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DETERMINATION OF CAUSE-CONSEQUENTIAL CHANGES IN THE MECHANISM OF BIOTIC SELF-REGULATION OF WATER BODIES BY URBOECOSYSTEMS (ON THE EXAMPLE OF THE CITY OF KYIV, UKRAINE)

ABSTRACT. *Deterioration of the ecological condition of the surface waters of the land is due to the qualitative and quantitative depletion of the factors of their formation, which in some cases makes their use for economic purposes impossible. The intensity of pollution of individual components of the biosphere depends on the migration of pollutants, their transformation, destruction and accumulation. All obtained research results allow us to affirm the main provisions of the mechanism of biotic self-regulation of the water basin. Conceptually, this approach is an integrative trend of preserving the stability of the development of hydroecosystems due to the restoration of the ecological and functional inseparability of the unity of the water ecosystem as a mutually conditioned necessity for its further development. It is the environment-forming role of biota under the conditions of interrelationships of environmental and specific modifying factors with consistent adaptation.*

Keywords: *urban ecosystem, biotic self-regulation, water bodies, environmental safety, pollution, pollutants, technogenic flows, anthropogenic load*

Introduction. The most important component of the ecologically safe development of natural and socio-economic systems is such nature management, which involves the organization of the use of water resources, in which sustainable development is ensured and sufficient water resource potential is preserved for a long time. The 19th century was characterized by significant negative changes in the natural environment caused by the uncontrolled use of natural resources, the development of industry and transport, which led to an increase in water consumption and, at the same time, an increase in its pollution. This became especially noticeable during the last 50 years, when human influence on the planet's water cycle reached a global scale.

Deterioration of the ecological condition of the surface waters of the land is due to the qualitative and quantitative depletion of the factors of their formation, which in some cases makes their use for economic purposes impossible. Thus, the statistical characteristics of water drainage in Ukraine indicate that there is pollution of water basins of rivers due to irrational use of nature, the consequence of which is a violation of their environmentally safe development. At the same time, in recent decades, the opinion of leading environmental scientists has appeared that the problem can be solved thanks to the elucidation of the mechanism of biotic self-regulation and its use for predictive purposes regarding the characteristics of the level of ecological stability of the development of water basins of rivers. But these are still declarative principles, although they have a scientific basis thanks to the known role of biota in ensuring the sustainable development of natural systems. It is these questions that became the subject of dissertation research and will contribute to the scientific substantiation of acceptable eco-safe changes in the hydroecosystems of river basins, which will allow establishing the permissible limits of man-made load on water systems.

World forums (Rio de Janeiro, 1992; Johannesburg, 2002) have confirmed that the sustainable development of socio-economic systems is connected with the success of environmental protection activities. At the same time, at the current stage of the development of the biosphere, all its components are subject to significant technogenic influence [1-7]. The total mass of the modern human economy and products of the technosphere is 140 Gt/year annually (emission into the atmosphere – 35 Gt/year, discharge into water bodies – 15 Gt/year, placement on the surface of the earth – 90 Gt/year). Man-made pollutants (pollutants) belong to different classes of danger, in quantitative terms they amount to 250-300 kg for every inhabitant of the planet. Man-made load on the environment leads to pollution with toxic compounds: first, heavy metal ions that have been stored in natural systems for a long time; secondly, substances of synthetic origin (xenobiotics) that were not available to them before, etc. Biotic processes of their detoxification require a long time for their disinfection due to the lack of adaptive mechanisms of the biota.

Among the current measures related to the preservation of ecologically safe development of hydroecosystems of water basins of rivers, one of the key values is production and economic regulations [1], which limit the activity of one or another production to a certain amount in return waters (the content of harmful substances, the amount of suspended particles , biochemical oxygen consumption, active water reaction, concentration of acids and bases, etc.). The conditions for draining return water into water bodies are established taking into account possible mixing and dissolution, background water quality [2].

Materials and methods. In order to find out the changes in the cause-and-effect relationships between biotic, abiotic and anthropogenic factors during the transition of natural hydroecosystems to the state of natural-anthropogenic ones, we took into account the following methodological approaches to their research:

1) Establishment of scientific regularities of the development of water ecosystems taking into account the system-basin principle [6];

2) Carrying out an ecological assessment [7,8] of the state of hydroecosystems of the water basin;

3) Creation of an information control program using engineering and environmental indicators and their parameters;

4) Adjustment, on the example of water basin studies, of the requirements for discharge of return water into surface reservoirs.

The program of information control of the ecological state of the water basin is presented in fig. 1. At the same time, it should be noted that technical indicators characterize the effect of pollution sources in their interaction with water resources in the process of their use, economic indicators show their use, and ecological indicators show the state of water resources and their ability to self-renew.

The intensity of pollution of individual components of the biosphere depends on the migration of pollutants, their transformation, destruction and accumulation. It is known from the scientific literature that in man-made flows of pollutants, the key place is occupied by the environments that transport them (Fig. 2).

Heavy metals occupy a prominent place among environmental pollutants. The danger of contamination of natural systems with heavy metals is explained by the fact that they are eternal and do not destroy when using traditional technologies for their disinfection, but only pass from one form of existence to another, for example, they are included in the composition of salts, oxides, organometallic compounds, chelates, etc.

In the XX-XXI centuries. so-called priority ecotoxicants appeared within the biosphere [8] – the most toxic xenobiotics for natural systems, which are characterized by the ability to accumulate in trophic chains [9,10], ecotoxic stability in the natural environment. Among the indicators of toxicity for humans, the authors note: carcinogenicity, mutagenicity, reproductive and endocrine status of exposure, etc. Heavy metals, volatile phenols, synthetic surfactants, and petroleum products are among the priority xenobiotics found in the water basin [11].

Pollution of individual components of the biosphere depends on the migration of pollutants, their transformation, destruction and accumulation. According to the sources of scientific literature, it is known that in man-made pollutant flows, the environment that transports them (atmospheric air and water) plays a decisive role.

Heavy metals occupy a prominent place among environmental pollutants. The danger of contamination of water systems with heavy metals is explained by the fact that they are not destroyed when using traditional technologies for their disinfection, but only change from one form to another. Heavy metals are characterized by different toxic effects on living organisms: low - Cu, Mn, Fe, Zn, Ni, Sr, Rb, Sc; medium - Cr, Ag, Al; high - Sb, As, Ba, Se; very high - Be, Cd, Pb, Hg, Ti.

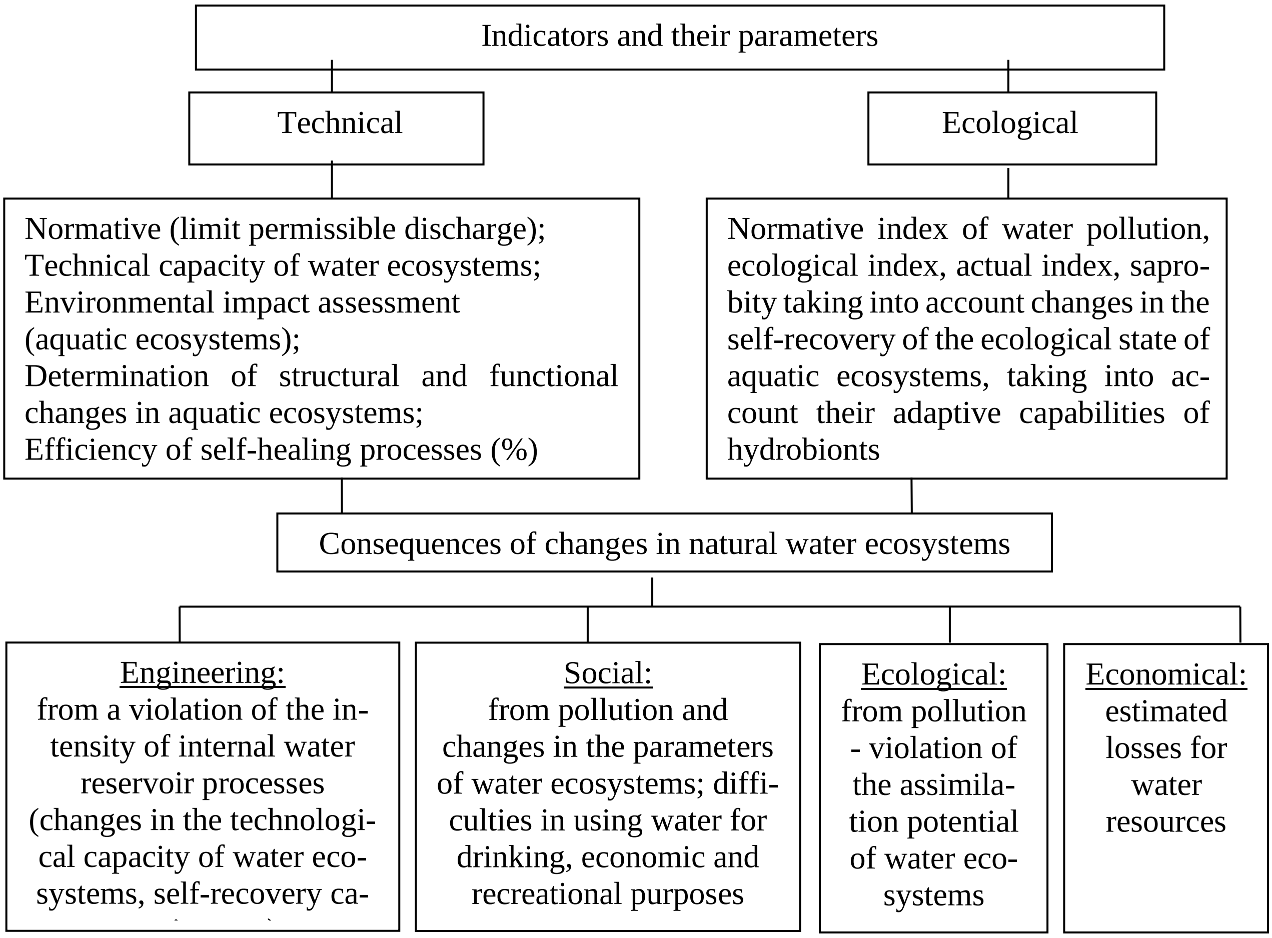

Figure 1. Program of information monitoring of the state of water ecosystems

The toxic properties of heavy metals have special effects:

- the toxicity of the element depends on the chemical form in the aqueous environment and in the living cell, for Hg it increases significantly in the series: $Hg_2Cl_2 < HgCl_2 < CH_3Hg < (CH_3)_2Hg$
- the content in the environment of elements with high biophilicity for living organisms has a positive value;
- when technogenicity is higher and biophilicity of an element is lower, it becomes more dangerous for biota;
- with an increase in the environment of elements with low biophilicity, the functions of organisms and the entire biological system are also disrupted;
- a certain concentration is necessary for the manifestation of a toxic effect;
- in the water environment, Cd, Pb, and Hg dominate as poisonous metals.

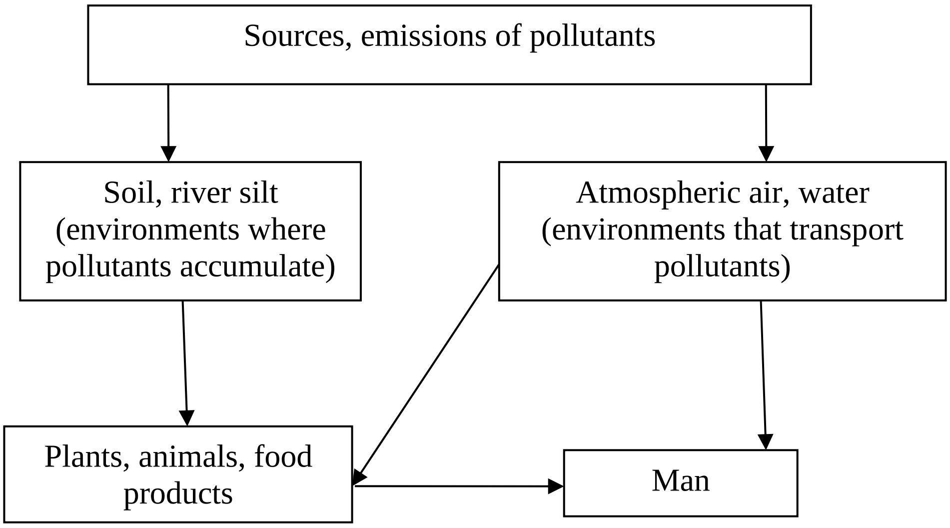

Figure 2. Technogenic flows of pollutants

Under the influence of substances of anthropogenic origin (specific modifying (anthropogenic) factors), the process of transformation of hydroecosystems takes place, which can schematically be represented as a sequence of certain stages [2, 11]:

- when the water technogenic load exceeds the maximum allowable concentrations for individual and total indicators (by 1.5-2.5 times), the chemical composition of water changes, which subsequently leads to changes in indicators that characterize the state of hydrobiocenoses [11], but the main ones remain structural parameters of self-organization of hydroecosystems;
- the structural reconstruction of hydroecosystems begins when the man-made load exceeds the maximum allowable concentrations by 3-5 times;
- at the stage of the appearance of degradation processes of water systems (when the maximum permissible concentration is exceeded by 6-7 times), the biological structural organization of hydroecosystems changes, the self-regulating ability decreases;
- at the stage of qualitative depletion of water systems (exceeding the multiplicity of maximum permissible concentrations in relation to the "background" state by 10 times), not only the self-regulating capacity, but also the assimilative capacity, etc., decreases.

Thus, as a result of the action of modifying factors, taking into account our data, the following processes occur [9]:

- when exceeding the maximum allowable concentration of pollutants at the first stage, the chemical composition of water systems changes as a result of the pollution of the water basin;
- the effect of ecotoxicants on the biota is manifested in two opposite trends: the harmful effect of pollutants and the adaptive reactions of hydrobionts to changes in their habitat [12-15];
- the level of intoxication of biota depends on such factors as the physical and chemical structure of pollutants, toxicity, concentration and time of their action, the ecological state of aquatic ecosystems at the time of action of xenobiotics, the intensity of intra-aquatic processes;
- violation of the dynamic equilibrium of hydroecosystems due to the action of specific modifying factors;
- violation of the structural and functional self-organization of water ecosystems in the process of their development;
- violation of the environmentally safe development of the water basin due to the advantages of degradation processes over the assimilative capacity of water ecosystems.

Hydrochemical monitoring data for each water body are grouped according to the season. This approach will make it possible to form homogeneous data series and calculate average values.

Under the influence of anthropogenic load, surface waters change their natural physico-chemical properties, therefore ecological assessment is the main condition that allows assessing the ecological state of water bodies, identifying the main water management and ecological problems, determining the main directions of nature use in river basins and substantiating the feasibility of recommendations regarding improvement of the ecological state of water bodies [16].

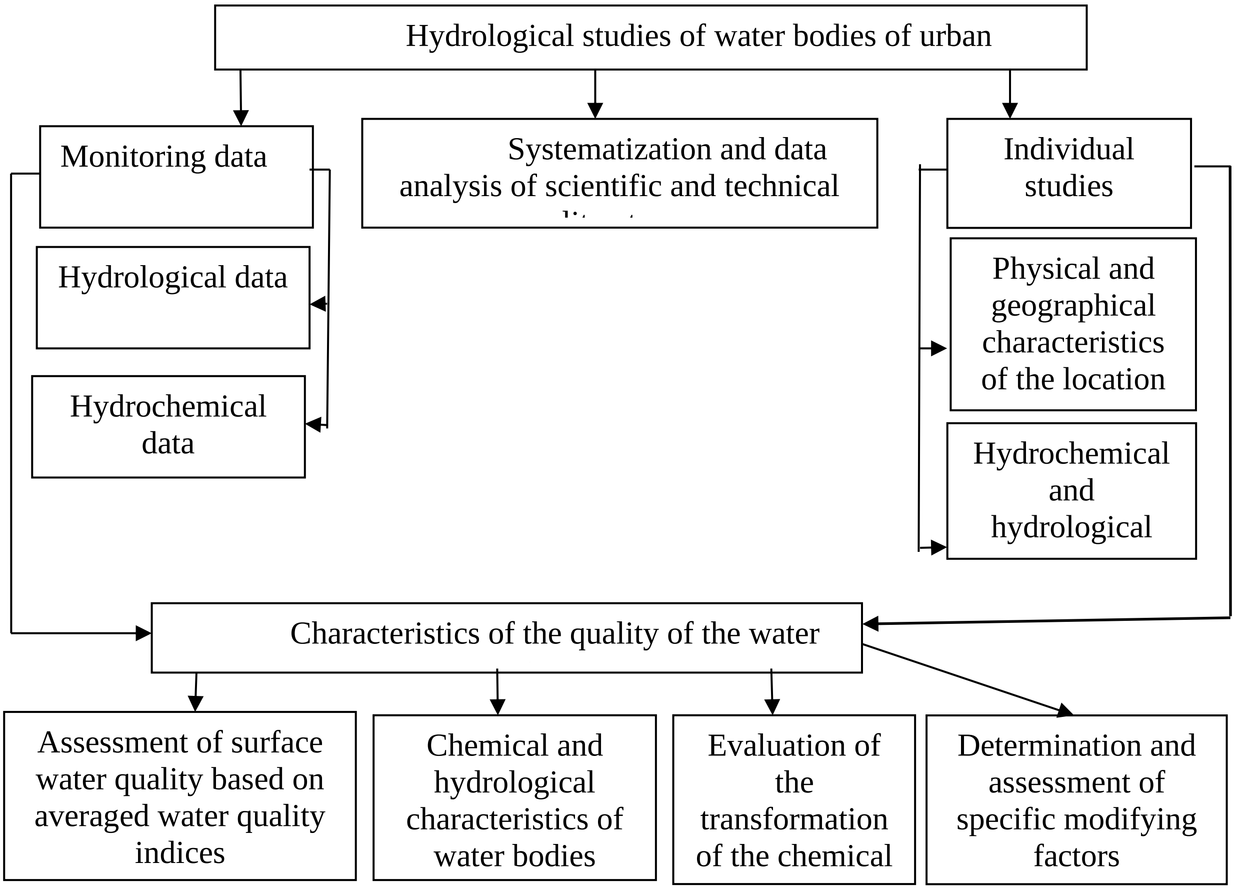

Figure 3. Algorithm of complex research of aquatic ecosystems

Anthropogenic exchange, unlike the biotic cycle, has an open nature: natural resources are at the input of the anthropogenic cycle, and industrial and economic wastes are at the output. The ecological imperfection of the anthropogenic exchange of material substances is that the coefficient of useful use of natural water resources is very small and therefore production waste changes the natural environment.

One of the conditions for achieving ecological safety of water ecosystems is the development and implementation of a complex of regional environmental standards, requirements, rules, as well as the creation of geo-informational systems to support management decision-making in economic practice.

In Ukraine, for the assessment and prevention of harmful anthropogenic influence on water bodies, a number of normative documents have been developed, which are based on a comparison of the concentrations of pollutants with normative indicators, based on these comparisons, a conclusion is drawn about the ecological state of water bodies [17-19] .

To determine the prerequisites for the action of modifying anthropogenic factors on changes in the mechanism of biotic self-regulation, several water bodies of the Dnipro River were selected, the development of which occurs under different conditions of man-made load (Table 1).

As shown by the results of the influence of modifying factors on the natural water ecosystems of the Dnipro, they turned into natural-anthropogenic systems with changed structural and functional properties [20] due to the occurrence of degradation processes and gradual qualitative depletion in them. We have shown that the development of the water systems of the Dnipro is determined by the following main trends:

- internal features of the development of water ecosystems, related to ecotoxicokinetic processes in water systems and its components, which characterize their assimilative and self-regulating ability;

- external features of the influence of anthropogenic factors on aquatic ecosystems, which are related to ecotoxicodynamic processes [6] and characterize the level of man-made load on the aquatic environment;

- the defining principle of water basin development is the functional interrelationships and interdependencies between ecological and anthropogenic factors;

- the stable state of aquatic ecosystems depends on the ratio of biotic potential and resistance of the abiotic environment, which act in opposite directions.

At the same time, it should be stated that ecosystem evolution is associated with the constant action of modifying factors, with negative changes in the environment-forming function of biota (Table 1), when the ability of hydrobiocenoses to maintain the stability of the functioning of the water basin deteriorates (Tables 2, 3) on the border of the marginal ecological containers

Table 1 - Generalized complex hydrochemical indicators of state assessment

Calculated hydraulic reservoirs	Water pollution index	Classes of pollution of the water system	Water quality indices				Technical capacity index	Intensity index of intrareservoir processes	Self-cleaning coefficient		
			Index of pollution by components of the salt composition (I_1)	Ecological and sanitary index (I_2)	Index of specific indicators of toxic action (I_3)	Ecological index (I_e)			Low (0-0,35)	Average (0,36-0,70)	High (0,71-1,0)
The city of Kyiv	1,65	polluted	1,33	3,44	3,67	2,81	0,2	0,36	18,51	70,44	11,05

Regarding the changes in biological and physiological features that ensure the ecological functions of hydrobiocenoses in aquatic ecosystems, which occur in the direction of improving the chances of their survival due to the mechanism of metabolic adaptations in hydrobionts. Given this course of development of aquatic ecosystems, we found that in the process of forming adaptive mechanisms in the biota, it is not so much the preservation of the constancy of their composition that is important, but rather the constancy of their functions.

First of all, the cause-and-effect changes in the relationships between environmental and anthropogenic factors were clarified and it was shown that in the conditions of the SMF action and in the process of formation of the biota mechanism of adaptation to them, functional dependence of hydrobionts regarding assimilative and self-regulating functions is preserved.

In order to exclude the parallel (combined) influence of the abiotic environment, we chose an object located in different physical and geographical zones (Carpathians, Prykarpattia, plain territory) - the Prut water basin. Analyzed and systematized environmental monitoring data (hydrological, hydrochemical, hydrobiological data) over the past 10 years for 3 reservoirs and obtained the following results: abiotic factors practically do not affect changes in relationships and their functional dependence between environmental and anthropogenic factors. The method of identifying the self-healing capacity under the conditions of the effect of modifying factors on the Prut water basin using bioindicators has been patented and a patent for a useful model has been obtained [21].

Table 2 - Generalized hydrobiological indicators of water basin condition assessment

Calculated hydraulic reservoirs	Saprobity index	The number of the main groups of biota (10^3 cells/ml)/biomass, mg/dm^3	Number of species in the group	The number of saprophytic bacteria, $cells/dm^3$	Index of changes in the structural self-organization of aquatic ecosystems	Shannon index by biomass
The city of Kyiv	0,15	0,678/1,072	12	hundreds-thousands	0,38	6,97

In addition, it should be noted that preservation of self-regulatory ability is not possible without preservation of assimilative ability. Thus, the main functional properties related to the preservation of the mechanism of biotic self-regulation are not disturbed. In the future, similar studies were carried out for aquatic ecosystems (Table 3) and similar results were confirmed. The method of identifying the self-recovery ability of a water basin is a complex method, which uses total indicators (biological and chemical oxygen consumption), indicator indicators (saprobability index, taking into account the self-cleaning coefficient, etc.).

Effectiveness of self-healing ability ($E_{еф}$) is determined by the formula [21]:

$$E_{еф} = \sum_{i-1}^{n} N_{кр} \cdot К_{ст} \cdot I_{с} \quad (1)$$

where: $N_{кр}$ - the multiplicity of the excess of chemical oxygen consumption and biological oxygen consumption in relation to the maximum permissible concentration; $К_{ст}$ - coefficient of resistance to anthropogenic load; $I_{с}$ - modified saprobability index.

Taking into account the fact that the development of aquatic ecosystems takes place in dynamic conditions and changes in time and space, we found out the functional and structural changes of aquatic ecosystems under the influence of modifying factors (Fig. 4).

Data analysis of fig. 4 allows us to state the fact that the mechanism of readaptive reconstruction of biota (hydrobiocenoses) characterizes the role of the mechanism of biotic self-regulation of natural-anthropogenic ecosystems at different functional levels of the development of aquatic ecosystems. And quantitative indicators (P) characterize the environmentally safe development of aquatic ecosystems, taking into account the self-regulating ability of aquatic ecosystems.

All the results obtained in relation to the research allow us to confirm the basic provisions of the mechanism of biotic self-regulation of the water basin. Conceptually, this approach is an integrative trend of preserving the stability of the development of hydroecosystems due to the restoration of the ecological and functional inseparability of the unity of the water basin as a mutually determined necessity for its further development. It is the environment-forming role of biota under the conditions of interrelationships of environmental and modifying factors with successive adaptation (a zone of aquatic ecosystems with practically intact structural and functional features of their development, an area above the city where water is taken for centralized water supply - 1 km above the city) reconstruction of hydrobiocenoses, which ensures the stability of their functions.

Table 3 - Generalized parameters and their indicators, which characterize the level of stability of the development of hydroecosystems

Calculated water reservoirs	Man-made load on hydrobiocenoses (according to the Shannon index) taken into account			Factors of formation of the mechanism of biotic self-regulation of aquatic ecosystems					Characteristics of the state of water ecosystems	Modified saprobity index	Coefficient of self-recovery ability of water ecosystems	Ability to self-clean,%
	index changes saprobity	changes in the technical capacity index	changes in the index of structural self-organization	Sustainability of the development of aquatic ecosystems (U_E)	Dynamic equilibrium of aquatic ecosystems (S_E)	Vitality water ecosystems (R_E)	Optimal level self-organization of water ecosystems (C_E)	Safe ecological development of water ecosystems (P_E)				
The city of Kyiv	0,15	0,2	0,258	2,8	0,71	8	0,11–0,24	0,8	The intensity of technogenic influence is less than the adaptive capabilities of aquatic ecosystems; high resistance to man-made load	0,35-1,0	0,71-1,0	4,2

This conclusion is consistent with the Le-Chatalier-Brown law, when under the influence of modifying factors, the dynamic balance in aquatic ecosystems shifts to the zone of the least man-made load, which allows for the formation of an adaptive (readaptive) mechanism in the biota, as a result of which the mechanism of biotic regulation of the water basin is preserved .

All obtained research results allow us to state the following. It is known that river basins, the water of which is used for centralized water supply, in the catchment area of which water ecosystems are preserved, practically, not anthropogenically disturbed (above the city), where due to the action of the mechanism of biotic co-regulation, adaptation of the biota to low concentrations of pollutants occurs, which allows to preserve the local their ecostabilizing role for hydroecosystems [22]. Equilibrium-dynamic status of water basin systems, at different levels of spatio-temporal structural self-organization, which water ecosystems provide for water basin conditions for their environmentally safe development.

Thanks to this parameter, it can be concluded that biotic self-regulation provides potentially relatively dangerous conditions for the energetic (thermodynamic) and trophic status (assimilative capacity) of aquatic ecosystems. In view of this, the processes of formation and dynamics of the structure of hydrobiocenoses change significantly.

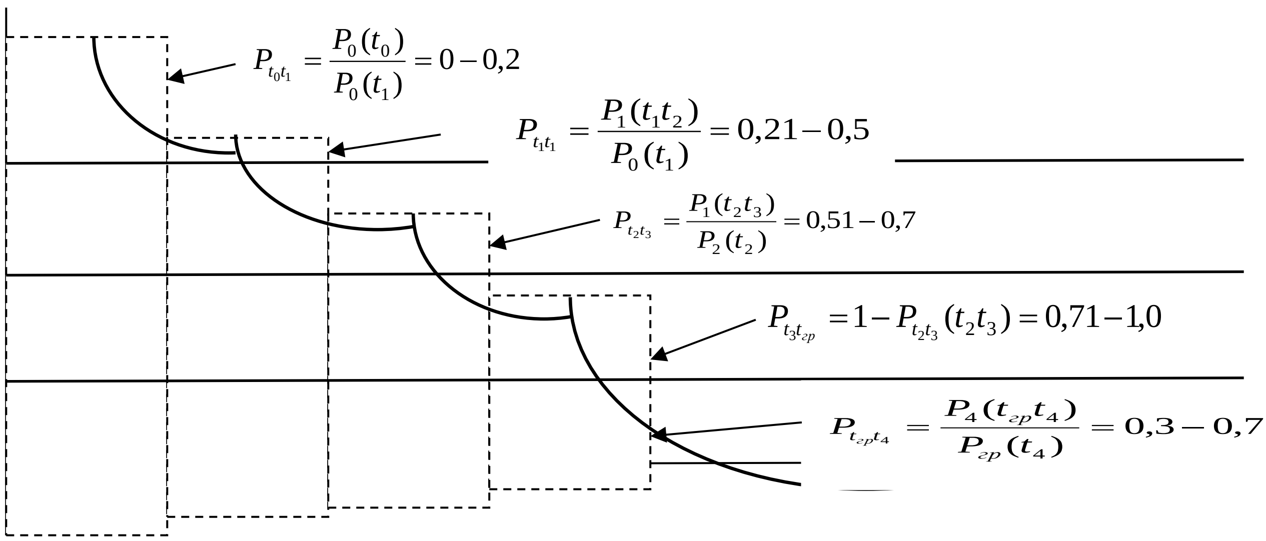

Figure 4. Scheme of functional transitions in the development of aquatic ecosystems by stages of anthropogenic changes:

I – - the zone of the initial (background) state of water ecosystems; II – the zone of appearance of moderate local changes in the development of aquatic ecosystems; III – the zone of powerful anthropogenic changes within the maximum effect of modifying factors; IV - the zone of restoration of the self-regulating ability of water ecosystems

Concentrations of pollutant substances of anthropogenic origin during their impact on biota are related to each other by a simple relationship (Hubber's equation): small concentrations of pollutants over a long time ultimately affect the stability of aquatic ecosystems in the same way as large concentrations over a short time. In addition, we have shown that the final result of biota intoxication depends on the combination of natural and anthropogenic factors that affect the change in the abiotic environment and lead to changes in physicochemical factors according to the following parameters: dissolved oxygen content, salt composition, pH, temperature, etc. One of the manifestations of such changes, for example, the water temperature activates, and when it increases, on the contrary, the enzymatic activity of the biota is suppressed, which is associated with the provision of bioenergetic processes in hydrobionts, and oxygen deficiency develops especially acutely against the background of intoxication.

The salt composition also significantly affects the level of toxicity of specific pollutants (Table 1). In connection with this, functional transitions (Fig. 1), which are associated with changes in environmental environmental factors in areas from, practically, the background state of aquatic ecosystems through water flow zones with varying degrees of man-made transformation and to areas characterized by a moderate degree pollution. The fact that the assimilative and self-regulating capacity in relatively "clean" sections of the water flow is within the ecological capacity of water ecosystems, it can be noted that the mechanism of biotic self-regulation is not disturbed (Fig. 3). This is possible due to functional relationships between individual organisms of hydrobiocenoses and, in general, between biotic and abiotic factors. It is precisely to assess the consistency of interrelationships of factors that there is such a concept as "ecological capacity of ecosystems" - one of the components of biotic regulation. Under such conditions, a common type of relationship in aquatic ecosystems that affects the mechanism of biotic self-regulation is symbiosis, in which hydrobiont organisms better adapt to the environmental conditions of aquatic ecosystems.

Conditional possibilities of the transition of aquatic ecosystems from one state to another depend (Fig. 3) on structural and functional changes in aquatic ecosystems that change the ecological situation in them [23]:

$P_o \to P_{t_o t_1}$ - the transition of aquatic ecosystems from one state to another without significant anthropogenic changes in them; dynamic balance is not disturbed;

$P_1 \to P_{t_1 t_2}$ - the transition of aquatic ecosystems to a state characterized by minor anthropogenic changes - Δ g; conditionally balanced state;

$P_2 \to P_{t_2 t_3}$ - the transition of aquatic ecosystems from the initial anthropogenic changes - Δe_1 in a state with the level of anthropogenic changes, respectively, of natural and anthropogenic ecosystems;

Δe_2 ($\Delta e_2 > \Delta e_1$) – local disturbance of dynamic equilibrium;

$P_3 \to P_{t_3 t_{гр}}$ - the transition of aquatic ecosystems to a limit state on the verge of breaking the ecological capacity; complete violation of dynamic balance.

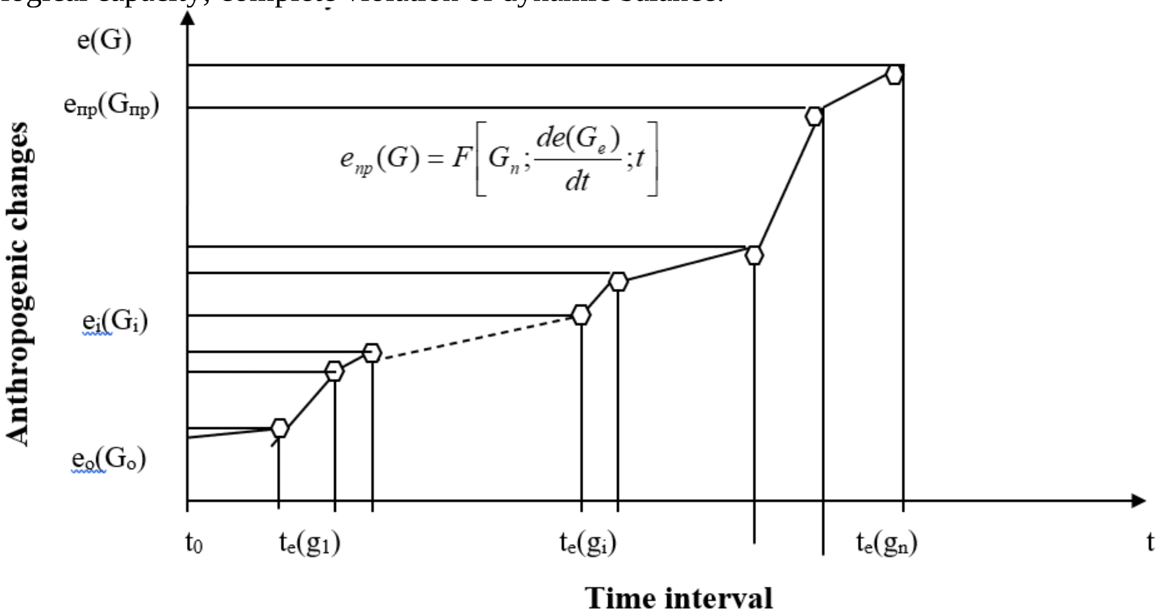

Figure 5. The process of accumulation of anthropogenic changes in aquatic ecosystems

We have proposed another stage of the development of aquatic ecosystems, which is characterized by the process of partial self-regeneration, namely: $P_4 \to P_{t_{гр} t_4}$ - restoration of dynamic balance.

The main toxicokinetic dependencies include the accumulation of ecotoxicity in biota with subsequent biotransformation (Fig. 5). In fig. 5 shows a geometric interpretation of the influence of modifying factors in different zones of the river's water flow. The real progress and development of natural-anthropogenic water systems is accompanied by the natural accumulation of pollutants (g) and anthropogenic changes in hydrobiocenoses (biota) or properties of water ecosystems (e) under the influence of ecotoxicodynamic factors.

Therefore, the mechanism of formation of water ecosystems does not cause contradictions in the scheme of accumulation of man-made changes, namely:

$$e(G_e) = e(g_1) + e(g_2) + ... + e(g_i) + e(g_n) \quad (2)$$

where: $e(G_e)$ - each time interval Δt correspond to an increase in anthropogenic changes in aquatic ecosystems (Fig. 5); g_1, g_2, g_i, g_n - local anthropogenic changes (which are random variables).

As a result of the interaction of environmental and anthropogenic factors, the transition from the initial stage of development, through the intermediate, to the limit, which is characterized by a critical level of accumulation of anthropogenic changes, namely:

$$t_{np} = \sum_{i=1}^{n} t_{e(g_i)} = t_{e(g_1)} + t_{e(g_2)} + ... + t_{e(g_n)} \quad (3)$$

That is, the physical content of the ecological security of the state consists of a sequential summation of the time of transition of systems from one stage to the next and is decided on the basis of the product of probabilities. The probability of an ecologically balanced state of aquatic ecosystems with the accumulation of anthropogenic changes in it is determined $P_{G_\Sigma}(t)$, and the probability of maintaining a dynamic equilibrium state from t=t_0 over the studied periods (hydraulic reservoirs) to t – through P(t), then the probability of accumulation of anthropogenic changes in water bodies [23] $\sum_{i=1}^{n} g_i$ is equal to:

$$P(\frac{G_\Sigma}{t}) = \frac{P_{G_\Sigma}(t)}{P(t)} \quad (4)$$

This course of determination allows us to establish the nature of the spread of anthropogenic changes in water ecosystems. That is, each time interval t corresponds to an increase in the accumulation of anthropogenic changes in aquatic ecosystems - and the probability that it will occur in the interval considered dt. In this way, a chain of mutual correspondence arises - $e(G_e)$ and the probability that it will occur in the interval considered dt. In this way, a chain of mutual correspondence arises dt→Δ e(G_e)→Δ P to the sustainable functioning of aquatic ecosystems and is characterized by the following equations:

$$\left.\begin{array}{l} \Delta P = P(t+dt) - P(t) \\ \Delta e(G_\Sigma) = e(t = dt) - e(t) \\ \Delta G(\sum_{i=1}^{n} g_1) = G(t+\Delta t) - G(t) \end{array}\right\} \quad (5)$$

The general form of equation (1) has the following form in relation to the ecological stability of the state of aquatic ecosystems:

$$\Delta P = -\mu_e \Delta e(t) \quad (6)$$

where: μ_e - coefficient that depends on the intensity of accumulation of anthropogenic changes in water ecosystems $\left[\mu_e = f(\frac{de(G_e)}{dt})\right]$.

Conclusions. Thus, the obtained research results allow us to adequately and reliably assess the role of the mechanism of biotic regulation of the water basin, taking into account the fact that we took into account the established cause-and-effect changes in the assimilative and self-recovery abilities and biotic self-organization of the water basin over a long-term period, taking into account the ecological approach and basin principle.

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