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ASSESSMENT OF SAFETY INDEX FOR WATER ECOLOGICAL SYSTEM

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Обґрунтовано механізм та наведено розрахунки індексу безпеки природної системи. Експериментально встановлено рівень шкодочинність фактору стічних вод для стенобіонтних організмів. На основі визначених екологічних характеристик гідробіонтів річки розраховано індекс безпеки екологічної системи, на прикладі гирлового комплексу Південного Бугу (Миколаївська область, Україна). Вдосконалено алгоритм управління та забезпечення екологічної безпеки

Ключові слова: індекс екологічної безпеки, водна екосистема, стенобіонти, показник смертності, алгоритм управління екобезпекою

Обоснован механизм и приведены расчеты индекса безопасности экологической системы. Экспериментально установлен уровень вредоносности фактора сточных вод для стенобионтных организмов. На основе определенных экологических характеристиках гидробионтов реки расчитан индекс безопасности экологической системы, на примере устьевого комплекса Южного Буга (Николаевская область, Украина). Усовершенствован алгоритм управления и обеспечения экологической безопасности

Ключевые слова: индекс экологической безопасности, водная экосистема, стенобионты, показатель смертности, алгоритм управления экобезопасностью

1. Introduction

The subject of scientific works in recent decades is increasingly directed at finding optimal conditions of interaction between the economic complex of human and ecological systems. This gradual and sure development of “co-evolutionary” theme occurs because in this era of computer’s mobile information technology it is much easier to understand the main vector of negative human impact on nature, see and feel the effects of it at every corner of the biosphere. Therefore, it is easy to conclude that preserving modern (consumer) models of production, attitude to natural resources and assessment of the impact on the environment, will not improve the quality of people’s lives (welfare).

Ukraine, as known, according to the classification of the United Nations (UN) belongs to the category of developing countries. This suggests not so much backwardness in social and economic terms, but the lack of balance in most issues of development, scientific validity, appropriateness of any actions, which is the root cause of low socio-economic and environmental indicators and negative effects.

Today, in all regions of Ukraine, without exception, the processes of technical and technological modernization of industrial production, which are focused on reducing the pressure on the environment are gradually occurring. Thus, we can talk about changes in people’s minds, their philosophical positions. And an especially important element of these changes at this stage of development of society is an objective assessment from the position of those, who are suffering from human activities. That is ecological systems, and people are an integral part of them (regardless of the subjective self-positioning) and completely dependent on ecosystem services.

The environmental component of development, which is recognized as equivalent to social and economic, at the same time is crucial for the development of the latter. Therefore, the development and the use of new methods for assessing the environmental safety of natural systems, which are based on the ecosystem approach and the basic principles of sustainable development are of particular importance today. The main reason that caused the need for this study is prolonged deterioration of ecosystems (rivers, seas, soil, etc.) in Ukraine, especially in southern regions, and in other places of the world, which is due to a number of anthropogenic factors.

As a result of irrational nature management, we invest much more energy in support of ecosystem services (stocking of rivers, dredging of channels, reclamation of soils, importation of animals in the areas where they have been destroyed and others) than we get in the result, instead of picking up clearly defined part of any resource. Besides, most modern official environmental assessment indexes, which is based on the use of the term “maximum allowable concentration”, do not fix this deterioration. In other words – today they are not enough suitable and objective, do not provide sufficient ecological accuracy [1, 2] to describe the relations of the “man – nature” system due to a significant distortion of the final result, which, by the way, is not comprehensive, and built on an assessment of the standard indicators group.

In the context of the above given, an actual problem today is to develop and improve methods of the environmental condition (quality) assessment, based on an analysis of ecological characteristics of the ecosystems biotic component. In other words – the methods of bioindication and biological testing that more objectively describe the safety of the ecological system.

2. Literature review and problem statement

Humanity is in large excess over the natural "standard" today, technosphere circulation of substances is considerably open-circuited in quantitative and qualitative terms. As a man-made mass transfer constitutes a significant part of the global cycle of matter, through its unlocking it violates the necessary high degree of completeness of biotic circulation that is produced in the course of evolution and is essential for the stationary state of the biosphere [3]. Overall, this suggests a very serious violation of biosphere equilibrium that was transformed into a global environmental crisis.

Modern development of society is based on the indissoluble comprehensive analysis of the ecological, economic and social component. However, it remains questionable, how to do this and make progress, how to rank them.

Such aspects as the quality of human existence (welfare) and subjective decision-making (including natural reflex actions) at the stage of formulating the scope and conditions of anthropogenic impact on the environment lay great errors. So, it is important to determine the place of man in the proposed evaluation system of ecological safety of natural systems. In [4, 5] it was emphasized that man is an integral part of the environment. The analysis of this issue from the standpoint of human duality [6], with further decomposition of the biosphere ecological system, can not give a clear answer, on what concept (ecosystem or socioecosystem) is better in the evaluation process.

However, if we focus on the main object of changes – the human, in dealing with regional or local environmental problems, it is appropriate to use the term "ecological system". In this situation, it does not affect the logical connection of such elements of the conceptual-categorical apparatus of environmental safety as "agent – object of action", "danger – safety". Socioecosystem is lower in rank in relation to the ecological system, always depends on the latter and is the part of it.

According to [7], the socioecological system should be considered as territorial socio-natural self-regulating system, dynamic balance of which is largely provided by human society. This system is anthropocentric because of the special humanity self-positioning in it. This feature has a dual nature – humanity serves as a driving force of the system, which affects the integrity of the system. While most people think, that satisfaction of their personal needs is the purpose of the system, thus destroying it.

Socioecological systems include two vectors of self-regulating – natural and human, the goals of which are often not the same, but united by single streams of matter, energy and information.

There are opposing views on this thesis. For example, the source [8] argues that "social person can not be considered as a component of the ecosystem", and "human society can not be treated as a subsystem of the biosphere".

Summarizing the above considerations, it seems reasonable to conclude that society can not be seen in isolation from the natural component in the development. Regardless of separating the natural and the social, they are surely interconnected by flows of matter, energy and information at all levels of the global ecological system. From this perspective, this is unambiguously an ecosystem.

Taking into account the huge role of living matter (biodiversity) in the biosphere [9, 10], it was determined that the biotic components of ecosystems can be considered the best indicator of complex changes in the environment, and ecological safety assessment should be carried out on the basis of their ecological characteristics. The sources [3] and [11] on this subject, state that in many cases a generalized response function, which reflects the degree of favorability of environment impact, is the so-called welfare function of the species or community. It reflects the environmental potency of the species with respect to this factor and its quantitative expression can be the indicator of survival or realized population size.

The advantages of this method of ecosystems assessment consists in the fact that as a result, unlike the maximum allowable concentration (MAC) concept, we get a generalized indicator that characterizes the natural system not pointwise in time, but includes its history of transformation and synergistic "relationships" with anthropogenic factors.

The first and very important step in the evaluation process of ecological safety is the selection of representative indicators. Based on the vision of the theoretical basis of ecological safety in the region [4, 12], such test organisms should be primarily stenobionts. With regard to the aquatic organisms importance in the evaluation process, the works [11, 13, 14], due to the increasing anthropogenic pressure on freshwater ecosystems, justified the use of macrozoobenthos as an indicator of water systems condition. In [11], for example, some general patterns of macrozoobenthos reaction to multifactor anthropogenic impact for its environmentally sound rationing and the regulation on hydroecosystems were investigated and approximated. It was emphasized that the regularity of the benthos reaction to a set of external negative factors can be the basis of the evaluation and standardisation procedure. However, there are no records about the "wide" range of tolerance to the complex negative action that can also significantly affect the validity of the assessment results. The work [13] argues the representativeness of benthos quantitative indicators (number, biomass) in the context of the water object assessment. But nowhere (including foreign scientific writings) is said about the importance of "width" of aquatic organisms tolerance range to complex negative effect or one factor that can also significantly affect the reliability of the assessment results.

Among the many species of benthos, most of the works are devoted to studying the environmental characteristics of species of the family *Gammaridae*. So, the crustacean *Gammarus pulex* is defined by the indicator of clean water in [15–19]. In addition, the analysis of scientific papers [20–22] suggests its important role in the food chains of inland waters and in the Sea of Azov and the Black Sea. In some periods of the year, the share of amphipods in the diet of sturgeon and bream can be up to 80 % [20].

By investigating these works more thoroughly in [15] we find the conclusion, that the quality of water is proposed to evaluate through the developed scale of amphipods growth, that is how fast it grows and multiplies. Moreover, it is concluded that such approach (when studying the effect of a complex of pollutants) was approximately 8 times more sensitive to changes in the amphipod food chain than the established LD_{50} value. It should be added that in the laws of most European countries and the USA *Gammarus pulex* is recognized as one of the key test-organisms to determine the environmental quality.

In the source [16], a significant impact of toxicants on the behavior of amphipods (nutrition, reproduction, etc.), which further complicates the adaptive capacity of the organism to the stress factor is observed. Amphipods are defined as one of the most sensitive aquatic organisms to the action of xenobiotics. The result of negative factors action may be a substantial reduction in the species population, causing a chain reaction in food and energy chains of the ecosystem.

Species of the *Gammaridae* family are one of the best indicators of the quality of the water environment due to the following factors: a wide trophic spectrum and weight rate, migration ability and tendency to drift, allowing them to easily colonize ecosystems, high reproductive capacity (several broods per female per year) and a large number of offspring and relatively long life [17].

In [18], to determine the water quality by The Trent Biotic Index, except amphipods, it is suggested to use stoneflies and mayflies.

In the source [19], the results of the investigation, which show how parasites in the amphipod body effect the duration of its life at different concentrations of pollutants in the water are presented. According to this, it should be noted that very often parasites supported the functioning of the crustaceans organism, until they produce offspring or it reaches a certain level of maturity.

The economic value of benthos is confirmed by the analysis of the results of the research [21] and data on industrial fish diet [22].

Reaction of aquatic organisms to the contaminant as an integral indicator of aquatic ecosystem was studied in [23]. The pollutants were synthetic surface-active substances and the test body – great pond snail (*Lymnaea stagnalis L.*). It should also be emphasized that much more research now focus on phytoindication [24, 25], which is more convenient for some reasons. While the animals, especially zoobenthos, remain undervalued in the context of their use to assess the quality of the environment [11].

Summarizing the foregoing, it could be concluded that the use of only stenobiont fauna species for the aquatic ecosystems state assessment (safety) is little-investigated. That is today the approaches based on quantitative analysis of population [26, 27] or their combination with further interpretation of the results in the system of assessing the environment quality are the most theoretically and practically developed.

Despite the high level of investigation and wide use of biological indication methods in the practice of environmental research, the issues of application of this approach to assessing the ecological safety of natural systems remain poorly understood. Therefore, in this study the new mechanism of ecological system safety evaluation and management, which is based on a quality improvement of the biological indication method is justified. In contrast to existing methods of ecosystems condition assessment that are based on the analysis of quantitative characteristics of biodiversity, the proposed approach implies the use of only ecological characteristics of stenobionts.

3. The purpose and objectives of the study

The study aims to assess the safety of aquatic ecological system (estuarine complex of the Southern Bug, Nikolaev region, Ukraine).

To achieve this goal, it was necessary to perform the following tasks:

– to justify the use of ecological characteristics of living organisms (especially stenobionts) as indicators of the environment quality;

– to research the object, create a database and calculate the proposed index;

– to identify causal relationships of deterioration processes in the water ecosystem;

– to analyze the normative (acting) and proposed approaches to the assessment of ecological safety from the position of objectivity of the results;

– to improve the algorithm of ecological safety management.

4. Research Methodology

For the Mykolaiv region, where the investigation was made, the main characteristic feature is the biggest water deficit per one resident among the regions of Ukraine. Thus, in the context of the deterioration of qualitative and quantitative characteristics of the rivers in the region, there are several actual problems to be solved. The first is an objective assessment of aquatic ecosystems for further optimal decision-making system creating. The second – to justify the use of aquatic organisms' ecological characteristics as an integral indicator of safety of the entire basin. And the third – to develop a new comprehensive alternative methodology for assessing the ecological safety of the natural system.

Taking into account that almost the whole region is located in the basin of the Southern Bug, a study was conducted in the estuarine part of it, which is considered as the most representative area of water ecosystem in relation to human impacts.

In the source [28], it is emphasized that multifactorial impact on aquatic ecosystem objectively can be assessed only in research of aquatic organisms *in situ* or in conditions close to them in the laboratory. Indicators of changes in the ecosystem can be the rate of mortality, migration or inhibition of reproductive function of hydrocoles. In [29], the study is focused on the analysis of toxic effects of agrochemicals on aquatic biota. Thus, various acting combinations of agrochemicals (from 178 substances) and communities of aquatic species (from 42 species) were formed.

Despite the fact that abiotic parameters are more convenient, because they directly characterize the structure of the medium (the specific negative changes) and are clearly expressed by a numerical value, it is impossible to get through it a full description of the environment. The main criterion – biota reaction to it – remains unaccounted. In addition, the modern human impact on aquatic ecosystems is generally very difficult, and even if a significant number of abiotic parameters are controlled, there is always doubt that any influential factors still remain unaccounted. Finally, the response of ecosystems essentially depends not only on the composition of the factors, but also on their interaction. Therefore, according to the findings [30], it is very difficult to assess the state of ecosystems and the quality of the water environment solely by abiotic parameters.

Using the results of the analysis of previous studies, as indicator organisms, which satisfy the current requirements, we selected the following 5: amphipods, stoneflies, mayflies, caddisflies and alderflies. They can live in fresh water and are very sensitive to water pollution. Thus, the definition of the ecological safety index (ESI) for water ecosystem, according to [4], will be have the following fully formalized form (1):

$$ESI = \frac{1}{1 + k_{am} + k_s + k_m + k_c + k_{al}}, \quad (1)$$

where k_{am}, k_s, k_m, k_c, k_{al} – mortality rate (indicator) of each test-organisms group.

The next step was the selection of the research field and organization of capturing test organisms. Based on the conclusion that mouth and estuary areas of rivers are the most representative in terms of nature management quality upstream throughout the basin (total anthropogenic impact on the ecological system), sampling point was city beach "Strilka" (Fig. 1).

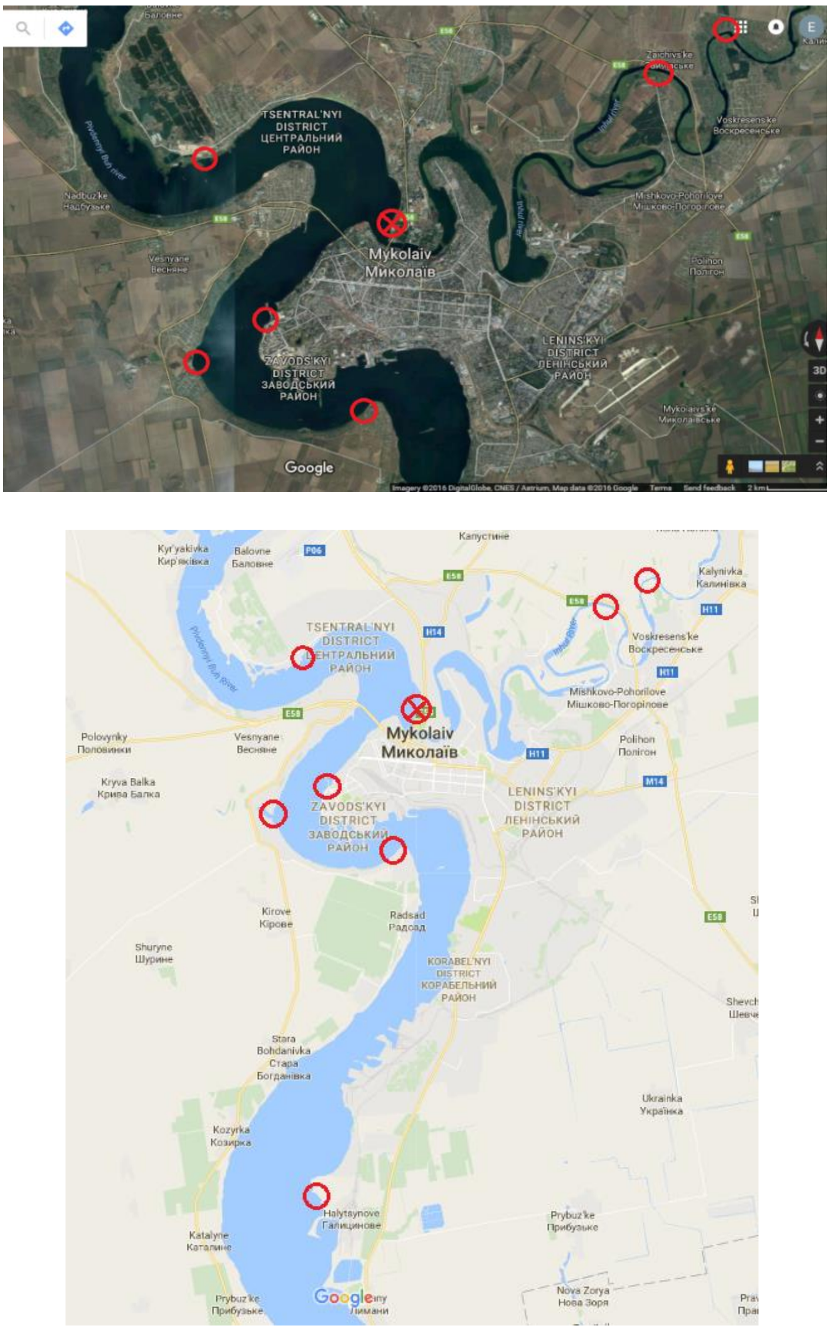

Fig. 1. Arrangement of sampling points in the estuarine complex of the Southern Bug

This point is also a kind of compromise between the two requirements. First, of course, for a comprehensive evaluation the estuaries of rivers should be explored. Moreover, it is known that estuary is a flooded river mouth. Secondly, it was necessary to minimize the impact on the results of studies of the Dnieper-Bug estuary waters (fresh waters from all over Ukraine and marine). In other words, the control point should be located above the Bug estuary, which is the most polluted and productive part of the Dnieper-Bug estuary [31] and as low as possible in the mouth.

Thus, evaluation of the ESI complex of ecosystems of the region, is proposed to make by analyzing the identified hydrocoles in the river (rivers) estuarine systems, which are integral indicators of the basin(s) condition in the whole region. Because [3] emphasized, that aquatic ecosystem is the most representative for the comprehensive analysis of the dynamics of human impact on the environment.

During field studies, only amphipods were detected in the chosen point. Use of them as test organisms is studied poorly by Ukrainian scientists. Much more attention is paid to them by foreign scientists.

That is why, ESI evaluation methodology based on research of the defined aquatic organisms ecological characteristics was proposed and approved.

The experimental procedure consisted of several stages:

– water sampling and capture of aquatic organisms;

– preparation of samples;

– imitation of negative factors of anthropogenic origin that are typical for the region;

– monitoring and recording of results;

– data processing.

In general, the aim was that organisms caught in the river were placed in containers with water, where pollutants (detergent "Gala") were added, and the lifetime or death rate of each of them were recorded. Let's note the composition of the washing powder, which was listed on the package: "30 %: sulphates; 15–30 %: carbonates, silicates; 5–15 %: anionic surface active agents (surfactants); less than 5 %: oxygen bleaches, polycarboxylates, nonionic surfactants, citric acid, stabilizers, phosphonates, complexing agents, enzymes, anti-foaming agent, optical brighteners, dyes, fragrances. The phosphate content of 0.2 to 5 % is allowed".

At the preparatory stage of the research, which lasted about 45 days, possible limiting factors that could affect the outcome or progress of the experiment were found [32]. First, it was found that the density of planting does not affect the amphipods. The same results of life activity were observed in liter, half-liter and quarter-liter containers, with 3–10 individuals of amphipods.

Second, it was investigated whether the nature of water has any harmful influence on vital activity. For each bulk group (1, 0.5 and 0.25 liters), the following samples were prepared: water from the river, the filtered water from the river (white strip filter – 2 mcm), the water from the municipal water supply, the water from the river with the addition of detergent "Gala" at a concentration of 1 %. As a result, after 80 days of observations, it was found that in the samples of water from the river the proportion of dead crustaceans was only 10 %. Moreover, after the space limitations, some crustaceans started copulating in the vessels and after some time younger generation appeared, which subsequently was eaten by adults.

By the results of this phase of the experiment, we can conclude that the continued lack of nutrients in the water is also a limiting factor for amphipods in the natural environment. Thus, the first to die are individuals that were placed in the samples of filtered water from the river and water from the municipal water supply – after 6 days 50 % of the individuals died. In other samples, the changes in their number for two weeks were not observed.

Thirdly, the influence of water temperature on the vital activity of amphipods was investigated. It was revealed that the water temperature over 28 °C for 0.5–1 hour, 100 % of individuals die in the samples of both river and contaminated water (technical oils, solvents and detergent were added in different vessels). Overall, it was found that the temperature factor (as the estuary water is never heated above 27–28 °C) does not affect the vital activity of crustaceans in vivo.

It was also noted that in the samples with petroleum products amphipods are often raised up with oxygen. As the result, a small amount of air attached to their bodies in the surface oily layer and then they could not go to the bottom and rest (as it was in control samples). They were constantly lifted up. The presence of such stressors also hastened their death.

However, if the probability of oil spill in the waters of the Bug estuary and in the town borders is very small (due to a small number of tankers coming to the city ports and non-threatening strength of storms), the pollution of the aquatic ecosystem by domestic wastewater is typical and very high for over 35 years. It is known that the major part of these discharges are household detergents. Particularly harmful to the aquatic ecosystem are surface-active agents (SAA) and phosphates, which is highlighted in the research [33–35]. As to the first, [33] emphasized their toxicity towards all aquatic organisms: algae – 0.5–6.0 mg/dm^3, microorganisms – 0.8–4.0 mg/dm^3, invertebrates – 0.01–0.9 mg/dm^3. Surfactants are accumulated in all without exception flora and fauna of the water object, thereby decreasing their toxicity. Analysis of data [34] reveals the nonionic surfactants as the most dangerous group among other units given in classification. The results of the research of washing powder "Lotus" influence on the vital activity of great pond snail (*Lymnaea stagnalis*) are presented. However, the choice of this aquatic organisms is not justified. And the source [35] states that the study of the surfactants effect on hydrocoles is an excellent basis for wastewater quality control and reduction of their negative effect on internal communications of the water ecosystem.

An important result of the previous stage of the experiment was the highlighting of the main negative anthropogenic factor on the Southern Bug ecosystem in its lower reaches – household waste water, which within an hour, as illustrated below, can cause the death of all experimental species.

As inoperative factors had been determined, the experimental work was structured as follows: some amount of detergent was added in tanks with tap water (amphipods were deprived of food, which made the research faster) to simulate possible concentrations in aquatic ecosystems (Table 1).

Table 1

Model concentrations of detergent in water

Model number	1	2	3	4	5	6	7	8	9	10
C, mg/l	100	200	300	400	500	600	700	800	900	1000

The study of the complex action of detergent components without allocation of certain hazardous substances was built in such a way because this version is more reliable due to accounting for the synergistic effects of pollutants on a living organism (or the whole food chain).

5. Assessment of the ecological safety index and results analysis

As a result of observations and various kinds of modeling of pollution of the aquatic environment, it was found that powder concentration of 100 mg/l is critical to species of the family *Gammaridae*. The individuals may be about 12 hours in this water without lethal consequences (Fig. 2).

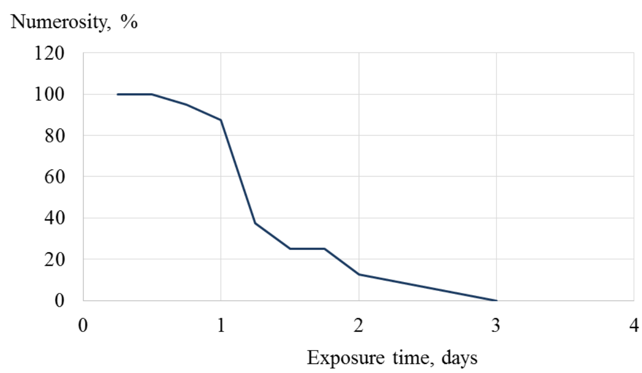

Fig. 2. The number of amphipods in the water at the powder concentration of 100 mg/l, %

Note that two scenarios for this situation were investigated. First, when the water in the vessel has not changed and the negative process was limited only by time, that is stagnant conditions (calm and lack of flow) were actually simulated. In fact, Fig. 2 represents the following conditions. The second – after 12 hours some of the crustaceans were removed from the experimental solution and placed in clean water. In this case, there was a five-seven days activity and then they also died.

Thus, it can be concluded that, upon condition of receipt of uncontaminated water from the upper reaches of the river (which will result in dilution of contaminant), the availability of nutrients in the water and the lack of reproductive disorders due to short-term action of negative factors, individuals of amphipods can function normally for some time (the processes of mating and birth of crustaceans, according to the observations in the samples, took about 7–10 days).

On the basis of logical analysis, the quality form of two-factor investigated functional dependence was determined (2):

$$k_i = f(C, \tau), \qquad (2)$$

where, k_i – mortality rate of living organisms of a certain species, measured in % or unit fractions; C – concentration of pollutant, mg/l; τ – time of negative factors action, days.

Based on the three-time repetition of the experiment with each defined model concentration of powder, research data were averaged and systematized in tabular form (Table 2).

Table 2

The data of experimental investigation

№	C, mg/l	k_i, %	τ, days
1	100	0	0.25
2	100	0	0.5
3	100	5	0.75
4	100	12.5	1
5	100	62.5	1.25
6	100	75	1.5
7	100	75	1.75
8	100	87.5	2
9	100	100	3
10	200	100	0.25
11	300	100	0.25
12	400	100	0.25
13	500	100	0.25
14	600	100	0.25
15	700	100	0.25
16	800	100	0.25
17	900	100	0.25
18	1000	100	0.25

On its basis, a three-dimensional model of ecological characteristics of the hydrocole (Fig. 3) was constructed in MS Excel.

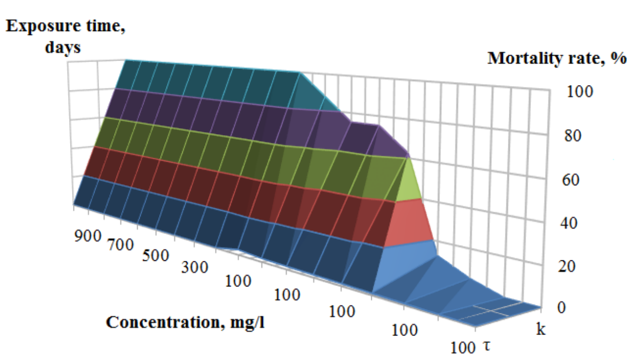

Fig. 3. The mortality rate of amphipod species depending on the amount of pollutant in the water and the duration of its action

Turning to the two-dimensional display (Fig. 2), we note that the previous works of the author [4] paid attention to the segment of the normal distribution curve, which is between the optimum zone and the zone of stress and death. This section of the environmental characteristics of an organism can be described by a linear function (Fig. 4).

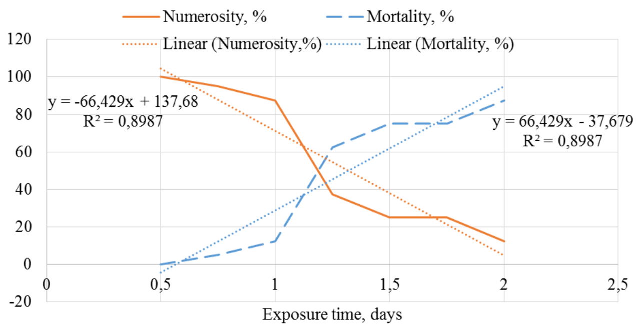

Fig. 4. The number and death rate of amphipods individuals at the detergent concentration of 100 mg/l for some time

The degree of proximity (R^2) of chosen approximation option – linear relationship – is about 0.9, which suggests a fairly high probability of getting of the expected result in a formalized dependence of mortality of the species on the effects of factors combination.

Another, perhaps the most important task of this study was to develop a mechanism of practical application of the results obtained.

The first option, which has a purely theoretical basis, is to place grown or caught test organisms in water samples and record the reaction of the body. However, because except amphipods in the estuarine part of the Southern Bug there were no other aquatic stenobiont organisms, this method has not been tested. In this case, it is not possible to determine how well the studied organisms are represented in their ecological niches through density or population size indicators.

Therefore, the assessment was made by the second option, which is to build the evaluation system based on the historical features of the aquatic ecosystem followed by a comparison of modern indexes of its condition.

According to the studies [31], the total number of species of benthos, which includes representatives of the family *Gammaridae*, after the regulation of the Dnieper, which certainly affected the Bug estuary, has not changed, but their relationship has undergone significant changes.

We know that amphipods are one of the most nutritious primary consumers in aquatic ecosystems. Thus, they play an important role in the formation of the biomass of young fish, especially migratory. However, synthesizing the results of studies [31, 36] we get a negative trend of populations of crustaceans along with the total capacity of the components of one level of the food chain (Fig. 5).

In 2008–2012, in the Bug estuary, the benthos biomass varied within 27.43–60.09 g/m^2.

Note also that due to increased salinity and trophicity of the Dnieper-Bug estuary, worsening of the gas conditions in the bottom layers of water (because of regulation of the flow of both rivers), the proportion of shellfish in the total benthos biomass increased and is about 90–95 % now. While the number of amphipods, together with the general indicators of the performance of benthos have been decreasing since 1967 (Fig. 6) (according to [31]).

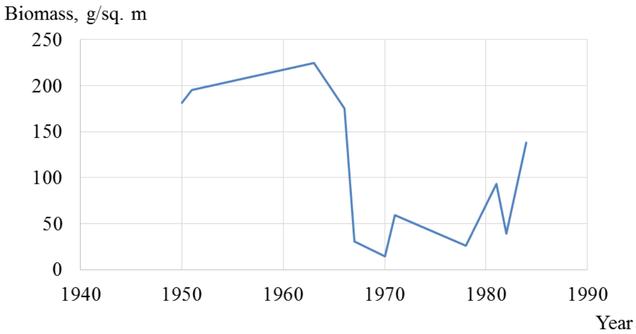

Fig. 5. Dynamics of the total biomass of benthos in the Bug estuary

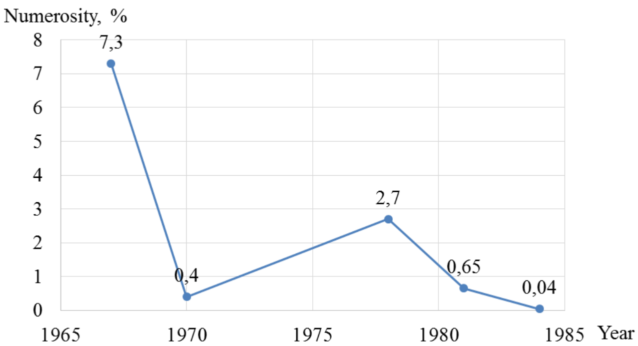

Fig. 6. Amphipods share in the total benthos of the Bug estuary

Because the test-organisms (amphipods) were caught directly from the reservoir, the ecological safety index of which is evaluated, the exploitation of environmental characteristics seems not possible in the absence of the value of "reference" (initial) number. Therefore, in this case, it is necessary to use historical data.

The oldest indicator of amphipods for the Bug estuary is of 1967 and makes up 2.21 g/m^2 (Fig. 6), while the total biomass of benthos – 30.48 g/m^2 (Fig. 5). In 2012 (latest available data), these indicators constitute 1.1 and 60 g/m^2, respectively. It should be noted that hydrobiological research on the most rivers of the Mykolaiv region are point, unsystematic and very incomplete. In particular, information about the zoobenthos of the Southern Bug estuary in a very general framework can only be found in the annual reports on the state of the natural environment. This greatly affects the quality and objectivity of decision-making.

After some simple calculations, according to the above actual data, we find the mortality rate k_{am} (3)

$$k_{am} = \frac{1,1}{2,1} = 0,497 \approx 0,5. \quad (3)$$

The next phase of the estimation algorithm has to have two ways: defining the safety index of the ecological system only by amphipods ("rough") or a comprehensive assessment of 5 groups of test organisms (by stenobionts).

Since stoneflies, mayflies, caddisflies and alderflies in the hydrocele samples from the river were not detected, we take: k_s=1, k_m=1, k_c=1 k_{al}=1 and k_{am}=0.5. The expression (1) with the following output data takes the next form:

$$ESI = \frac{1}{1+1+1+1+1+0,5} = 0,18.$$

Thus, we can talk about extreme pollution of water ecosystems of the Southern Bug by household wastewater. In addition, the siltation of river bottom has a significant effect, particularly on the individuals of the *Gammaridae* family, due to agricultural activities in the first floodplain and the lack of contour reclamation.

Objectivity of the proposed ecological system safety assessment method is confirmed by qualitative and quantitative depletion of fish fauna in the investigated natural water system (Fig. 7).

According to [31], in the 50ies of the twentieth century, this indicator was 20 thousand tons of fish. Today, due to several reasons, including the huge levels of the Dnieper and the Southern Bug flow regulation, the volume of fish capture varies within 2–4 ths. tons.

The intensification of the eutrophication process, siltation of riverbeds, change of the hydrological regime of rivers and other negative processes are the result of irrational and unbalanced nature management in the water ecosystem basin. Therefore, it makes sense to change approaches to management in the environmental system and to the control of influence on it.

Amplification, deletion or modification of one or more abiotic factors in an ecosystem necessarily affect the structure and quantitative indicators of biotic diversity. The method of biological indication that characterizes intensity and balance of energy flows in a natural system in any case be will more accurate because it reflects a significant effect of the complex of natural and artificial factors. The main objective in this case is to identify causal relationships between existing environmental problems and economic activities.

Indicative in terms of the negative impact of the river flow regulation by riverbed reservoirs are the results of the research [37]. Special attention in this work is focused on the fact that water is an important part (the deciding factor [38]) of sustainable social and economic development of territories and it is relevant at the time to develop methods for objective evaluation of water resources for the sustainable management of complex technoecological systems. Given the intensification of resource saving direction of improving industrial production, the idea is stated, on the example of the Dnieper river, about the irrelevance of functioning of the most existing reservoirs in the modern structure of the Ukrainian economy. In the context of these research findings, the authors' conclusion that water resources in Ukraine remains largely undervalued, which should stimulate research work in this direction deserves attention and support.

Another, no less important, element of the problem of ensuring natural systems ecological safety is safety management.

It is known that ecological safety is recognized as an integral part of human development, which in the best way takes into account the biological nature of human existence. As the need to review approaches to safety assessment of ecological systems is outlined and its current state is designed, it will be advisable to justify a mechanism to ensure that seems an important component in the strategic development planning.

An obligatory feature of any planning is clearly defined time limit, the amount of material and human resources, and the most importantly – the goal, which is expressed through a number or figure. The latter condition largely determines the structure of the first three components. Thus, it could be argued that the stop of deterioration and improvement of ecological systems are possible when the problem is clearly stated. For example, in 2014 ESI was estimated 0.2, while in 10 years it should be 0.5.

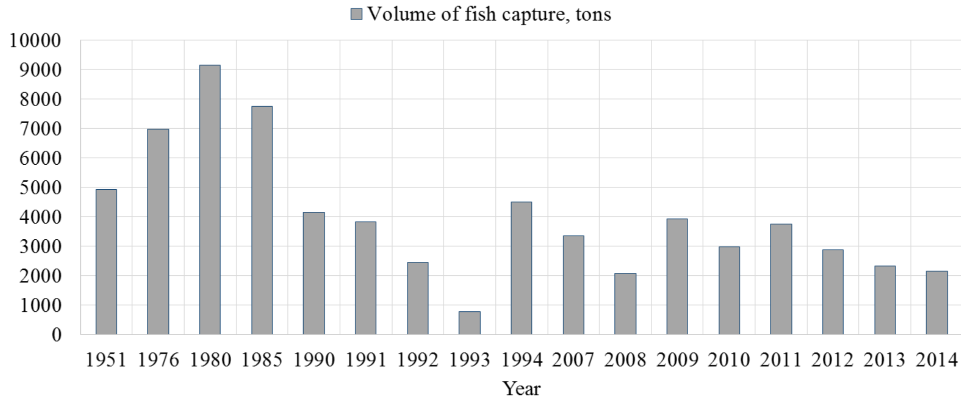

Fig. 7. Dynamics of fish capture in the Dnieper-Bug estuary

When we talk about sustainable development as a tool for building harmonious long-lasting relationships in the "man-nature" system, it is fair to assume that in such circumstances ESI has to be as close to 1 as possible. Fig. 8 presents the multiphase model of implementation of the ecological safety concept in the region or ecological policy. The name of any strategic document may be different, but the aim is one – to ensure ecological safety, which is a component of national security [39].

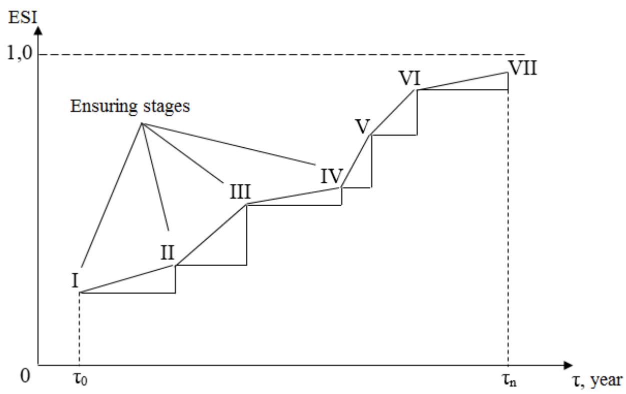

Fig. 8. Multiphase model of ensuring the ecological safety of natural systems (I–VII — ESI value in each particular year from τ_0 to τ_n)

Thus, the competent authority or expert council form the ESI final values at the end of some development period τ_n (or specifically in years) and a notional number of steps (six of them in the example (Fig. 8) – they are six, and I – initial (starting) value). The possibility of adjusting the number of steps is due to the need to quickly and situationally respond to unpredictable phenomena or processes that do not depend on the local community (e. g., war, transboundary pollution, etc.). Fig. 9 schematically presents such unpredictable situation and the algorithm of further actions.

Development planning as triangles explains is due to simple and functionally convenient structure of this figure. First, each side of it is well described by the equation of line. And secondly, the hypotenuse (AC) serves as the vector of development, which is planned; the base leg (BD) – the line between progress and regression, balanced and unbalanced development (vector B-3); DC leg – maneuvering area. And if the plan with the situation, described by the vector B-3 is understood (it is necessary to recover to its original state), perhaps it is useful to explain why in the case of vector B-1 it is necessary to go to the intended point C. This approach is explained by the fact that the growth of quantitative indicators is not always indicative of their quality (salary growth is leveled by against the backdrop of rising inflation, high rate of the ecosystem productivity can not always be taken for progress (agro-ecosystems, eutrophication)). In other words, with real quantitative increase or benefit, it is better to send the excess to other, lagging, areas or keep it.

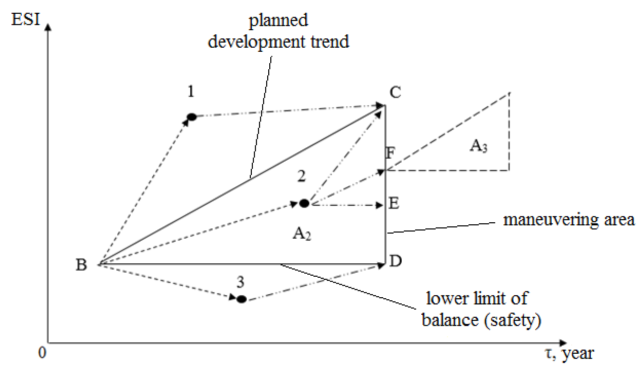

Fig. 9. Algorithm of natural system ecological safety management in a period of time

At point 2, depending on the expert solution, the direction of further development vector is formed. The movement downwards from the reached level should be seen as an imbalance and violation of the functional integrity of the investigated ecological system.

As to the issue of determining the weight of each of the three components of sustainable development, as opposed to the opinion about the crucial role of experts in this matter, it is solved quite simply. By assimilating the development of environmental, social and economic component to the straight line (vector), each equation will have one or two coefficients, which describes it. Knowing the current and planned values of sustainable development, it is easy, based on vector mathematics or through the matrix evaluation, to determine the equation of development of each component. So, by this way it is possible to minimize the share of subjective decisions at all stages of their adoption.

6. Discussion of research results and assessment of ecological safety index

The research is a continuation of previous works of the authors [4, 12] towards the development and justification of methods of assessment and ensuring of ecological safety of natural systems. When analyzing the results, it should be noted that the main reason of the low value of the calculated ecological safety index is unbalanced and unjustified environmental management system in the river basin. Today we can confidently talk about the disappearance of sturgeon fishing in the estuary of the Southern Bug River due to flow regulation by the Oleksandrivska hydroelectric power plant. Migration routes of commercial fish and significantly altered hydrological regime of the water object are violated. Leveling of the spring flood riverbed purges caused the disappearance of navigation on the river and the need for regular cleaning of the channel in the context of combatting siltation (Fig. 10).

Significant changes have occurred in the quality (about two dozen fish species disappeared from the river) and quantitative (50 % of the annual fish catch accounts for sprat) fish fauna composition, as confirmed by [31]. Any changes in the environment of the river biota functioning more or less affect it and the food and energy chains in which it is involved. Therefore, instead of taking off a clearly defined, scientifically grounded part of water or hydrobiological resources every year without harming the aquatic ecosystem, now it is necessary to invest millions of hryvnias in fish farming and dredging.

Thus, it is proved that the normative approach to the valuation of anthropogenic impact on aquatic ecosystems objectively does not reflect the real situation. Non-exceedance of the maximum allowable concentrations of pollutants in 2015 in the Southern Bug is not supported by the recovery of the ecosystem.

It should be noted also, what needs further focus. First, it is necessary to continue the research of the influence of detergent concentrations less than 100 mg/dm^3 in water on 5 groups of aquatic organisms. These experiments should be conducted in the early summer to find and capture mayflies, stoneflies, caddisflies and alderflies. This will increase the objectivity of the evaluation. By building ecological characteristics of the defined hydrobionts, it is needed to calculate the economic risk of river contamination by sewage. Losses from unsustainable river management can be presented in material or energy terms. Some authors'–calculations have already been carried out and highlighted in previous works.

Second, it is necessary to develop a classification of the calculated ESI values, which also requires additional field and laboratory studies.

Any water ecosystem is characterized by a certain set of stenobiont organisms and more or less constant flow of matter and energy. Therefore, the scope of the proposed method of ecological safety assessment is geographically wide enough and less expensive than determining the MAC. In addition, it is much easier to understand and use in practice, and more objective from the position of displaying the results, as shown in the paper.

In general, the studies will allow at the regional level (Mykolaiv region, Ukraine) to form the ways of stopping the deterioration of the river for stabilizing the level of ecological safety in the region and laying the foundations of its increase.

7. Conclusions

1. Deepening existing theoretical and practical research about the assessment of the ecological safety of natural systems and areas, the method of testing the natural environment of stenobiont organisms is justified for practical use and approved (by the example of the Southern Bug mouth aquatic ecosystem).

2. The index of the basin area ecological safety, which in the range of 0<ESI<1 takes the value of 0.18 is calculated. This suggests about the crisis ecological situation in the ecological system of the river and is confirmed by the graphic and analytical material, presented in the paper. In particular, the trophicity of the water system has increased significantly, the diversity of fish fauna has reduced qualitatively and quantitatively, the hydrological regime has also changed.

3. The main reason for the negative ecological effects in the basin, which significantly affect the welfare of the local population, seems the excessive regulation of the flow by artificial hydraulic reservoirs. They detaine water in the volume of 1.5 km^3, with an average many year's river flow of 2.6 km^3. Therefore, the primary objective should be an inventory of all the reservoirs and ponds in the basin, for the purpose of decommissioning functionally unusable ones.

4. The experimental work with further ESI_w calculations proves the failure of the regulatory evaluation concept of human impact on the environment to ensure the objectivity of evaluation.

5. The theoretical base with regard to the algorithm of ensuring (management) of natural and socio-natural systems ecological safety is also extended. The improved technique can also be used to assess the social and economic development component and for a generalized indicator of sustainable development.

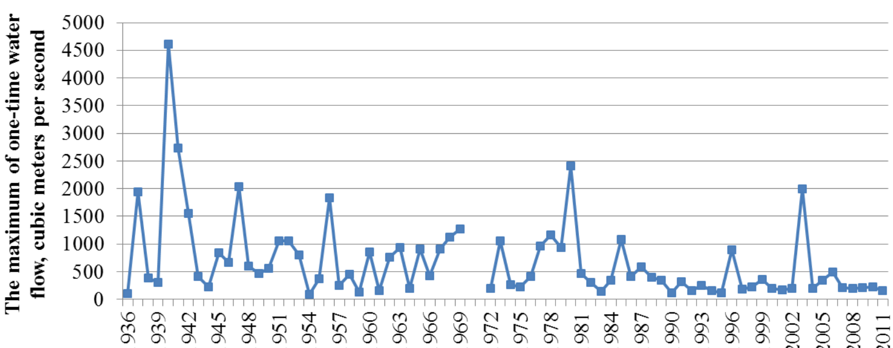

Fig. 10. Reducing the extremes value of daily water flow in the Southern Bug River

References

1. Statyuha, H. O. To issue of ecological safety quantitative evaluation at EIA [Text] / H. O. Statyuha, V. A. Sokolov, I. B. Abramov, T. V. Boiko, A. O. Abramova // Eastern-European journal of enterprise technologies. – 2010. – Vol. 6, Issue 6 (48). – P. 44–46. – Available at: http://journals.uran.ua/eejet/article/view/3347/3147

2. Cherkashyn, S. A. Biotesting: terminology, objectives, basic requirements and application in fisheries toxicology [Biotestirovanie: terminolohia, zadachi, osnovnye trebovania i primenenie v rybohoziaistvennoi toksikolohii] [Text] / S. A. Cherkashyn // Izvestia TINRO. – 2001. – Vol. 128, Issue 1-3. – P. 1020–1035. – Available at: http://cyberleninka.ru/article/n/biotestirovanie-terminologiya-zadachi-osnovnye-trebovaniya-i-primenenie-v-rybohozyaystvennoy-toksikologii
3. Akimova, T. A. Ecology [Ekolohia] [Text] / T. A. Akimova, V. V. Haskin. – Moscow: UNITI, 1999. – 455 p.
4. Bezsonov, Ye. M. Justification and formalization of approach to regional environmental safety evaluation [Text] / Ye. M. Bezsonov, V. I. Andreev // Eastern-European journal of enterprise technologies. – 2016. – Vol. 2, Issue 10 (80). – P. 9–18. doi: 10.15587/1729-4061.2016.64843
5. Bezsonov, Ye. M. Reorientation of ecological safety performance indicators [Pereorientatsia otsinochnyh pokaznykiv ekolohichnoi bezpeky] [Text] / Ye. M. Bezsonov // V-j Vseukrai'ns'kyj z'i'zd ekologiv z mizhnarodnoju uchastju (Ekologija/Ecology-2015). – Vinnycja: TOV «Nilan–LTD», 2015. – P. 33.
6. Dobrovolskyi, V. V. Dualism of human in the socioecological system [Dualism liudyny v sotsioekolohichnii systemi] [Text] / V. V. Dobrovolskyi // Naukovi pratsi: Naukovo-metodychnyi zhurnal. – 2004. – Vol. 39, Issue 26. – P. 11–17.
7. Dobrovolskyi, V. V. Fundamentals of the theory of ecological systems [Osnovy terii ekolohichnyh system] [Text]: textbook / V. V. Dobrovolskyi. – Kyiv: VD Profesional, 2006. – 272 p.
8. Holubets, M. A. Ecosystemology [Ekosystemolohia] [Text] / M. A. Holubets. – Lviv: Polli, 2000. – 316 p.
9. Vernadskyi, V. I. Living matter [Zhyvoe veshchestvo] [Text] / V. I. Vernadskyi. – Moscow: Nauka, 1978. – 358 p.
10. Ecosystems and Human Well-being: Biodiversity Synthesis. Millennium Ecosystem Assessment [Text]. – Washington, DC., 2005. – Available at: http://www.millenniumassessment.org/ru/Synthesis.html
11. Shuiskii, V. F. Laws of limiting freshwater macrozoobenthos by environmental factors [Zakonomernosti limitirovania presnovodnoho makrozoobentosa ekolohicheskimi faktorami] [Text]: avtoref. dis. ... d-ra biol. nauk / V. F. Shuiskii. – Sankt-Peterburg, 1997.
12. Bezsonov, Ye. M. The environmental component of sustainable development: study priorities and ways to ensure [Ekolohichna skladova staloho rozvytku: obgruntuvannia priorytetnosti ta shliahy zabezpechennia] [Text] / Ye. M. Bezsonov, V. I. Andreev // Visnyk Vinnytskoho politehnichnoho instytutu. – 2015. – Issue 6 (123). – P. 23–29.
13. Horbut, N. Zoobenthos of small rivers in conditions of oil pollution [Zoobentos malyh richok v umovah naftovoho zabrudnennia] [Text] / N. Horbut // Visnyk Prykarpats'kogo nacional'nogo universytetu imeni Vasylja Stefanyka. – 2007. – Issue VII-VIII. – P. 204–206. – Available at: http://www.nbuv.gov.ua/old_jrn/Chem_Biol/vpnu_biol/2007_7-8/7-79.pdf
14. Bezmaternyh, D. M. Zoobenthos as an indicator of the ecological status of aquatic ecosystems of Western Siberia: an analytical review [Zoobentos kak indicator ekolohicheskoho sostoiania vodnyh ekosistem Zapadnoi Sibiri: analiticheskii obzor] [Text] / D. M. Bezmaternyh. – Novosibirsk, 2007. – 87 p.
15. Maltby, L. Stress, shredders and streams: using gammarus energetics to assess water quality [Text] / L. Maltby; D. W. Sutcliffe (Ed.) // Water quality and stress indicators in marine and freshwater systems: linking levels of organisation. – Ambleside, UK, Freshwater Biological Association, 1994. – P. 98–110.
16. Maltby, L. Evaluation of theGammarus pulexin situ feeding assay as a biomonitor of water quality: Robustness, responsiveness, and relevance [Text] / L. Maltby, S. A. Clayton, R. M. Wood, N. McLoughlin // Environmental Toxicology and Chemistry. – 2002. – Vol. 21, Issue 2. – P. 361–368. doi: 10.1002/etc.5620210219
17. Gerhardt, A. Gammarus: Important Taxon in Freshwater and Marine Changing Environments [Text] / A. Gerhardt, M. Bloor, C. L. Mills // International Journal of Zoology. – 2011. – Vol. 2011. – P. 1–2. doi: 10.1155/2011/524276
18. Estimating environmental damage in freshwater [Text]. – The Nuffield Foundation, 2008. – Available at: http://www.nuffieldfoundation.org/sites/default/files/25_Estimatg_env_freshwater.pdf
19. Pascoe, D. Gammarus pulex (L.) feeding bioassay?Effects of parasitism [Text] / D. Pascoe, T. J. Kedwards, S. J. Blockwell, E. J. Taylor // Bulletin of Environmental Contamination and Toxicology. – 1995. – Vol. 55, Issue 4. doi: 10.1007/bf00196046
20. Ustarbekov, A. K. Qualitative and quantitative characterization of young fish feeding in the western part of the Middle Caspian [Kachestvennaia i kolichestvennaia harakteristika pitania molodi ryb v zapadnoi chasti Srednego Kaspia] [Text] / A. K. Ustarbekov, T. A. Mahomedov, Z. S. Kurbanova, Z. M. Kurbanov et. al. // IX Sezd Gydrobyologycheskogo obshhestva RAN. – Toliatti: IEVB RAN, 2006. – P. 209. – Available at: http://www.shuisky-vf.narod.ru/V2.pdf
21. Zadoenko, I. N. Results and prospects of acclimatization Baikal gammarids reservoirs in the USSR [Resultaty i perspektivy akklimatizatsyi baikalskih gammarid v vodoemah SSSR] [Text] / I. N. Zadoenko, O. A. Leis, V. F. Hrigoriev // Sbornik nauchnyh trudov. – 1985. – Issue 232. – Available at: http://www.reabic.net/publ/Zadoenko_etal_1985.pdf
22. USSR Commercial fish [Promyslovye ryby SSSR] [Text] / L. S. Berg, A. S. Bohdanov, N. I. Kozhyn, T. S. Rass (Eds.). – Moscow: Pishchepromizdat, 1949. – 793 p. – Available at: http://herba.msu.ru/shipunov/school/books/promysl_ryby_sssr1949_opis.pdf
23. Mazur, R. The application of the Lymnaea stagnalis embryo-test in the toxicity bioindication of surfactants in fresh waters [Text] / R. Mazur, A. Wagner, M. Zhou // Ecological Indicators. – 2013. – Vol. 30. – P. 190–195. doi: 10.1016/j.ecolind.2013.02.002
24. Favas, P. J. C. Accumulation of arsenic by aquatic plants in large-scale field conditions: Opportunities for phytoremediation and bioindication [Text] / P. J. C. Favas, J. Pratas, M. N. V. Prasad // Science of The Total Environment. – 2012. – Vol. 433. – P. 390–397. doi: 10.1016/j.scitotenv.2012.06.091

25. Kosior, G. Bioindication capacity of metal pollution of native and transplanted Pleurozium schreberi under various levels of pollution [Text] / G. Kosior, A. Samecka-Cymerman, K. Kolon, A. J. Kempers // Chemosphere. – 2010. – Vol. 81, Issue 3. – P. 321–326. doi: 10.1016/j.chemosphere.2010.07.029
26. Franzle, O. Complex bioindication and environmental stress assessment [Text] / O. Franzle // Ecological Indicators. – 2006. – Vol. 6, Issue 1. – P. 114–136. doi: 10.1016/j.ecolind.2005.08.015
27. Quantitative methods of ecology and hydrobiology (collection of scientific papers dedicated to the memory of A. I. Bakanov) [Text] / G. S. Rozenberg (Ed.). – Tolyatti: SamNC RAN, 2005. – 404 p.
28. Water quality assessment: a guide to the use of biota, sediments and water in environmental monitoring [Text] / D. Chapman (Ed.). – Great Britain, 1996. – 609 p. – Available at: http://eng.harran.edu.tr/moodle/moodledata/11/Dosyalar/Water_Quality_Assessments.pdf
29. Mayer, F. Manual of acute toxicity: interpretation and data base for 410 chemical and 66 species of freshwater animals [Text] / F. Mayer, M. R. Ellersieck // US Dep. Inter. Fish and Wildlife Serv. Resour. Publ. – 1986. – Available at: http://www.cerc.usgs.gov/pubs/center/pdfDocs/90506-intro.pdf
30. Shuiskii, V. F. Bioindication of water quality, the state of freshwater ecosystems and their anthropogenic changes [Bioindikatsia kachestva vodnoi sredy, sostoiania presnovodnyh ekosistem i ih antropohennyh izmenenii] [Text] / V. F. Shuiskii, T. V. Maksimova, D. S. Petrov // VII mezhdunar. konf. "Ekolohia i razvitie Severo-Zapada Rossii". – Sankt-Peterburg: Izd-vo MANEB, 2002.
31. Zhukinskii, V. N. Dnieper-Bug estuary ecosystem [Dneprovsko-Buhskaia estuarnaia ekosistema] [Text] / V. N. Zhukinskii, L. A. Zhuravleva, A. I. Ivanov, et. al.; Ju. P. Zajcev (Ed.); AN USSR/In-t gidrobiologii. – Kyiv: Naukova dumka, 1989. – 240 p.
32. Holodov, V. I. Planning of experiments in hydrobiological investigations [Planirovanie eksperimentov v hidrobiolohicheskih issledovaniah] [Text] / V. I. Holodov; V. N. Eremeev (Ed.); Institut biologii juzhnyh morej im. A. O. Kovalevskogo. – Sevastopol, 2014. – 182 p.
33. Sverguzova, S. V. Development of a method for purification of model solutions of synthetic surfactants [Razrabotka sposoba ochistki modelnyh rastvorov ot synteticheskih poverhnostno-aktivnyh veshchestv] [Text] / S. V. Sverguzova, Yu. N. Malahatka // Nauchno-tehnicheskij sbornik. – 2010. – Issue 93. – P. 162–166. – Available at: http://eprints.kname.edu.ua/16970/1/162-166_%D0%A1%D0%B2%D0%B5%D1%80%D0%B3%D1%83%D0%B7%D0%BE%D0%B2%D0%B0_%D0%A1%D0%92.pdf
34. SPAV [Electronic resource]. – Available at: http://www.moreprom.ru/article.php?id=39
35. Ostroumov, S. A. Biological effects of surfactants [Text] / S. A. Ostroumov. – CRC Press, 2006.
36. Report on the state of the environment in the Mykolaiv region for 2012 [Dopovid pro stan navkolyshnoho pryrodnoho seredovyshcha v Mykolaivskii oblasti za 2012 rik] [Electronic resource]. – Avaialble at: http://www.menr.gov.ua/index.php/dopovidi/regionalni/1124
37. Shapar, A. H. The impact of reservoirs on water resources state of Dnipro River basin [Vplyv vodoshovyshch na stan vodnyh resursiv baseinu r. Dnipro] [Text] / A. H. Shapar, O. O. Skripnik // Ekolohia i pryrodokorystuvannia. – 2013. – Issue 17. – P. 49–57. – Available at: http://nbuv.gov.ua/UJRN/ecolpr_2013_17_8
38. Dmytrieva, O. O. Ecological and social assessment of the implementation an ecologically safe wastewater in Odessa [Ekoloho-sotsialna otsinka vprovadzhennia bezpechnoho vodovidvedennia u m. Odesa] [Text] / O. O. Dmytrieva // Agrosvi. – 2008. – Issue 7. – P. 15–22.
39. Law of Ukraine «On National Security of Ukraine» [Zakon Ukrainy "Pro osnovy natsionalnoi bezpeky Ukrainy"] with amendments from 07.08.2015 [Text]. – Verhovna Rada Ukrai'ny, 2003. – № 964-IV. – Available at: http://zakon3.rada.gov.ua/laws/show/964-15