

Досліджено основний параметр функціонування гідроекосистем – екологічну ємність. Параметр є ефективним показником порушення структурно-функціональних змін техногенно трансформованого водного об'єкту. Застосована адаптована концептуальна модель системи індикаторів: “Дії – Стану – Наслідків”.

Відповідно до розробленої класифікації системи індикаторів, баланс екологічної ємності гідроекосистеми виступає частиною інтегрального показника стану водної екосистеми, як наслідок дії екзогенних факторів антропогенного походження. Завдяки застосуванню інтегральних систем індикаторів стало можливим надати не лише якісну, а й кількісну характеристику екологічної ємності.

В якості об'єкта досліджень обрано гирлову ділянку середньої рівнинної річки, яка виступає найбільш репрезентативною її складовою, та віддзеркалює наслідки антропогенного впливу які відбуваються в басейні річки. Враховуючи ієрархічність рівнів розвитку водних систем, дослідження стану середніх річок на локальному рівні дозволить розробити водоохоронні заходи, які сприятимуть покращенню якості великих річок. Розроблена методика може бути успішно адаптована для інших техногенно змінених річок рівнинних територій.

Результати проведених математичних розрахунків представлені у вигляді графіків залежності екологічної ємності та техноємності від численних параметрів функціонування гідроекосистеми. Показано динаміку змін цих параметрів за 2009–2017 роки. Результати дослідження свідчать, що біота адаптувалася до певного рівня техногенного забруднення і в період 2012–2016 року екологічна ємність була стабільною (27–37), що є оптимальними умовами існування гідроекосистеми. Узагальнена оцінка змін за весь досліджуваний період дає підстави стверджувати, що відбулася втрата екологічної ємності (знижується до 13,3) внаслідок понаднормативного техногенного впливу на річкову гідроекосистему, і це створює передумови для формування техноємності. Як наслідок, фіксується зниження рівня залишкового екологічного резерву, необхідного для відновлення техногенно зміненої гідроекосистеми річки

**Ключові слова:** екологічна ємність, екологічний резерв, техногенно змінена водна екосистема, екологічні індекси

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# DEVELOPMENT OF A PROCEDURE FOR DETERMINING THE BASIC PARAMETER OF AQUATIC ECOSYSTEMS FUNCTIONING – ENVIRONMENTAL CAPACITY

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## 1. Introduction

Excessive anthropogenic impact on aquatic ecosystems violates their stable functioning. One of the main causes of river degradation is technogenic conditionality of development as a result of influence of urbanized areas. Because of anthropogenic impact, many parameters of water medium in natural aquatic ecosystems have changed which has led to destruction of homeostasis and biogeochemical cycles, loss of environmental capacity of aquatic ecosystem and other changes.

Assessment of water quality based on hydro-chemical parameters cannot be sufficient for ecological characterization of aquatic ecosystems. Studies aimed at development of ecological indicators which would make it possible to obtain a generalized

quantitative and qualitative estimate of ecological state of water ecosystems of rivers should be considered urgent.

It is important to note that the problem of stable functioning of aquatic ecosystems is characteristic of virtually all European river basins. Despite EU laws and numerous directives, only 40 % of surface water bodies surveyed by the European Environment Agency (EEA) correspond just to “good” ecological status [1].

## 2. Literature review and problem statement

The problem of stability, ecosystem homeostasis, is central problem of present-day ecology which, unlike the “old

ecology”, focuses on detecting hidden interrelations based on establishment of general laws [2]. Stability of aquatic ecosystems is associated with an ability to withstand changes caused by exogenous effects and return to the original state while maintaining structure and functional characteristics. Contradictions arise when it turns out that influence of some factors leads to minor changes in the structure and functioning of the ecosystem and its biocenoses. At the same time, other factors cause significant violation of interconnections that have already developed in the ecosystem and now suffer destruction of their equilibrium [3].

That is why two types of stability are distinguished in ecosystems [4]: elastic stability (rapid return of the system to its initial state) and resistance (ability to avoid changes). Stability of the ecosystem should not be considered from the standpoint of stability of mechanical systems as it is typical for ecosystems to have several equilibrium states. After stressful effects, they often return not to the lost state of equilibrium but to a new state in which the initial structure was subjected to certain violations but did not lose its stability [4]. In this regard, a question arises about obtaining a quantitative estimate of the span and limits of possible pressure of technogenic factors that can affect stability of the aquatic ecosystem under study. That is why the authors refer to the notion of environmental capacity of ecosystems.

The notion of environmental capacity is derived from the notion of “carrying capacity” which was widely used in numerous studies of various scientific fields from the end of the nineteenth century [5]. At the current stage of scientific studies, the notion of capacity has become quite complex going beyond definition of the quantity of living beings in a certain space.

Simultaneous rapid growth of anthropogenic impact on the state of aquatic ecosystems has led to the use of the notion of environmental capacity of aquatic ecosystems which arose from the notion of maximum load on environment [6, 7]. A comprehensive approach to assessing environmental capacity of the Wun district in the Thai Lake basin was proposed in [8]. Large volumes of various data were used to assess the basin state: the MODIS model, images of NDVI series, geoinformation systems and technologies, aquatic network maps, population statistics and economic indicators. Indicators characterizing population density, economic growth, water consumption and environmental load were also indispensable in this estimation. In this case, the environmental capacity describes importance of critical factors in relation to the progress of human activity. Calculations and forecasts of the upper limit of population and economic growth for normal functioning of the area under study were made in [8]. This approach to assessment of the environmental capacity is not effective for application to Ukrainian water basins as there are no standardized procedures and corresponding databases that would involve all indicators needed for calculations. To do this, it is necessary to reform the national monitoring system. In this case, the notion of environmental capacity is used more to account for economic losses from reducing water resources and not for their qualitative control with subsequent restoration.

Environmental capacity of water resources for Liaoning province with the use of a system of indicators was determined in [9]. Such system makes it possible to fully reflect state of the city’s socio-economic and ecological environment and water resources and ensure coordination between them. On the example of the Liaoning province, the system

of indicators can reflect basic situation of regional environmental capacity of aquatic ecosystems which is the basis for finding dominating factors of influence on the aquatic ecosystem. However, the study was focused mainly on quality of water for the water supply system but assessment of environmental indicators to maintain dynamic equilibrium of aquatic ecosystems was ignored [9]. Self-purifying ability of aquatic ecosystems was not taken into account in similar studies and an aquatic ecosystem was generally considered as a water body, that is, as an abiotic component without taking into account the biotic component.

A notion of matter-energy approach was taken in [10] as the basis for determination of environmental capacity of the ecosystem. This approach reflects the idea of ecosystem functioning as a process of transformation of energy and matter coming from environment and returning to it. However, dynamic and metabolic characteristics of the biotic component of the aquatic ecosystem were considered without taking into account aquatic and hydro-chemical characteristics of the basin.

Environmental capacity is the maximum amount of energy and matter that can be involved by the ecosystem within a cycle in a certain period of time without significant violation of its structure and functions. Essence of the environmental capacity consists in the basin’s ability to take a certain amount of load and transform it without apparent harm to the ecosystem. It is namely this ability that ensures absorption and neutralization of ecotoxicants of anthropogenic origin.

At the current stage of socio-economic development, intensity and nature of technogenic activity determine direction and basic parameters of functioning of the aquatic ecosystem. That is, they directly affect environmental capacity of the aquatic ecosystem thereby violating its self-organization. Under natural conditions, the ecosystem is in a steady dynamic state when arrival of biogenic components in the system is balanced by their outflow and transition to other ecosystems ensuring global cycles in the biosphere. Violation of balance of energy and matter in different ecosystems or their individual components aggravates loss of internal stability [4]. The process of transformation of natural aquatic ecosystems and the formation of techno-capacity commence under the effect of ecotoxicants of anthropogenic origin.

According to [11], such newly created ecosystems cannot be considered completely natural, so it is advisable to apply the notion of technogenic altered aquatic ecosystems of varying degrees of pollution. Altered aquatic ecosystems no longer have necessary internal stability and the mechanism of self-regulation is destroyed in them.

According to the European classifications [12], the technogenically altered aquatic ecosystems can be considered rivers with water corresponding to quality Classes III and IV. They are characterized by excessive content of pollutants in ecosystems [13], structural and functional violation of intra-basin processes [11] and hydrodynamic regime, bottom accumulation of ecotoxicants and their toxic effects on the components of aquatic ecosystems. Ecologically dangerous endo-risks are the final stage of formation of technogenically altered aquatic ecosystems regarding their development.

Difficulty of characterizing the technogenically altered aquatic ecosystems consists in distinction of the processes of matter and energy circulation in such aquatic ecosystems compared with those in intact ones. This is because of violation of ecological balance of the system towards degradation

of its structure and functions. This is caused by reduction of ecological reserve of the ecosystem (determined by the change of the environmental capacity balance) and metabolic regress (determined by effectiveness of the mechanism of plastic metabolism of chemical compounds) as well as worsening efficiency of intra-basin processes [11]. That is, the environmental capacity characterizes balanced functioning of the aquatic ecosystem [2], resistance to the effect of natural and anthropogenic factors and, consequently, the level of natural and technogenic safety of water bodies.

Analysis of published data indicates lack of information that would make it possible to characterize structural and functional violations of technogenically altered aquatic ecosystems. Thereupon, it became necessary to study fundamental changes of river ecosystems through the use of the indicator of environmental capacity. It is one of the fundamental notions that adequately reflect ability of individual ecosystems to adapt to technogenic loads. The environmental capacity should be considered as an environmental standard for surface waters based not on the maximum permissible concentration (MPC) but on the regulatory background concentrations of chemicals in the main components of the basin. i.e. water, bottom sediments, hydrobionts.

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### 3. The aim and objectives of the study

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The study objective was to develop a procedure for determining environmental capacity as the main parameter of functioning of aquatic ecosystems with the help of integral indicator systems.

To achieve the objective, the following tasks were set:

- develop information and methodological base of ecological indicators used in the control of structural and functional intra-basin process changes in technogenically altered aquatic ecosystems;
- calculate environmental capacity and determine level of ecological reserve for the object under study.

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### 4. Materials and methods used in creation of an information and methodological base of ecological indicators of control of the technogenically altered aquatic ecosystem

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#### 4.1. Methods for determining ecological state of aquatic ecosystems

Standardized procedures based on application of MPC of substances and the procedure of environmental control indicators have formed basis of the procedure for determining the main indicator of existence of aquatic ecosystems.

A river or its certain section is usually monitored at the first study stage. Water samples are taken and examined or available monitoring information is analyzed and systematized. On their basis, a retrospective database of ecological state of the studied aquatic ecosystem is formed. Indicators that significantly effect change of the environmental situation are determined, e.g. it may be toxic metals, radionuclides [13] or ammonium nitrogen compounds. Due to application of procedures based on regulation of MAC of harmful matters, water quality class is determined by the index of water pollution (IWP) and ecological state of river ecosystem, i. e. general ecological index ( $I_e$ ) is determined according to the procedure considered in [14].

The complex ecological index of state of river ecosystems,  $I_e$ , depending on the value of various parameters is determined as follows:

$$I_e = \frac{I_A + I_B + I_C}{n}, \quad (1)$$

where  $I_A$  is the maximum value of the hydro-chemical parameter which includes water mineralization, contents of sulfates and chlorides;  $I_B$  is the set of ecological and sanitary characteristics including content of suspended matter, chemical oxygen consumption (COC), biochemical oxygen consumption for 5 days (BOC<sub>5</sub>), dissolved oxygen, ammonium nitrogen, nitrate ammonium, nitrite ammonium, phosphates, phytoplankton biomass, saprophytic index; toxicological index,  $I_C$ , i. e., a set of specific characteristics of toxic and radiation action of copper, chromium, manganese, zinc, phenols, nickel, etc. Indices  $I_A$ ,  $I_B$ ,  $I_C$  are calculated by the formula:

$$I_x = \sum \frac{C_{i.act} / C_{i.opt}}{n}, \quad (2)$$

where  $C_{i.act}$  is the actual concentration of the  $i$ -th hydro-chemical or trophic-saprobiological factor;  $C_{i.opt}$  is the optimum concentration of the  $i$ -th hydro-chemical factor (or MAC).

The degree of water pollution in the body under study is characterized according to the generalized indicator of water pollution (IWP) which is equal to the arithmetic average:

$$IWP = \frac{1}{n} \sum_{i=1}^n \frac{C_i}{MAC}, \quad (3)$$

where  $C_i$  is concentration of the  $i$ -th normalized component, mg/dm<sup>3</sup>;  $MPC_i$  is the maximum permissible concentration of the  $i$ -th normalized component for the corresponding basin type, mg/dm<sup>3</sup>;  $n$  is the number of indicators used to calculate IWP.

These procedures do not provide a detailed characteristic of quantitative and qualitative assessment of violation of structure and functioning of a technogenically altered aquatic ecosystem, they just ascertain the fact of pollution and the system state worsening. However, it is impossible to provide a preliminary assessment of the aquatic ecosystem state and identify causes of its worsening without them. In the last decade, a shift in emphasis when assessing state of aquatic ecosystems towards assessment of the state of environment not as a resource but as a human and biota habitat was observed in the worldwide practice. The problem of quantitative and qualitative assessment of the state of technogenically altered aquatic ecosystems is closely linked with development of monitoring indicators [16] which allow one to trace step by step dynamics of changes in these ecosystems.

The Pressure-State-Response (PSR) model proposed by the Organization for Economic Cooperation and Development (OECD) and United Nations Environment Program (UNEP) was adapted [17]. The point is to apply a conceptual model of the system of environmental indicators divided into three groups: indicators of pressure, state and response.

Therefore, an information and methodological base of environmental indicators was developed following recommen-

dations of the OECD and UNEP [18]. It makes it possible to track changes in aquatic ecosystems using the ecosystem approach and the basin management principle. Taking into account the goal orientation and in accordance with peculiarities of development and functioning of technogenically altered aquatic ecosystems, indicators are divided into three groups:

- action indicators: estimation of influence of technogenic factors on the object under study: the index of technogenic effect, the index of plastic metabolism of chemical compounds, the general ecological index;
- state indicators: the state of environment subjected to anthropogenic action: the index of balance of the environmental capacity, the index of techno-capacity;
- response indicators: response of the aquatic ecosystem to violation of sustainable functioning: the criterion of biotic self-regulation of water, the index of ecological reserve.

To calculate the indicators, an optimal number of indicators was selected. It is difficult to arrange a large number of indicators in real time, analyze and determine relationships between characteristics of the natural system and the factors bringing about change of these characteristics. Therefore, in order to calculate balance of the environmental capacity, a limited number of accessible, simple, understandable and informative indicators were used to reflect basic ecological situation of the aquatic ecosystem under study. This is an important stage in theoretical support of the regional management of water resources in Europe and worldwide. Indicators characterizing ecological hydrology of a water body, structural and functional properties of aquatic ecosystems, anthropogenic load on aquatic ecosystems and self-purifying capacity of water were used.

Such study approach makes it possible to assess state of a particular area of a water body that needs to be studied and identify sources of anthropogenic influence for taking necessary measures [19]. It is effective when applied to technogenically altered aquatic ecosystems of small and medium rivers, plain areas with temperate continental climate.

#### 4. 2. The procedure for calculating environmental capacity of an aquatic ecosystem

In accordance with the proposed classification of indicators, environmental capacity of the aquatic ecosystem acts as a part of an integral indicator of state of the aquatic ecosystem after action of exogenous factors of anthropogenic origin. Thus, environmental capacity characterizes in a certain sense ability of the ecosystem to transform, migrate and accumulate matters involved in the cycle. It serves as an important criterion for balanced functioning of the ecosystem, numerically corresponds to the maximum technogenic load that a set of recipients and ecological systems of the basin can endure for a long period without harm to their structural and functional features.

To calculate balance of the environmental capacity, we suggest to use the following formula:

$$I_{e.c} = \sum_{i=1}^n \left[ \frac{Kr_{biom} + I_s + (C_1 \times K_{s.p} + C_2 \times K_{s.p} + \dots + C_n \times K_{s.p})}{n} \right] \times K_m, \quad (4)$$

where  $Kr_{biom}$  is the criterion of biomass which characterizes survivability of hydrobiocenosis in conditions of their habitat change;  $I_s$  is the index of self-purification;  $C_1, C_2, C_n$  are pollutant concentrations;  $n$  is the quantity of pollutants;  $K_{s,p}$

is the cumulative rate of water self-purification (Table 1);  $K_m$  is the compound coefficient of river and sewage waters: 0.8 for medium rivers, 0.6 for large rivers.

Table 1

Tentative values of coefficients of rate of self-purification of river water from some pollutants

Matter and indicator of chemical composition of water	Water temperature, °C		
	<10	10–15	>15
NH <sub>4</sub>	0.9	1.8	2.7
Cu	0.6	1.2	1.8
Zn	0.1	0.3	0.6
Fe	0.1	0.2	0.3
Cr <sup>6+</sup>	0.1	0.2	0.3
BOC <sub>5</sub>	0.5	1.0	1.5
BOC <sub>full</sub>	0.2	0.3	0.7
COC	0.1	0.2	0.3

Self-purifying ability of an aquatic ecosystem is characterized to some extent by its environmental capacity. It can express potential ecosystem’s adaptability and resistance to new condition of existence. Self-purifying ability is the consequence of this ability and characterizes results of the ecosystem functioning in concrete conditions. Thus, one can assert that the self-purifying ability is one of the main quantitative indicators of the environmental capacity. To evaluate efficiency of the process of self-purification of the river section under study from hard-oxidized compounds, it is proposed to use the following formula:

$$I_s = \frac{R}{COC_{init} - BOC_{init}}, \quad (5)$$

where  $R$  is the amount of substrate used for plastic purposes;  $COC_{init}$  is chemical consumption of oxygen in the river water in the initial location;  $BOC_{init}$  is the total biochemical consumption of oxygen in the initial location.

The mechanism of plastic metabolism characterizes amount of substrate that can be used for plastic purposes and is calculated from formula:

$$R = (COC_{init} - BOC_{init}) - (COC_{finit} - BOC_{finit}), \quad (6)$$

where  $COC_{init}$  is chemical consumption of oxygen of the river water in the initial location;  $BOC_{init}$  is total biochemical consumption of oxygen of the river water in the initial location;  $COC_{finit}$  is chemical consumption of oxygen of the river water in the final location;  $BOC_{finit}$  is complete biochemical consumption of oxygen of the river water in the final location.

The index of techno-capacity characterizes the amount of matter of anthropogenic origin which can be neutralized by ecosystem and is determined by:

$$I_{t.c} = \frac{I_{e.c}}{I_{t.i}}, \quad (7)$$

where  $I_{e.c}$  is the environmental capacity of the ecosystem;  $I_{t.i}$  is the index of technogenic influence.

### 5. The results of application of the procedure of ecological indicators for controlling structural and functional changes in the aquatic ecosystem

#### 5. 1. Analysis of the ecological state of the studied section of the aquatic ecosystem

A 45 km long section of a medium river, the Irpin River (the right inflow of the Dnipro River), was selected as an object for testing the proposed procedure. Retrospective database was formed based on our own studies and official monitoring data [20, 21] for the period from 2006 to 2017. Water quality class was determined according to the procedure of [16] with application of (1) in accordance with the legislation of Ukraine. The requirements to establishment of European water quality standards are given in Article 13 of Directive 2008/105/EC [17]. Methodical techniques of determining maximum permissible concentrations MPC used in Ukraine and European Union for establishing water quality standards virtually coincide. However, the European procedure defines criteria not only for water but also for bottom sediments and biota. Comparison of values of concentration of some pollutants adopted in Ukraine and Europe for various classes of water quality is given in Table 2. Class IV by European classification [12] of water

quality corresponds to Classes IV and V specified by standards of Ukraine [14].

The following results were obtained in the study of the river section according to the IWP procedure (3):

- class III of quality: water is moderately polluted (in 40 % of cases);
- class IV of quality: water is polluted (in 40 % of cases);
- class V of quality: water is highly polluted (in 10 % of cases).

The results of calculation of complex  $I_c$  (1) by the average values of indicators for the studied section of the Irpin River in the observation period (2006–2017) are shown in Fig. 1.

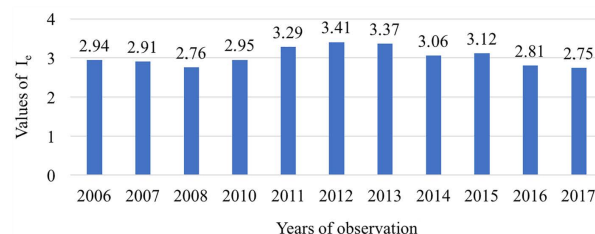


Fig. 1. Dynamics of  $I_c$  changes in the studied section of the Irpin River over 2006–2017

Table 2

Characteristics of various classes of surface water quality in Ukraine and EU countries by some hydro-chemical indicators

Indicator, mg/dm <sup>3</sup>	Water quality classes						
	Ukraine	EU	Ukraine	EU	Ukraine	EU	Ukraine
	I (1)*	I	II (2)	I–II	II (3)	II	III (4)
Nitrate nitrogen	<0.2	≤1	0.2–0.3	≤1.5	0.31–0.50	≤2.5	0.51–0.70
Nitrite nitrogen	<0.002	≤0.01	0.002–0.005	≤0.05	0.006–0.01	≤0.1	0.011–0.020
Ammonia nitrogen	≤0.10	≤0.04	0.1–0.2	≤0.1	0.21–0.3	≤0.3	0.31–0.5
Phosphate phosphorus	<0.015	≤0.02	0.015–0.030	≤0.04	0.031–0.05	≤0.1	0.051–0.1
Dissolved oxygen	>8	>8	7.6–8	>8	7.1–7.5	>6	6.1–7.0
Chlorides	≤20	≤25	21–30	≤50	31–75	≤100	76–150
Sulphates	≤50	≤25	51–75	≤50	76–100	≤100	101–150
BOC	<1.0	≤2	1.0–1.6	≤3	1.7–2.1	≤5	2.2–4.0
COC	<9	«0»	9	≤10	16–25	≤25	26–30
Indicator, mg/dm <sup>3</sup>	EU	Ukraine	EU	EU	Ukraine	EU	Ukraine
	II–III	III(5)	III	III–IV	IV(6)	IV	V
Nitrate nitrogen	≤5	0.71–1.00	≤10	≤20	1.01–2.5	>20	>2.5
Nitrite nitrogen	≤0.2	0.021–0.050	≤0.4	≤0.8	0.051–0.100	>0.8	>0.1
Ammonia nitrogen	≤0.6	0.51–1	≤1.2	≤2.4	1.01–2.5	>2.4	>2.5
Phosphate phosphorus	≤0.2	0.101–0.2	≤0.4	≤0.8	0.201–0.300	>0.8	>0.300
Dissolved oxygen	>5	5.1–6.0	>4	>2	4.0–5.0	≤2	<4
Chlorides	≤200	151–200	≤400	≤800	201–300	>800	>301
Sulphates	≤200	151–200	≤400	≤800	201–300	>800	>301
BOC	≤10	4.1–7.0	≤20	≤40	7.1–12.0	>40	>12.0
COC	≤50	31–40	≤100	≤200	41–60	>200	>60

Note: I (1)\*= Class I, Category 1



Three characteristics of the river aquatic ecosystem were taken into account in calculation of the ecological index,  $I_e$ : hydro-chemical, trophic-saprobiological and radiation. The results of calculation given in Fig. 1 show that for the period 2006 to 2007, water quality corresponded to the Class II with the index value of 2.6–2.8. There was worsening of quality, water belonged to the Class III in the period from 2008 to 2017 since the value of the  $I_e$  index was 3–3.6. The worst indicator was the set of ecological and sanitary characteristics according to which quality of the river water generally corresponded to water quality Categories 4 and 5 (Table 2). The observed tendency to worsening was caused by exceeding permissible concentrations of pollutants: concentration of Cr (VI) was 0.0037–0.01 mg/dm<sup>3</sup> (at MPC 0.001 mg/dm<sup>3</sup>), concentration of ammonia nitrogen was 0.4–3.6 mgN/dm<sup>3</sup> (at MPC 2.0 mg/dm<sup>3</sup>), the indicator of COC was 25.7–44 mgO/dm<sup>3</sup> (at MPC 25mgO/dm<sup>3</sup>).

**5. 2. Results of calculation of environmental capacity of the aquatic ecosystem**

Intra-basin changes in the aquatic ecosystem were observed at the next stage of the study using the developed procedure of ecological indicators. The environmental capacity of the aquatic ecosystem and its deterioration by excessive techno-capacity were quantitatively determined. Visualization of the balance of environmental capacity (4) and techno-capacity (7) is presented in Fig. 2. Calculations were made using a retrospective database for the studied river section in a ten-year observation period.

Environmental capacity of the aquatic ecosystem serves as a part of the integral indicator of hydrosphere reaction to exogenous factors of anthropogenic origin. It is evident from Fig. 2 that the value of  $I_e$  was worsening in recent years but fluctuated practically within the limits of one class of water quality (Class III). This was caused by intensive technogenic impact of economic activities of numerous enterprises and farms located in the river basin. Technogenic impact on the aquatic ecosystem is expressed by  $I_{t,i}$  and is in the ranges of 1.7–1.9 and 2.0–2.5 for the Class III and Class IV of water quality, respectively.

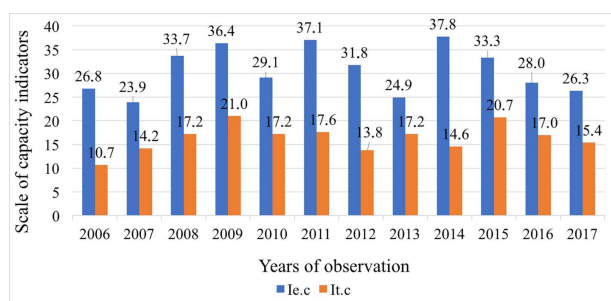


Fig. 2. Dynamics of changes in the balance between the environmental capacity and techno-capacity for the studied river section over 2008 2017

Balance between the environmental capacity and techno-capacity was characterized by the level of ecological reserve and was in the range of 11.7–17.0 for water quality of Class III. At the same time, there was a violation of structural and functional organization of the aquatic ecosystem. In accordance with the principle of Le

Chatelier Brown, dynamic equilibrium of development of aquatic ecosystem is shifted towards the least technogenic load and hydrobionts are adapted to new conditions of existence. This results in restructuring of biocenoses associations in the direction of strengthening of  $\beta$ ,  $\alpha$ -saprogenous species, reduction of the species diversity of hydrobionts. Thus, further growth of technogenic impact will disturb dynamic equilibrium of the aquatic ecosystem breaking the ability of biota to self-regulation:  $I_{biot.self}$  was 25.0–27.0 for water quality of Class III and 17.0–6.0 for water quality of Class IV.

The multi-index approach to assessing the environmental capacity and development of the aquatic ecosystem is effective since it can maximally integrate relevant factors and changes in the aquatic ecosystem. It makes it possible to provide on-line quantitative information on alteration of the ecological state of the aquatic ecosystem, thereby providing theoretical support for the bodies of regional management of water basins in European countries.

Since rivers with water quality of Class III and IV should be considered technogenically altered water ecosystems, the calculation results were systematized according to these classes (Table 3).

Table 3

The values of calculated indices for the prevailing water quality classes of the technogenically altered aquatic ecosystem of the medium river

Indicator of	Index of	Water quality of Class III	Water quality of Class IV
action	the technogenic impact	$\frac{1.7 - 1.9}{1.8}^*$	$\frac{2.0 - 2.5}{2.9}^*$
	the mechanism of plastic metabolism	$\frac{2.8 - 3.0}{2}$	$\frac{0.5 - 1.5}{1}$
state	the balance of environmental capacity	$\frac{26.7 - 35.0}{30.85}$	$\frac{13.3 - 17.8}{15.55}$
	the balance of techno-capacity	$\frac{15.0 - 18.0}{16.5}$	$\frac{6.7 - 7.12}{6.91}$
response	the level of ecological reserve	$\frac{11.7 - 17.0}{14.35}$	$\frac{6.6 - 10.8}{8.7}$
	biotic self-regulation	$\frac{25.0 - 27.0}{26.0}$	$\frac{6.7 - 17.0}{11.5}$

Note: \* –  $\frac{(\text{minimum value} - \text{maximum value})}{\text{average value}}$

The study data presented in Table 1 confirm regularities in reducing the balance of environmental capacity and growth of techno-capacity in the aquatic ecosystem of the river. This causes reduction of the balance of the ecological reserve which characterizes the potential level of restoration of the technogenically altered aquatic ecosystem functioning. Biochemical activity of the water biota decreases with respect to the pollutant matters as evidenced by a decrease in the value of the biotic self-regulation index. The obtained data can serve as a benchmark for determining parameters of existence of other technogenically altered aquatic ecosystems of small and medium penneplain rivers.

## 6. Discussion of the results obtained in calculation of ecological and technical capacities of the aquatic ecosystem of the mouth area of the Irpin River

It was shown that functioning of a technogenically altered aquatic ecosystem is determined by the consistent change of interaction of environmental and anthropogenic factors. First, emergence of ecologically dangerous exo-risks is associated with the altering effect of technogenic factors on effectiveness of the mechanism of plastic metabolism of chemical compounds of anthropogenic origin. Secondly, emergence of ecologically dangerous endo-risks is caused by biochemical activity of the water biota in relation to the substances of water pollutants. Compensatory mechanism of the water biotic self-regulation is their integral indicator.

In order to ensure natural and technogenic safety of development of the aquatic ecosystem, main parameters of its functioning were assessed with the help of an information and methodological base of ecological indicators. The applied method is based on the three-dimensional orientation of the quantitative characteristic of structural and functional disturbances of technogenically altered aquatic ecosystems. The consecutive set of indicators includes indicators of action (assessment of impact of technogenic factors on the object under the study: the index of technogenic impact, the index of plastic metabolism of chemical compounds, the general ecological index), indicators of the state (state of environment as a result of technogenic action: the balance index, environmental capacity, index of technology), indicators of response (response of the aquatic ecosystem to violation of sustainable functioning: the criterion of biotic self-regulation of water, index of the level of ecological reserve).

It was established on the basis of systematization and formalization of data of ecological monitoring that the basis of development of aquatic ecosystems of rivers is characterized by environmental capacity. It should be noted that the environmental capacity is changing in the course of its development because of excessive technogenic impact and is transformed into a residual ecological reserve. Quantitative values were calculated using environmental monitoring indicators (Table 3). This is important for the control of trends in the change of structural and functional peculiarities of development of technogenically altered aquatic ecosystems, detection of the laws of qualitative and quantitative violations. Reduction of the environmental capacity indicator shows violation of self-regulation of the aquatic ecosystem. The obtained information on the balance of environmental capacity presented in the Table 3 testifies development of the technogenically altered aquatic ecosystem in the studied section of the river within its class of water quality (Class III, sometimes Class IV).

In this study, environmental capacity was first considered as an indicator that quantitatively represents anthropogenic impact and violations that occur in the aquatic ecosystem. Environmental capacity gets violated and decreased as a result of an increase in techno-capacity. It equals to  $I_{e,c}=26.7-35.00$  at  $I_{t,c}=15-18$ . With growth of techno-capacity, mechanisms of biotic self-regulation and plastic metabolism of chemical compounds are violated in hydrobionts. This is evident from the dependence (the index of technogenic impact – the index of biotic self-regulation – the index of the mechanism of plastic metabolism): 6.91-2.9-26 for Class III; 16.5-1.2-11.5 for Class IV. However, the aquatic ecosystem is capable of maintaining the required level

of natural and technogenic safety due to conservation of the ecological reserve which is quantitatively expressed by difference between the environmental capacity and techno-capacity as well as due to re-adaptation of biota to new conditions of existence.

The concept of this study consists in the study of the technogenically altered aquatic ecosystems of peneplain rivers which include more than half of the rivers in Europe. The offered approach has allowed us to establish state of the aquatic system under study, make quantitative estimation of technogenic factors and forecast consequences of their influence. This will enable future development of a system of environment protection measures in order to return the technogenically altered aquatic ecosystems to a state of dynamic equilibrium [13, 19].

However, the study involves formation of an individual set of criteria for each type of aquatic ecosystems, ensure availability of monitoring data for at least 10 years, monitoring patterns of development of the aquatic ecosystem under study. Therefore, the set of indicators is individual for each aquatic system type and adaptable only for medium and small rivers.

The procedure for calculating environmental capacity and the search for regularities in reduction of the balance between the environmental capacity and techno-capacity of medium and small rivers require further improvement. Further development of this study may consist in development of a procedure for calculating environmental capacity and techno-capacity for large rivers. The principle of Le Chatelier Brown requires detailed future studies to elucidate intra-basin changes occurring in technogenically altered aquatic ecosystems.

## 7. Conclusions

1. A methodological base of ecological control indicators was developed which enables detection of quantitative and qualitative changes in structural and functional features of development of technogenically altered aquatic ecosystems. The procedure makes it possible to determine pressure of technogenic factors on a water body (the index of technogenic effect: 1.7–1.9 for Class III; 2.0–2.5 for Class IV; change of the mechanism of plastic metabolism: 2.8–3.0 for Class III; 0.5–15 for Class IV. State of the aquatic ecosystem resulting from the change of ecological situation is characterized by the fundamental indicator of ecosystem functioning: environmental capacity 26.7–35.0 for Class III; 13.3–17.8 for Class IV; techno-capacity 6.7–7.12 for Class III, 15.0–18.0 for Class IV. Response of the aquatic ecosystem to violation of stable functioning is characterized by the biotic water self-regulation index: 25.0–27.0 for Class III, 6.0–17.0 for Class IV; balance of ecological reserve 11.7–17.0 for Class III, 6.6–10.8 for Class IV.

2. Based on analysis, systematization and formalization of the data on ecological state of the river aquatic ecosystem, it was established that the basis of their development is related to the environmental capacity. The environmental capacity varies in the process of its development and is transformed into a residual ecological reserve. Loss of environmental capacity as the main parameter of the aquatic ecosystem was quantitatively estimated. Consequences of a ten-year anthropogenic alteration of the studied river section were analyzed. The study confirmed reduction of the environmen-

tal capacity balance (35→17.8), increase in techno-capacity (6.7→18) and reduction of ecological reserve (17→6.6).

3. The high level of functionality of the integrated systems of indicators makes it possible to quantitatively characterize structural and functional changes in the intra-basin processes of the technogenically altered area of the aquatic ecosystem under study. With their help, it is possible to determine optimal parameters of existence (27.6 for environ-

mental capacity; 6.3 for techno-capacity) which will not lead to ecosystem changes in the future.

4. A scale of limit parameters of functioning of aquatic ecosystems for Classes III and IV of water quality was built. The level of ecological safety of a technogenically altered aquatic ecosystem was found as acceptable (for the Class III of water quality) and moderately permissible (for the Class IV of water quality).

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