformations performed by excretion of chemical substances and enzymes 3.3 Accumulation by organisms 3.4 Filtering of water by suspension-feeding organisms 3.5 Excretion of molecules that are instrumental in increasing the rate of some chemical processes of degradation of pollutants (*e.g.*, photodegradation) 3.6 Producing oxygen that is involved in chemical oxidation of pollutants 3.7 Transpiration 3.8 Regulation of biological processes of water purification by other organisms

The Main Processes of Water Purification in Aquatic Ecosystems

Many physical, chemical, and biotic processes are important determinants of water quality and water purification in aquatic ecosystems [1–3, 7, 13, 15]. Earlier this author published the list of these processes [15, 16]; a revised list of the most important 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 [17] depends on the concentration of phytoplankton cells. Furthermore, photo-chemical decomposition of substances [17] is only possible in transparent water, and the transparency is ensured by the filtration activity of aquatic invertebrates. Thus, biotic processes are pivotal for most of the processes of water self-purification.

The Main Functional Processes of Self-purification of Water in Aquatic Ecosystems.
The dominant processes of the self-purification of aquatic ecosystems are [15]: (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. Each of the processes is defined or commented in following sections.

Filters (see also [7, 14]). Filters comprise the following functional systems:

(a) all invertebrate filter feeders;
(b) macrophytes, which take up and sorbs part of the nutrients (including N, and P) and pollutants entering the ecosystem from adjacent areas;
(c) benthos, which takes up, consumes, and sorbs part of the nutrients and pollutants at the water–bottom sediment interface; and
(d) microorganisms adsorbed on suspended mineral and organic particles moving relative to the mass of water due to gravity, which is equivalent to filtration through granular substrate with attached microorganisms, the latter taking up and sorbing dissolved organic compounds and nutrients from the water [7].

Pumps that move chemicals from one ecological compartment (or medium) to another.
Pumps comprise the following functional systems:

(a) process of transfer of part of pollutants from the water into sediments as a result of sedimentation of suspended particles and of contaminants sorbed to the particles (sedimentation and sorption);
(b) the functional pump transferring part of pollutants from the water to the atmosphere (evaporation);
(c) the functional pump that transfers of some part of nutrients (N, P) from the water to the surrounding terrestrial ecosystems as a result of the birds' consumption of fish and other aquatic organisms: the fish-eating birds remove biomass from the aquatic ecosystem, but they inhabit the terrestrial area adjacent to the water system.

The role of birds in marine trophic webs is illustrated by the data on the upwelling ecosystem off Central Chile [18]. The biomass of sea birds (penguins, pelicans, cormorants) was estimated 65 kg per km^2, which is next to the biomass of sea lions (90 kg per km^2) and more than the biomass of cetaceans (23 kg per km^2). Important is the ratio Q/B (year –1), where Q – consumption of fish by sea birds (kg km^{-2} $year^{-1}$), B - biomass of sea birds (kg km^{-2}). The ration Q/B for sea birds was estimated 20 $year^{-1}$, which is more than that ration for cetaceans (0.15), macrobenthos (14.1), mesopelagic fish (12.0), pelagic fish (4.4 – 5.0), and demersal fish (3.5) [18].

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.

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.

Under anaerobic conditions, energetics of bacteria is driven by using electron acceptors other than oxygen. Anaerobic activity of bacteria in sediments is important part of the removal of some amount of contaminants including nutrients. Under anaerobic conditions, nitrate is utilized by many facultative anaerobic bacteria, particularly of the genera *Pseudomonas, Achromobacter, Bacillus, Micrococcus*, and *Escherichia* as the exogenous terminal electron acceptor in the oxidation of organic substances.The role of anaerobic bacteria is illustrated by relatively high rates of denitrification in sediments. Denitrification rates of sediments are 2 to 4 orders of magnitude greater than those of overlying water [19]. The role of anaerobic bacteria in anaerobic metabolism of xenobiotics, including dechlorination of xwnobiotics, is significant [3].

Roles of the Main Taxa in Water 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. Even the organisms that are not involved directly in the process of improving water quality, are often helpful in the key processes of water purification. For example, many phytophagous organisms cut the large structures of plants into smaller pieces or homogenous mass that is more appropriate substrate for protozoa, bacteria, and fungi that biodegrade that material. The organisms of higher trophic levels are instrumental in regulating the numbers of organisms of lower levels that are the direct participants of water purification. The diversity of organisms that are involved in the biomachinery for water purification is impressive and it reminds us of the words of Leonardo da Vinci (1452-1519) about Nature: "In her inventions nothing is lacking, and nothing is superfluous."

Reliability of the Biomachinery for Water Self-purification

In technology, the reliability of a system is often ensured by duplicating critical components of the system. Analysis of the functions of ecosystems shows the same principle being applied. For example, the filtration activity of aquatic organisms is duplicated by two large groups of organisms: the plankton and the benthic invertebrates. Both groups filter water rapidly [1, 13].

Benthic organisms not only filter large volumes of water at the interface (water/bottom), but also they contribute to the filtration of the upper part of the water column, because the larvae of many benthic filter feeders are components of the plankton. In the plankton, two groups of invertebrate multicellular filter feeders, crustaceans [13] and rotifers [7, 15] are involved in filtration. 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 cyanobacteria, bacteria, fungi, phytoplankton, and higher plants. Almost all aquatic organisms that, to different extents, can take up and oxidize dissolve organic compounds also fulfill 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. In turn, water purification and maintaining water quality is among the most important elements of the self-sustaining stability of the entire aquatic ecosystem.

The long-term maintenance of water quality is absolutely necessary for the stability of ecosystems to withstand the constant inflow of autochthonous and allochthonous organic compounds and nutrients carried with water from the adjacent land and tributaries, as well as by precipitation and the settling of 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.

Regulation of Self-purification

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

Various signals, including chemical information carriers, are involved in the regulatory mechanisms of ecosystems. These chemical substances were termed ecological chemoregulators and ecological chemomediators (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 of which the aquatic organisms are capable. For example, the rate of water filtration observed in natural water bodies is not high enough to remove all or virtualy all suspended organic matter (particles) from the water. In many filter feeders, the filtration rate decreases with an increase in the concentration of sestonic particles [13].

The Response of the Entire Self-purification System to External (Man-Made) Factors

The system of self-purification is labile [4, 6, 7] and is readily changeable as the environmental condition changes, which makes it difficult to determine general ecosystem functional patterns. The authors 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 aquatic organisms (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 and synthetic detergents. These filtration processes were inhibited by *sublethal* concentrations of artificial pollutants, namely, surfactants and mixed preparations containing surfactants. There are published data on similar effect of other pollutants on mollusks and zooplanktonic filter feeders [7]. These data (Table 2) demonstrate that a decrease in the effectiveness of self-purification (ecological remediation) of the water is hazardous under anthropogenic impact on aquatic ecosystems [7, 11, 14].

An Aquatic Self-Purification as an Analog of a Bioreactor Function

The specific features of water self-purification invite analogies with a bioreactor [4]. However, these analogies are by no means comprehensive of the essence of aquatic ecosystems, with all the diversity and variability. Note that the regulation of many important processes involved in the transfer of chemical elements in aquatic ecosystems is the dual effect of biotic and abiotic processes. The significant role of regulatory mechanisms is a characteristic attribute of modern technology. However, aquatic ecosystems are characterized by considerable variability of almost all main parameters. The almost complete absense of constant parameters makes aquatic ecosystems different from the rigid structures of technical devices. Therefore, the analogy with a bioreactor is useful but not comprehensive.

Table 2. Some chemicals that have an adverse effect on the filtering activity of the marine filter-feeders. As a result, the amount of suspended matter removed from the water by the filter-feeders decreased. Therefore the amount of suspended matter left in the water was more than that in control. The method described in [7].
LD – liquid detergent; SD- synthetic detergent; SDS - sodium dodecylsulphate; TDTMA - tetradecyltrimethyl ammonium bromide.

Chemical	Concentration of the chemical, mg l^{-1}	Organisms	Effect of the chemical (the ratio of the concentration of suspended matter in the system with the chemical to that in the control), %
heptane	16	*Mytilus galloprovincialis*	209.1
$CuSO_4 \cdot 5H_2O$	2	*M. galloprovincialis*	140.0
TDTMA	0.5	*Crassostrea gigas*	344.2
SD1	20	*C. gigas*	261.7
LD2	2	*M. galloprovincialis*	218.8
LD2	2	*C. gigas*	1790.0
SD2	10	*M. galloprovincialis*	157.8
SD3	30	*C. gigas*	5800.0
Triton X-100	1	*M. edulis*	236.2
Triton X-100	4	*M. edulis*	1505.6
SDS	1	*M. edulis*	271.1
SDS	4	*M. edulis*	1473.2

Implications for Environmental Protection

Taking into account the theory described above, as well as the results of the author's earlier experimental studies [4–11, 14] and data published by other researchers [1, 13, 15], the following conclusions, postulates, and recommendations contribute to solving some of the problems of 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 aquatic organisms are involved in the maintenance of water quality, self-purification of aquatic ecosystems, or the regulation of these processes. This is a primary reason for the necessity of the conservation of the entire biodiversity in aquatic ecosystems [9].
(3) Some of the 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) Hazards related to the chemical pollution of aquatic ecosystems have been identified that affect diversity and function of self-purificaiton [11]. Those hazards were not realized until now. 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 national and international laws and regulations. According to the theory described above, we may expect new examples of chemicals hazardous for the capacity of aquatic ecosystems for self-purification.

(6) When solving the problem of the eutrophication of aquatic ecosystems, this author's earlier suggestions should be taken into account [8] on what was suggested to call 'the synecological approach', which includes synergy of a dual effect on phytoplankton ysing both nutrients and grazing by filter-feeders [8].

(7) The comprehensive economic assessment of the anthropogenic damage to aquatic ecosystems and organisms should include the potential damage to the self-purification of aquatic ecosystems [12].

The results of the analysis performed allows the aquatic and riparian terrestrial biota (community of organisms) to be considered as biomachinery for ecosystem self-purification. The biomachinery is an essential part of what the father of biogeochemistry V.I. Vernadsky called "the biosphere apparatus." The analysis done and the roles of the biota proposed in this study have further developed and detailed some of Vernadsky's concepts (on the biota-driven migration of chemical elements, and the biosphere apparatus) [20].

It should be noted that the biomachinery of water self-purification is closely associated with the biotic processes that are crucial to global biogeochemical cycles and flows of chemical elements in marine and estuarine systems, which belong to the priority issues of ecology [21 - 24]. The complex biomachinery, including many organisms, works toward making water clean, clear and blue, to be described by the poetic words:

Roll on, thou deep and dark blue Ocean – roll! (Lord Byron, 1788-1824)

Acknowledgments

The author is 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. The author thanks J. Widdows, N. Walz, G.E. Shul'man, G.A.Finenko, and E.Matveeva for assistance. Part of this study was supported by the McArthur Foundation and the Open Society Institute.

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