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INTEGRATED BIOINDICATION-BASED ASSESSMENT OF NATURAL AND TECHNOGENIC SAFETY OF AQUATIC ECOSYSTEMS (CASE STUDY OF THE UPPER KANIV RESERVOIR)

The intensification of anthropogenic and technogenic pressure on aquatic ecosystems necessitates the improvement of methodological approaches to assessing their environmental safety, stability, and self-recovery capacity. This issue is particularly relevant for reservoirs operating under conditions of regulated flow, intensive water use, nutrient input, organic pollution, and the influence of urbanized areas. The article presents a comprehensive bioindication-based assessment of the qualitative and quantitative components of natural and technogenic safety of aquatic ecosystems, using the upper section of the Kaniv Reservoir as a case study.

The methodological framework of the study is based on the integration of hydroecological potential assessment, phytoplankton-based bioindication, and elements of statistical modeling. The study considers species composition, diversity level, dominance of individual taxa, species richness, and the response of phytoplankton communities to changes in environmental conditions.

The obtained results indicate that phytoplankton communities are sensitive indicators of anthropogenic transformation of aquatic ecosystems and are capable of reflecting changes in trophic status, organic pollution levels, ecological stability, and resilience of water bodies. Establishing the relationship between hydroecological potential and bioindication parameters enhances the objectivity of environmental monitoring and enables the early detection of ecosystem degradation processes.

The proposed approach contributes to the development of an integrated system for assessing the natural and technogenic safety of aquatic ecosystems by combining biological, hydroecological, and analytical criteria. Its application can be useful for improving surface water monitoring, substantiating environmental protection measures, and forming a scientific basis for sustainable water resource management under increasing technogenic pressure.

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Keywords: aquatic ecosystems, environmental safety, hydroecological potential, bioindication, phytoplankton, anthropogenic impact, ecosystem assessment.

Problem statement. The environmental safety of aquatic ecosystems has become a central issue in contemporary ecological research, particularly in the context of accelerating anthropogenic transformation of natural environments. Aquatic systems are increasingly exposed to complex and multifactorial pressures, including industrial discharges, agricultural runoff, urban wastewater inputs, and hydromorphological alterations. These factors act simultaneously and often synergistically, leading to profound changes in the structure, functioning, and resilience of hydrological systems.

Under conditions of sustained technogenic load, aquatic ecosystems experience a gradual decline in their capacity for self-regulation and natural purification. This results in the disruption of biogeochemical cycles, deterioration of water quality, and simplification of biological communities. One of the most critical consequences of such transformations is the loss of ecosystem stability, which manifests through reduced biodiversity, altered trophic interactions, and increased vulnerability to external disturbances.

Traditional approaches to water quality assessment, primarily based on hydrochemical indicators, are limited in their ability to capture the complexity of ecosystem responses. While these methods provide valuable information on the concentration of individual pollutants, they do not adequately reflect cumulative, long-term, and synergistic effects of multiple stressors. As a result, there is a growing need for integrated assessment frameworks that incorporate both abiotic and biotic components of aquatic ecosystems.

In this context, the concept of natural and technogenic safety of aquatic ecosystems is increasingly recognized as a key theoretical and practical construct. It is defined as the ability of a system to maintain its structural integrity and functional performance under external anthropogenic pressure without crossing critical ecological thresholds. A central element of this concept is the hydroecological potential, which characterizes the permissible level of environmental load that an ecosystem can sustain while preserving its stability and self-recovery capacity.

Biological indicators, particularly phytoplankton communities, play a crucial role in the development of such integrated assessment approaches. Due to their rapid response to environmental changes, high sensitivity to nutrient enrichment and pollution, and fundamental role in primary production, phytoplankton serves as effective indicators of ecosystem condition. Changes in their species composition, abundance, and diversity provide valuable insights into the direction and intensity of ecological transformations.

Therefore, the development of scientifically grounded methodologies that integrate hydroecological potential assessment with bioindication analysis represents an important and relevant research direction. Such approaches enable a more comprehensive evaluation of ecosystem safety and provide a reliable basis for environmental monitoring and sustainable water resource management.

Analysis of recent research. The environmental safety of aquatic ecosystems has become a central issue in contemporary ecological research, particularly under conditions of increasing anthropogenic transformation of natural environments. Aquatic systems are exposed to complex combinations of chemical, biological, and physical stressors, which interact nonlinearly and lead to significant alterations in ecosystem structure and functioning.

From a systems theory perspective, an aquatic ecosystem can be represented as a complex dynamic system:

$$S = \{X, Q\}, \quad (1)$$

where $X = \{X_1, X_2, \ldots, X_n\}$ – represents the set of ecosystem components (physical, chemical, and biological); Q – denotes the set of interactions and transformation processes between these components.

Such a representation emphasizes that ecosystem behavior is determined not only by the state of individual elements but also by the relationships between them. Under anthropogenic influence, these relationships are modified, leading to structural and functional transformations.

A more detailed representation of a natural-technogenic aquatic ecosystem can be expressed as:

$$S = Z \cdot Q \cdot W, \quad (2)$$

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where Z – the natural subsystem; W – the technogenic (anthropogenic) subsystem; Q – defines the interactions between them.

This formulation reflects the dual nature of modern aquatic ecosystems, which function as hybrid systems combining natural processes and human-induced impacts.

The state of the system evolves in space and time according to the following dependencies:

$$X = X(t,h); F = F(t,h); R = R(t,h), \quad (3)$$

where X – represents the set of internal components of the aquatic ecosystem, including physical, chemical, and biological parameters (such as temperature, dissolved oxygen, nutrient concentrations, and biological communities); F – denotes the set of external influencing factors, including both natural and anthropogenic drivers (such as climatic conditions, hydrological regime, pollutant inputs, and human activities); R – characterizes the system of relationships and interactions between ecosystem components, including trophic interactions, biochemical processes, and feedback mechanisms within the ecosystem; t – the temporal variable reflecting seasonal and long-term changes; h – the spatial variable representing heterogeneity within the aquatic system.

This representation emphasizes that the ecological state of an aquatic system is determined not only by the composition of its components but also by external forcing and the structure of internal interactions.

The component composition and spatiotemporal structure of a natural-technogenic aquatic ecosystem undergo changes according to a specific functional dependence M(t, h). Therefore, from the standpoint of mathematical formalization, such an ecosystem can be considered as a system formed by a set of internal components that interact with each other and are in continuous connection with the surrounding environment. A generalized representation of the formalized model of a natural-technogenic aquatic ecosystem is shown in Figure 1.

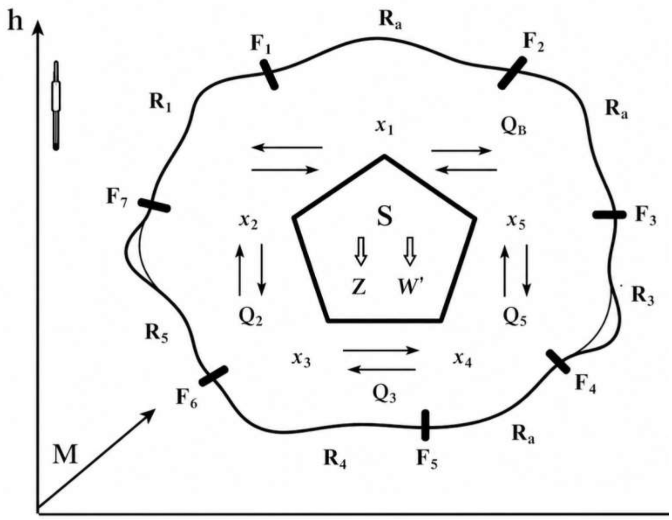

Figure 1. Formalized model of a natural-technogenic aquatic ecosystem

Under prolonged anthropogenic pressure, the system may approach critical thresholds beyond which irreversible changes occur. In this context, the concept of hydroecological potential becomes essential, as it characterizes the capacity of the ecosystem to maintain stability and resist external disturbances.

Traditional hydrochemical approaches are insufficient for capturing such complex system behavior, as they focus on individual parameters rather than system-level interactions. Therefore, there is a need for integrated methodologies that combine system modeling with biological indicators.

Phytoplankton communities, due to their sensitivity to environmental changes and their role in primary production, serve as effective indicators of ecosystem state. Their structural characteristics provide insight into the direction and intensity of ecosystem transformations.

Thus, the integration of system-based formalization with bioindication approaches represents a promising direction for assessing the natural and technogenic safety of aquatic ecosystems.

Aim, objectives and methodology. The aim of this study is to establish a quantitative relationship between hydroecological potential and phytoplankton characteristics in a technogenically influenced aquatic ecosystem.

The methodological approach is based on the integration of

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bioindication and hydroecological assessment, complemented by statistical analysis.

The evaluation of biodiversity was carried out using classical ecological indices. The Shannon diversity index was calculated as:

$$H = -\sum\left(\frac{n}{N} log \frac{n}{N}\right) , \quad (4)$$

where n – the number of individuals of a given species; N – the total number of individuals.

Species richness was determined using the Menhinick index:

$$M = \frac{A}{\sqrt{N}} , \quad (5)$$

where A – the number of species.

The dominance structure of phytoplankton communities was assessed using the Simpson index:

$$C = \sum\left(\frac{n}{N}\right)^2 , \quad (6)$$

Additionally, the saprobity index was applied to evaluate organic pollution levels:

$$S = \frac{\sum(s \cdot h)}{\sum h} , \quad (7)$$

where s – the saprobity value of species and h is its relative abundance.

To interpret the results, classification of water quality based on saprobity was used, which is presented in Table 1.

The hydroecological potential was calculated as an integral indicator combining hydrochemical and biological parameters. The relationship between phytoplankton characteristics and hydroecological potential was analyzed using correlation-regression methods.

Table 1

Water quality classification based on Saprobity Index

Saprobity Index	Zone	Water quality class
0.0 – 0.5	Xenosaprobic	Very clean
0.51 – 1.5	Oligosaprobic	Clean

Continuation of the table 1

1.51 – 2.5	β-mesosaprobic	Moderately polluted
2.51 – 3.5	α-mesosaprobic	Polluted
3.51 – 4.0	Polysaprobic	Heavily polluted

Results and discussion. The ecological state of the upper section of the Kaniv Reservoir was assessed through a combination of hydrochemical indicators, bioindication parameters, and integrated hydroecological potential evaluation. The obtained results reflect a complex interaction between anthropogenic load and internal ecosystem processes, which is expressed in both chemical transformations and structural changes of biological communities.

Hydrochemical analysis indicates that the studied water body is characterized by increased concentrations of biogenic elements, primarily nitrogen and phosphorus compounds, which act as key drivers of eutrophication. Periodic fluctuations in dissolved oxygen and elevated biochemical oxygen demand confirm the presence of organic pollution and active decomposition processes. These conditions create a favorable environment for intensive phytoplankton development, which, in turn, significantly affects ecosystem functioning.

The biological analysis revealed that phytoplankton communities are dominated by species typical for mesotrophic and eutrophic water bodies. The structure of these communities demonstrates a tendency toward reduced diversity and increased dominance of individual taxa, which is a characteristic feature of ecosystems subjected to prolonged anthropogenic pressure.

The calculated biodiversity indices are presented in Table 2.

Table 2

Biodiversity Indices of Phytoplankton Communities

Sampling Site	Shannon Index (H)	Simpson Index (C)	Menhinick Index (M)
Site 1	2.3	0.21	1.8
Site 2	2.1	0.27	1.6
Site 3	1.9	0.34	1.4

The obtained values indicate a moderate level of species diversity, with a clear trend toward increasing dominance of individual species. A decrease in Shannon index values from Site 1 to Site 3 corresponds to a growing anthropogenic influence and increasing environmental stress.

At the same time, the increase in Simpson index values reflects the intensification of dominance by pollution-tolerant species, which is a typical indicator of ecosystem degradation. The Menhinick index demonstrates a gradual decline in species richness, confirming the process of structural simplification of phytoplankton communities.

The ecological interpretation of these results suggests that the studied ecosystem is undergoing a transition from a relatively stable state toward a disturbed condition characterized by reduced resilience and increased sensitivity to external impacts.

The assessment of organic pollution using the saprobity index further supports this conclusion. The calculated values fall within the range corresponding to β-mesosaprobic conditions, indicating a moderate level of organic contamination. This classification is consistent with hydrochemical data and reflects the cumulative impact of anthropogenic factors.

The hydroecological potential (HEP) was calculated as an integral indicator representing the functional capacity of the ecosystem. The obtained values are presented in Table 3.

Table 3

Hydroecological Potential Values

Sampling Site	HEP Value	Ecological Interpretation
Site 1	0.72	Relatively stable
Site 2	0.65	Moderately disturbed
Site 3	0.58	Ecologically stressed

The spatial distribution of HEP values demonstrates a gradual decline in ecosystem stability along the studied section of the reservoir. Higher values correspond to areas with greater biological diversity and more balanced community structure, while lower values are associated with zones of increased anthropogenic pressure.

A comparative analysis of Tables 2 and 3 reveals a clear relationship between biodiversity parameters and hydroecological potential. Areas characterized by higher Shannon index values exhibit higher HEP values, indicating that biodiversity plays a crucial role in maintaining ecosystem stability.

To quantify this relationship, a correlation analysis was performed. The results show a strong positive correlation between HEP and Shannon index ($r \approx 0.82$) and a negative correlation with Simpson index ($r \approx -0.76$). This indicates that increasing dominance and decreasing diversity are directly associated with reduced ecosystem safety.

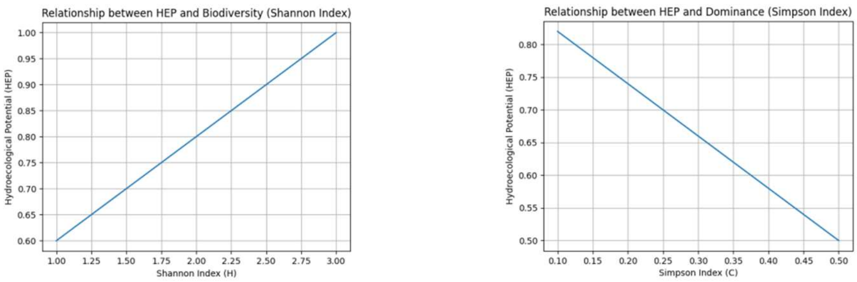
Based on these results, a regression model describing the dependence of hydroecological potential on phytoplankton characteristics was developed:

$$HEP = a + bH - cC + dM$$

where H – the Shannon diversity index, reflecting species diversity and structural complexity of the phytoplankton community; C – the Simpson dominance index, characterizing the degree of dominance of individual species within the community; M – the Menhinick index, representing species richness relative to total abundance; a – the intercept (constant term), reflecting the baseline level of hydroecological potential in the absence of variability in biological indicators; b, c, and d – regression coefficients that quantify the contribution of each respective variable to the overall hydroecological potential.

The signs and magnitudes of the regression coefficients have clear ecological interpretation. The positive coefficient b indicates that increasing species diversity contributes positively to ecosystem stability and enhances hydroecological potential. Conversely, the negative coefficient c reflects the adverse effect of species dominance, as higher dominance reduces ecosystem resilience. The positive coefficient d suggests that greater species richness is associated with improved ecological balance and functional capacity.

Graphically, this conceptual relationship can be interpreted as a multidimensional surface where hydroecological potential increases with biodiversity and decreases with dominance. In simplified form, this dependence can be represented as a rising curve with respect to diversity and a declining curve with respect to dominance (Figure 2).



a *b*

Figure 2. Relationship between hydroecological potential (HEP) and phytoplankton diversity (a) and phytoplankton dominance (b)

From an ecological perspective, this reflects fundamental principles of ecosystem functioning. High biodiversity enhances functional

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redundancy and resilience, allowing the system to maintain stability under stress conditions. Conversely, dominance of a limited number of species reduces ecosystem adaptability and increases vulnerability to disturbances.

The obtained results are consistent with modern ecological theories, particularly the concept of ecosystem resilience and the ecosystem-based approach. The observed transformations indicate that the studied water body is approaching a threshold beyond which further degradation may lead to irreversible changes in ecosystem structure.

An important aspect of the study is the confirmation that bioindication methods provide a more integrated and sensitive assessment of ecosystem condition compared to traditional hydrochemical approaches. While chemical indicators reflect instantaneous conditions, biological communities integrate the effects of environmental changes over time.

Thus, the combination of hydroecological potential assessment and bioindication analysis represents an effective tool for evaluating natural and technogenic safety of aquatic ecosystems.

Conclusions. 1. The conducted study confirms that anthropogenic pressure significantly affects both structural and functional characteristics of aquatic ecosystems. The upper section of the Kaniv Reservoir demonstrates clear signs of ecological transformation, including eutrophication processes, reduced biodiversity, and increased dominance of pollution-tolerant species.

2. Phytoplankton communities have been shown to be reliable indicators of ecosystem state, reflecting cumulative environmental changes and providing a basis for integrated assessment. The calculated biodiversity indices reveal a trend toward structural simplification, which is associated with decreased ecosystem resilience.

3. The hydroecological potential index has proven to be an effective integral indicator of ecosystem safety, reflecting both the assimilation capacity and stability of the aquatic environment. The established relationship between hydroecological potential and phytoplankton characteristics confirms the importance of biological indicators in environmental assessment.

4. The developed regression model provides a quantitative tool for predicting ecosystem condition based on bioindication parameters. This approach enhances the scientific basis for environmental monitoring and can be applied in water management practices.

5. Overall, the proposed integrated methodology contributes to improving the assessment of natural and technogenic safety of aquatic ecosystems and supports the implementation of sustainable water resource management strategies.

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ІНТЕГРОВАНА БІОІНДИКАЦІЙНА ОЦІНКА ПРИРОДНОЇ ТА ТЕХНОГЕННОЇ БЕЗПЕКИ ВОДНИХ ЕКОСИСТЕМ (НА ПРИКЛАДІ ВЕРХНЬОГО КАНІВСЬКОГО ВОДОСХОВИЩА)

Посилення антропогенного та техногенного навантаження на водні

екосистеми зумовлює необхідність удосконалення методичних підходів до оцінювання їх екологічної безпеки, стійкості та здатності до самовідновлення. Особливої актуальності ця проблема набуває для водосховищ, які функціонують в умовах зарегульованого стоку, інтенсивного водокористування, надходження біогенних речовин, органічного забруднення та впливу урбанізованих територій. У статті представлено комплексну біоіндикаційну оцінку якісної та кількісної складових природно-техногенної безпеки водних екосистем на прикладі верхньої ділянки Канівського водосховища.

Методологічну основу дослідження становить поєднання оцінювання гідроекологічного потенціалу, біоіндикаційного аналізу за показниками фітопланктону та елементів статистичного моделювання. У межах дослідження враховано видовий склад, рівень різноманіття, домінування окремих таксонів, видове багатство та реакцію фітопланктону на зміну умов водного середовища.

Отримані результати свідчать, що фітопланктонні угруповання є чутливими індикаторами антропогенної трансформації водних екосистем і здатні відображати зміни трофічного стану, рівня органічного забруднення, екологічної стійкості та резильєнтності водойми. Встановлення зв'язку між гідроекологічним потенціалом і біоіндикаційними параметрами дає змогу підвищити об'єктивність екологічного моніторингу та виявляти ознаки деградаційних процесів на ранніх етапах.

Запропонований підхід сприяє розвитку інтегрованої системи оцінювання природно-техногенної безпеки водних екосистем, поєднуючи біологічні, гідроекологічні та аналітичні критерії. Його використання може бути корисним для вдосконалення моніторингу поверхневих вод, обґрунтування природоохоронних заходів і формування наукових засад сталого управління водними ресурсами в умовах зростаючого техногенного навантаження.

Ключові слова: водні екосистеми; екологічна безпека; гідроекологічний потенціал; біоіндикація; фітопланктон; антропогенний вплив; оцінка екосистеми.

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