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IDENTIFICATION METHOD FOR THE LEVEL OF ENVIRONMENTAL SAFETY OF WATER BODIES

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Abstract. *A method for identifying the environmental safety of water bodies under conditions of uncertainty has been developed using systems analysis methods and a multicriteria approach. Improving the adequacy of identification involves searching for a more suitable criterion and using multiple criteria that comprehensively describe the goal of identifying the environmental safety level of water bodies and complement each other. The determination of environmental safety in the context of the requirements of the Water Code of Ukraine should be structured according to integrated criteria. The proposed identification method uses techniques for calculating scores of various factors that characterize the components of specific criteria. The objectivity of the identification process is ensured by using criteria that provide a sufficiently complete chain of assessment features of threats. The identification procedure is based on multicriteria evaluation approaches with subsequent aggregation into an integral index that defines the water body's environmental safety level. During the identification procedure, the values of indicators and indices of relevant characteristics are mapped to corresponding evaluation scales. The arguments of the target identification function, which are features of the evaluation factors according to their respective criteria components, are expressed as dimensionless scores. The identification problem for natural or artificial objects under uncertainty is solved using systems analysis methods and a multicriteria approach, and it is reduced to comparing the resulting scores and ranking them by a set of partial or integral criteria (index). The use of the Analytic Hierarchy Process to justify the contribution of comprehensive components to assessing the environmental safety level of Ukraine's water bodies is a key element that made it possible to select the most appropriate assessment methodology.*

Keywords: *anthropogenic load, water bodies, environmental safety, natural-technogenic geosystems*

Relevance of the research. Identifying the level of environmental safety for natural or technogenic (artificial) objects under conditions of uncertainty is addressed through systems analysis methods using a multicriteria approach.

To identify the environmental safety level of water bodies (WB), it is necessary to develop criteria not only in the narrow sense of a "criterion function" but in a broader sense, as a method for identifying the environmental safety level.

Cases where a single criterion successfully reflects the goal of identifying the environmental safety level are exceptions rather than the rule. A single criterion only approximately (as any model does) reflects the assessment objective, and its adequacy may be insufficient. Enhancing adequacy involves seeking a more appropriate criterion (which may not even exist) and applying multiple criteria that describe the objective of identifying the environmental safety level of WB from different perspectives and complement one another.

Analysis of recent research and publications. To date, the issue of defining the composition and structure of anthropogenic load factors remains insufficiently addressed in WB. As noted in publications [1–3], expert evaluation methods are commonly used for similar tasks in environmental engineering, including interval evaluation, the Analytic Hierarchy Process (AHP), stepwise matrices, and network diagrams. However, in our case – where data on the quantitative characteristics of anthropogenic load factors are lacking, and impact assessment for many factors is poorly formalized due to the absence of prior research – it is appropriate to combine methods such as stratification, cause-and-effect diagrams, the Delphi method, and Saaty's Analytic Hierarchy Process [4, 5]. Within existing resource and financial constraints, these approaches allow for the development of an effective, comprehensive method and creation of structured hierarchical trees depicting the influence of anthropogenic load factors on WB, as well as the development of information profiles for watershed and subwatershed areas.

A methodological manual [6] devotes considerable attention to classifying anthropogenic pollution sources. The classification features include the circumstances of pollution emergence, the nature of the sources, and their impact regularity. The resolution of the Cabinet of Ministers of Ukraine [7] describes the main types of water pollution and the frequency of monitoring their indicators. In the article [8], a systems approach is used to generalize anthropogenic load factors that may be applied in developing a systemic classification of sources and factors of anthropogenic load.

The aim of the research is to develop a method for identifying WB's environmental safety level using techniques for calculating point-based evaluations of various factors characterizing the individual components of specific criteria.

Materials and research methods. The objectivity of solving the task of identifying the environmental safety level of WB is ensured through the application of criteria that provide a sufficiently comprehensive chain for evaluating threat indicators. This means the requirements must cover all critical aspects of the evaluation objective while minimizing their total number. This latter requirement is satisfied when the criteria are independent and not interconnected (e.g., it is preferable not to use identical measured values or values derived from one another in different criteria components) [9].

Identifying the environmental safety level of WB utilizes techniques for calculating point-based assessments of various factors representing specific criteria components. A hierarchical structural-logical scheme of criteria and factors is shown in Figure 1.

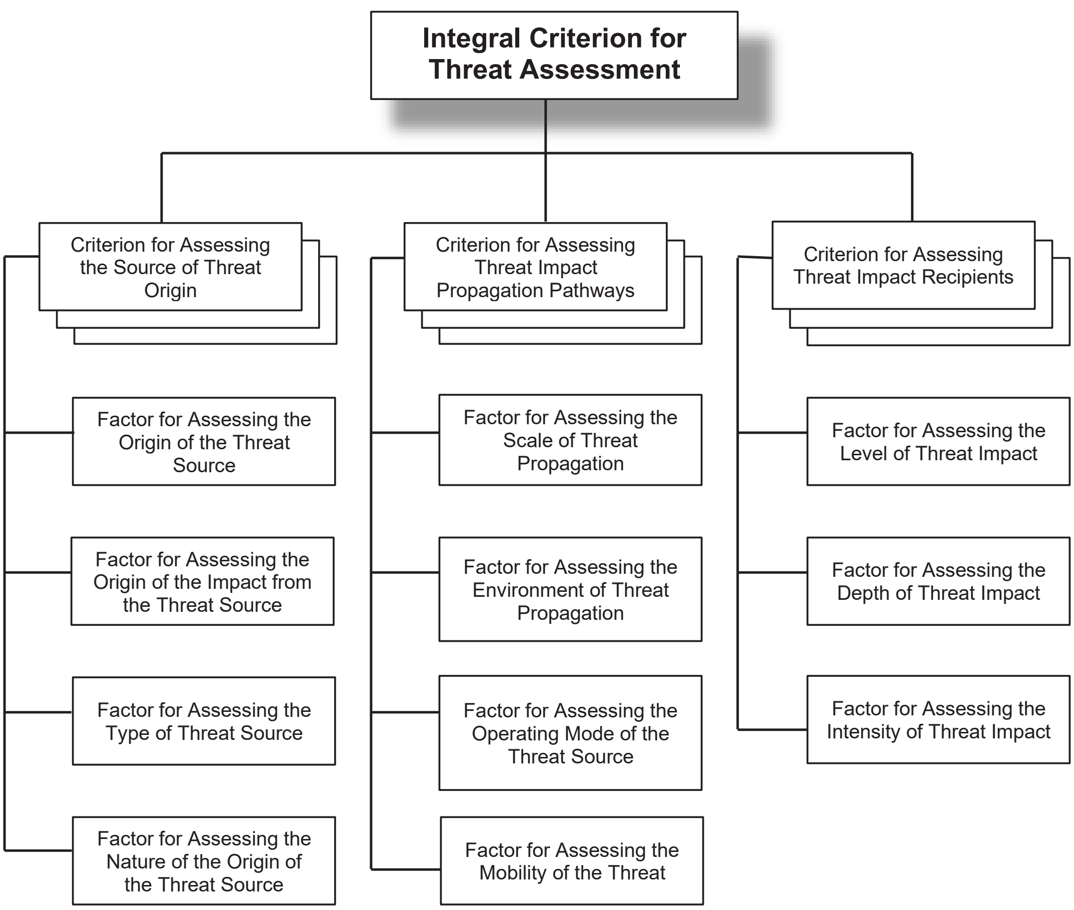

Fig. 1. Hierarchical structural and logical diagram of criteria and factors for identifying water bodies' environmental safety level

The comprehensive assessment procedure is based on multicriteria threat evaluation approaches, which are then aggregated into an integral index. This approach generally acquires practical significance only when the multicriteria task is reduced to a single-criterion one. However, the advantages of combining multiple criteria into a super-criterion come with specific difficulties and drawbacks that must be considered when applying this method.

The impact of anthropogenic load factors leads to the pollution of the components of the geospheres of natural-technological geosystems. Pollution of natural-technological geosystems should be understood as a change in the properties of its geosphere components (chemical, mechanical, physical, biological, and related informational properties), which occurs as a result of the action of anthropogenic load factors that cause the deterioration of the functions of aquatic ecosystems concerning living objects of the biosphere (humans, biological organisms, biocenosis, etc.).

A comparative analysis of existing classifications of technogenic load and the generalization of experience in this field of applied ecology allows the formation of the following classification features of anthropogenic load:

– nature of origin;
– type of origin;
– sphere of distribution;
– scale of distribution;
– type of source;
– operating mode of the source.

By the above approaches, a compilation of the characteristics of factors, partial and integral criteria, is carried out (Table 1). Based on this approach, the generalized additive and multiplicative objective functions can be represented as follows:

$$J_{\Sigma}(e) = \sum_{i=1}^{n} \frac{\alpha_i}{s_i} J_i(e_i), \quad (1)$$

$$J_{\Pi}(e) = \prod_{i=1}^{n} \frac{\alpha_i}{s_i} J_i(e_i), \quad (2)$$

where α_i and s_i are weighting coefficients that can be determined by expert judgment, for example, using the AHP procedures.

1. Classification of Criteria and Factors for Identifying the Level of Environmental Safety of Water Bodies

<table>
<tr><td colspan="7">Criterion for assessing the source of the threat</td></tr>
<tr><td colspan="7">1. Factor for assessing the origin of the threat source</td></tr>
<tr><td>Military actions</td><td>Global climate change</td><td>Emergencies</td><td>Industrial activity</td><td colspan="3">Agricultural activity</td></tr>
<tr><td colspan="7">2. Factor for assessing the origin of the threat source</td></tr>
<tr><td>Radioactive</td><td>Chemical</td><td>Electromagnetic</td><td>Mechanical</td><td>Acoustic</td><td>Vibrational</td><td>Thermal</td></tr>
<tr><td colspan="7">3. Factor for assessing the type of threat source</td></tr>
<tr><td>Unorganized</td><td>Organized</td><td>Group</td><td>Single</td><td>Planar</td><td colspan="2">Point</td></tr>
<tr><td colspan="7">4. Factor for assessing the nature of the origin of the threat source</td></tr>
<tr><td>Chain</td><td>Factor-forming</td><td>Direct</td><td colspan="4">Secondary</td></tr>
<tr><td colspan="7">Criteria for assessing the ways of spreading the threat impact</td></tr>
<tr><td colspan="7">1. Factor for assessing the scale of the threat spread</td></tr>
<tr><td>Global</td><td>Interstate</td><td>Regional</td><td>Includes objects of the nature protection fund</td><td>Localized</td><td colspan="2">Local</td></tr>
<tr><td colspan="7">2. Factor for assessing the environment of threat spread</td></tr>
<tr><td>Atmospheric air</td><td>Groundwater</td><td>Surface water</td><td>Soil</td><td colspan="3">Seawater</td></tr>
<tr><td colspan="7">3. Factor for assessing the mode of operation of the threat source</td></tr>
<tr><td>Constantly acting</td><td>Periodically acting</td><td>Episodic acting</td><td>One-time</td><td colspan="3">Random</td></tr>
<tr><td colspan="7">4. Factor for assessing the mobility of the threat</td></tr>
<tr><td colspan="2">Moving</td><td colspan="2">Slowly moving</td><td colspan="3">Immobile</td></tr>
<tr><td colspan="7">Criterion for assessing the recipients of the threat impact</td></tr>
<tr><td colspan="7">1. Factor for assessing the level of threat impact</td></tr>
<tr><td>Landscape</td><td>Ecosystem</td><td>Floristic</td><td>Faunistic</td><td>Population</td><td colspan="2">Species</td></tr>
<tr><td colspan="7">2. Factor for assessing the depth of threat impact</td></tr>
<tr><td colspan="2">Irreversible</td><td colspan="2">Partially reversible</td><td colspan="3">Reversible</td></tr>
<tr><td colspan="7">3. Factor for assessing the intensity of threat impact</td></tr>
<tr><td colspan="2">High</td><td colspan="2">Medium</td><td colspan="3">Low</td></tr>
<tr><td colspan="7">Integral threat assessment criterion</td></tr>
</table>

Each partial criterion J_i consists of a set of factors f_{ji}. To obtain expert assessments of the relevant impacts of threats, experts fill out questionnaires in which they assign appropriate scores to the characteristics of factors e_i, the values of which can be recorded in an evaluation scale or a scale corresponding to the MAI evaluation scale [10, 11]. The evaluation scale lies between ordinal and interval types. The processing of evaluation scores is carried out as follows: if there is confidence that all experts use a single evaluation scale (understand the "evaluation value" in the same way), as is the case, for example, in the presence of exceptional standards, then the evaluation scale approaches the interval scale, and the evaluation scores are processed as quantitative (and the evaluation scale itself has a large number of gradations).

Research results and their discussion. The analysis method of hierarchies (developed by the American mathematician Thomas Saaty in the early 1990s) is a method of systematic analytical research and solving multicriteria problems, which can be systematically hierarchically structured through step-by-step decomposition. The essence of which, as set out with the adaptation of the publication [12], is as follows:

1. Determination of the goal (focus) of the problem.
2. System analysis and structuring of the problem in a hierarchical model (goal, criteria, factors, characteristic indicators, alternative solutions).
3. A database of factors, conditions, characteristics, indicators, and alternatives is formed through expert-analytical systems research.
4. Formulate a block of questions for comparing elements of all levels of the hierarchy and identifying hierarchical relationships of subordination and dependence, surveying experts, and filling in matrices of pairwise comparisons of aspects of each level by a group of experts, which includes a system analyst.
5. Determination of eigenvectors of pairwise comparison matrices and their normalization. Assessment of the consistency of expert judgments based on the Consistency Ratio (CR). Verification of the consistency of comparison matrices. If necessary, clarification of experts' opinions should be provided through repeated analysis.
6. Determination of each hierarchy element's local and global priorities (weight coefficients).

Pairwise comparisons are made to determine the relative importance of elements. These comparisons are then expressed in integers on the Saati scale (Table 2). The same method and one evaluation scale should be given to unify the experts' responses. Experts fill in the matrices of pairwise comparisons of polygons for the corresponding criteria factors (Fig. 1).

When conducting pairwise comparisons, comparing an element with itself gives a unit; the result of comparing the first element with the second is the score a_{12}, the result of comparing the first element with the third is the score a_{13}, etc. Thus, each expert, independently of the others, conducts an examination, the results of which are recorded in a table representing the structure of the pairwise comparison matrices. At stage (3), $n(n–1)/2$ judgments are required to obtain each matrix [9].

2. Scale of evaluations of relative importance

Score	Definition	Explanation
1	Elements are equally important (priority)	Equal contribution of the two aspects to achieving the goal
3	Slight advantage of one over the other	Some conditions give a slight advantage to one over the other
5	Substantial advantage	There are strong facts that one is significantly more important than the other
7	Clear advantage of one over the other	There are undeniable facts about the advantages of one over the other
9	Extreme advantage	The obvious advantage of one over the other is beyond doubt
2, 4, 6, 8	Intermediate result of a decision between two neighboring considerations	Applied in a compromise case
Inverse sizes of the above numbers	If, when comparing one element with another, one of the above numbers is obtained (for example, 3), then when comparing the elements in reverse, we will get the inverse number (i.e., 1/3)	

The data of such assessments, obtained from m experts, are summarized in one general table or matrix of comparisons (Table 3) by the corresponding criterion, in each cell of which ij the number $\overline{a_{ij}}$, which is equal to the average sum of the scores of the advantage of the i-th polygon over the j-th by the corresponding criterion, obtained from all m experts:

$$\overline{a_{ij}} = \frac{1}{m} \cdot \sum_{k=1}^{m} a_{ij_k}, \quad (3)$$

where $k = \in \{1, 2, \ldots, m\}$, and m is the number of experts.

For each matrix of comparisons A, there is a solution to the equation

$$A \cdot w = \lambda_{\max} \cdot w, \quad (4)$$

where $\lambda_{\max}$ is the maximum eigenvalue.

3. Matrix of pairwise comparisons of the impact by criteria from the averaged ratings of all experts

Impact	x_1	…	x_i	…	x_n
x_1	$\overline{a_{11}} = 1$	…	$\overline{a_{1i}}$	…	$\overline{a_{1n}}$
…	…	…	…	…	…
x_i	$\overline{a_{i1}}$	…	$\overline{a_{ii}} = 1$	…	$\overline{a_{in}}$
…	…	…	…	…	…
x_n	$\overline{a_{n1}}$	…	$\overline{a_{ni}}$	…	$\overline{a_{nn}} = 1$

For each row of the matrix of comparisons of estimates averaged over “experts”, the components of the eigenvector are sequentially calculated concerning the rows of the matrix:

$$w_1 = \left(\overline{a_{11}} \cdot \overline{a_{12}} \cdot \overline{a_{13}} \cdot \ldots \cdot \overline{a_{1n}}\right)^{1/n},$$
$$w_1 = \left(\overline{a_{21}} \cdot \overline{a_{22}} \cdot \overline{a_{23}} \cdot \ldots \cdot \overline{a_{2n}}\right)^{1/n}, \quad (5)$$
$$w_1 = \left(\overline{a_{31}} \cdot \overline{a_{32}} \cdot \overline{a_{33}} \cdot \ldots \cdot \overline{a_{nn}}\right)^{1/n},$$

which are normalized by division by $\sum_{i=1}^{n} w_i$ and allow us to determine the weighting factors:

$$k_i = \frac{w_i}{\sum_{i=1}^{n} w_i}. \quad (6)$$

After normalization, the resulting vector w gives the importance or priority coefficients that show the contribution of each element to achieving the corresponding goal. These eigenvector components concerning the rows of the comparison matrix are also used to assess the consistency of the experts’ assessments.

After all pairwise comparisons are conducted, the Consistency Index (*CI*) and the *CR* are determined. The *CI*, which provides information about violating the numerical and transitive matrix of comparisons, is an essential element of this model for determining the weight coefficients of the compared impact. Therefore, this index can indicate the “degree of consistency”, i.e., the errors in the ratios $a_{ik} = a_{ij} \cdot a_{jk}$, $k = \overline{1,n}$, $i = \overline{1,n}$, and $j = \overline{1,n}$.

The following formula holds for *CI* [159]:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (7)$$

where n is the number of elements to be compared. For an inversely symmetric matrix, always

$$\lambda_{\max} \geq n. \quad (8)$$

Next, the *CI* obtained is compared with the value resulting from a random selection of numerical comparisons from the scale 1/9, 1/8, …, 1, 2, …, 9, forming a reciprocal (inverse symmetric) matrix.

If the *CI* is divided by the number corresponding to the average random consistency (*RI*) of a matrix of the same order, the result is the *CR*:

$$RI = \frac{CI}{CR}. \quad (9)$$

Table 4 shows the average consistency for different orders’ random (probability) matrices.

The *CR* should be on the order of 10 % or less to be acceptable. In some cases, 20 % can be assumed, but not more. If the *CR* exceeds these limits, experts need to review the problem from the start and check their reasoning about the weighting factors.

After checking the *CR*, proceeding with the synthesis of priorities is necessary. Priorities are synthesized starting from the second level and moving downward. Local priorities are multiplied by the priority of the corresponding element at the higher level and summed for each component according to the importance or priority coefficients of each element it influences at every level of the hierarchy [9].

4. Average random consistency values for random inversely symmetric matrices of different orders

Matrix size	3	4	5	6	7	8	9	10	11	12	13	14	15
Average Random Consistency	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49	1,51	1,48	1,56	1,57	1,59

The priority vector of the WB $P_{vp} = \{P_{vp1}, \ldots, P_{vpn}\}$, consisting of components $P_{vpij}\left(i = \overline{1,n},\ j = \overline{1,3}\right)$, is an integral assessment of the corresponding i-th WB by the respective j-th criterion. For example, for the first WB:

$$\begin{aligned} P_{vp11} &= k_1 \cdot \overline{a_{11}} + k_2 \cdot \overline{a_{12}} + k_3 \cdot \overline{a_{13}}, \\ P_{vp12} &= k_1 \cdot \overline{a_{21}} + k_2 \cdot \overline{a_{22}} + k_3 \cdot \overline{a_{23}}, \\ &\ldots \\ P_{vp1n} &= k_1 \cdot \overline{a_{n1}} + k_2 \cdot \overline{a_{n2}} + k_3 \cdot \overline{a_{n3}}. \end{aligned} \quad (10)$$

Based on the calculated priority vector P_{vpij}, it is possible to rank the WB according to the selected evaluation criterion and compile the priority matrix:

$$\left(\begin{array}{c|ccccc|c} & 1 & 2 & 3 & \ldots & L & \\ \hline x_1 & P_{vp_{11}} & P_{vp_{12}} & P_{vp_{13}} & \ldots & P_{vp_{1L}} & \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \\ x_i & P_{vp_{i1}} & P_{vp_{i2}} & P_{vp_{i3}} & \ldots & P_{vp_{iL}} & \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \\ x_n & P_{vp_{n1}} & P_{vp_{n2}} & P_{vp_{n3}} & \ldots & P_{vp_{nL}} & \\ \hline & & & & & & \end{array}\right). \quad (11)$$

To compare the polygons $VP_1, \ldots, VP_n$ with each other based on vector criteria (see Fig. 1 and Table 1), formulas (3), (5), (6), (10), and (11) are used to obtain the components of the eigenvector concerning the rows of the priority matrix:

$$W_i^* = \sqrt[L]{P_{vpi1} \cdot \ldots \cdot P_{vpiL}}\ , \quad (12)$$

These are normalized by dividing by the $\sum_{i=1}^{n} W_i^*$ and used to determine the weighting coefficients:

$$\overline{W_i^*} = \frac{W_i^*}{\sum_{i=1}^{n} W_i^*}, \quad (13)$$

with these, the integral evaluations of the corresponding i-th WB can be obtained (formula 1).

Stages (3), (4), and (5) are carried out for all levels and groups within the hierarchy.

Next, hierarchical synthesis is applied to weight the eigenvectors by the importance or priority coefficients of the criteria, and the total sums are calculated for all relevant weighted components of the eigenvectors at each lower level of the hierarchy.

$$\begin{array}{l|l} VP_1 & VP_1 = \overline{W_1^*} \cdot P_{vp_{11}} + \overline{W_2^*} \cdot P_{vp_{12}} + \overline{W_3^*} \cdot P_{vp_{13}} + \ldots + \overline{W_L^*} \cdot P_{vp_{1L}}, \\ VP_2 & VP_2 = \overline{W_1^*} \cdot P_{vp_{21}} + \overline{W_2^*} \cdot P_{vp_{22}} + \overline{W_3^*} \cdot P_{vp_{23}} + \ldots + \overline{W_L^*} \cdot P_{vp_{2L}}, \\ \ldots & \ldots \\ VP_n & VP_n = \overline{W_1^*} \cdot P_{vp_{n1}} + \overline{W_2^*} \cdot P_{vp_{n2}} + \overline{W_3^*} \cdot P_{vp_{n3}} + \ldots + \overline{W_L^*} \cdot P_{vp_{nL}}. \end{array} \quad (14)$$

The consistency of the entire hierarchy is found by multiplying each *CI* by the priority or importance coefficient of the respective criterion and summing the resulting values. The result is then divided by a similar expression using the *RI*, corresponding to each priority-weighted matrix's dimensions (Table 3). Notably, the acceptable *CR* should be around 10 % or less. Otherwise, the quality of judgments should be improved by reviewing the method of formulating pairwise comparison questions. If this does not help, the task should be restructured more precisely by grouping similar elements under more significant criteria. Returning to stage (2) is necessary, even if only the uncertain parts of the hierarchy require revision [9].

Then, based on the initial assumption that differences in expert responses are explained by random independent fluctuations around some "true" values, conventional statistical methods of point estimation can be applied to process the evaluation data. Each WB is assigned an average score:

$$x_j = \tfrac{1}{m} \cdot \sum_{i=1}^{m} x_{ij}, \ \ j = 1, 2, \ldots, n\,. \quad (15)$$

These evaluations (15) are considered group assessments. During the comprehensive evaluation procedure, the values of threat indicators and indices are projected onto the corresponding scale values.

The arguments of the target function e_i, which represent the factor indicators in the threat evaluations for the respective criteria components, are expressed in dimensionless scores. To evaluate the factors within partial criteria, three systems of equations are developed:

1. Criterion for assessing the source of the threat:

$$\begin{cases} f_{11}(e^1) = 0,29 \cdot e^1{}_{11} + 0,24 \cdot e^1{}_{12} + 0,19 \cdot e^1{}_{13} + \\ +0,14 \cdot e^1{}_{14} + 0,09 \cdot e^1{}_{15} + 0,05 \cdot e^1{}_{16}, \\ f_{12}(e^1) = 0,2 \cdot e^1{}_{21} + 0,18 \cdot e^1{}_{22} + 0,16 \cdot e^1{}_{23} + \\ +0,13 \cdot e^1{}_{24} + 0,11 \cdot e^1{}_{25} + 0,09 \cdot e^1{}_{26} + \\ 0,07 \cdot e^1{}_{27} + 0,04 \cdot e^1{}_{28} + 0,02 \cdot e^1{}_{29}, \\ f_{13}(e^1) = 0,29 \cdot e^1{}_{31} + 0,24 \cdot e^1{}_{32} + 0,19 \cdot e^1{}_{33} + \\ +0,14 \cdot e^1{}_{34} + 0,09 \cdot e^1{}_{35} + 0,05 \cdot e^1{}_{36}, \\ f_{14}(e^1) = 0,4 \cdot e^1{}_{41} + 0,3 \cdot e^1{}_{42} + 0,2 \cdot e^1{}_{43} + 0,1 \cdot e^1{}_{44}; \end{cases} \quad (16)$$

2. Criterion for determining the pathways of threat impact distribution:

$$\begin{cases} f_{21}(e^2) = 0,29 \cdot e^2{}_{11} + 0,24 \cdot e^2{}_{12} + 0,19 \cdot e^2{}_{13} + \\ +0,14 \cdot e^2{}_{14} + 0,09 \cdot e^2{}_{15} + 0,05 \cdot e^2{}_{16}, \\ f_{22}(e^2) = 0,33 \cdot e^2{}_{21} + 0,27 \cdot e^2{}_{22} + 0,2 \cdot e^2{}_{23} + \\ +0,13 \cdot e^2{}_{24} + 0,07 \cdot e^2{}_{25}, \\ f_{23}(e^2) = 0,33 \cdot e^2{}_{31} + 0,27 \cdot e^2{}_{32} + 0,2 \cdot e^2{}_{33} + \\ +0,13 \cdot e^2{}_{34} + 0,07 \cdot e^2{}_{35}, \\ f_{24}(e^2) = 0,5 \cdot e^2{}_{41} + 0,33 \cdot e^2{}_{42} + 0,17 \cdot e^2{}_{33}; \end{cases} \quad (17)$$

3. Criterion for assessing the recipients of the impact from the threat source:

$$\begin{cases} f_{31}(e^3) = 0,29 \cdot e^3{}_{11} + 0,24 \cdot e^3{}_{12} + 0,19 \cdot e^3{}_{13} + \\ +0,14 \cdot e^3{}_{14} + 0,09 \cdot e^3{}_{15} + \\ +0,05 \cdot e^3{}_{16}, \\ f_{32}(e^3) = 0,5 \cdot e^3{}_{21} + 0,33 \cdot e^3{}_{22} + 0,17 \cdot e^3{}_{23}, \\ f_{33}(e^3) = 0,5 \cdot e^3{}_{31} + 0,33 \cdot e^3{}_{32} + 0,17 \cdot e^3{}_{33}. \end{cases} \quad (18)$$

After evaluating the factors, the values of the partial criteria are calculated. If an additive target function is used, the partial criteria are computed using the following formulas:

1. Criterion for assessing the source of the threat:

$$J_1(e^1) = 0,47 \cdot f_{11}\left(e^1\right) + 0,28 \cdot f_{12}\left(e^1\right) + \\ +0,16 \cdot f_{13}\left(e^1\right) + 0,09 \cdot f_{14}\left(e^1\right), \quad (19)$$

2. Criterion for determining the pathways of threat impact distribution:

$$J_2(e^2) = 0,51 \cdot f_{21}\left(e^2\right) + 0,26 \cdot f_{22}\left(e^2\right) + \\ +0,14 \cdot f_{23}\left(e^2\right) + 0,09 \cdot f_{24}\left(e^2\right), \quad (20)$$

3. Criterion for assessing the recipients of the impact from the threat source:

$$J_3(e^3) = 0,67 \cdot f_{31}\left(e^3\right) + 0,2 \cdot f_{32}\left(e^3\right) + \\ +0,13 \cdot f_{33}\left(e^3\right), \quad (21)$$

4. Integral criterion for threat assessment:

$$J_\Sigma(e) = 0,65 \cdot J_1(e^1) + 0,23 \cdot J_2(e^2) + \\ +0,12 \cdot J_3(e^3). \quad (22)$$

Thus, with this approach, the task of identifying WB's environmental safety level is reduced to comparing the obtained score assessments and ranking them based on a set of partial or integral criteria.

According to the theory of the AHP, it is necessary to form the essential and sufficient elements at each level of the generalized factors for analyzing the environmental safety status of WB (Fig. 2). The hierarchical scheme

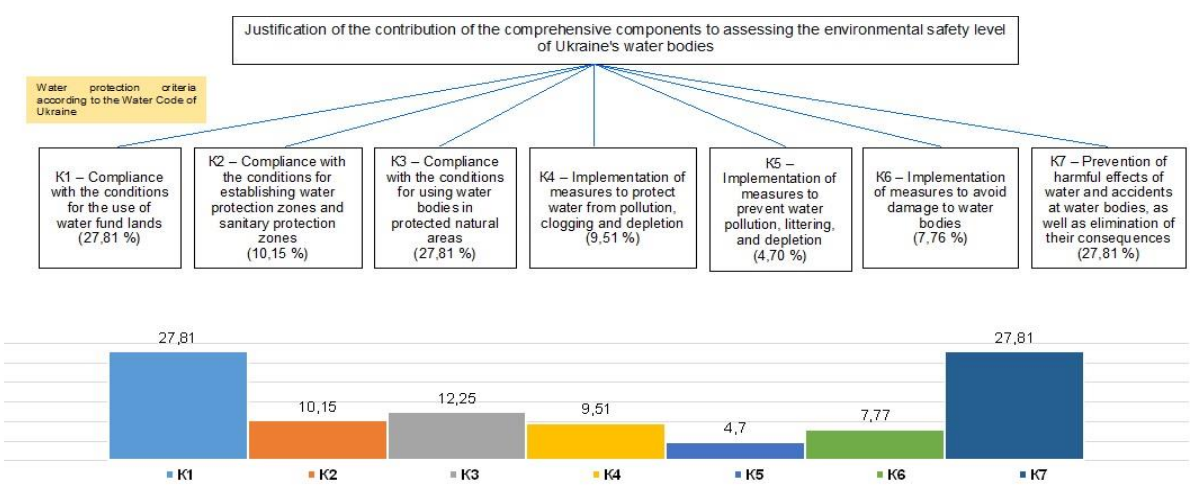

Fig. 2. Weighted contribution of each of the complex component criteria K in assessing the level of ecological safety of water bodies in Ukraine

titled "Justification of the Contribution of Comprehensive Assessment Components to the Level of Environmental Safety of Water Bodies in Ukraine" was developed based on expert ecological-analytical evaluation using the AHP method by T. Saaty [5].

The overall consistency score of the hierarchy is 0.02903, which meets the conditions for valid application of AHP. The generalized weight coefficients of the contributions of each element were obtained using computer software that implements the method.

Determining the environmental safety of WB, in the context of the requirements of the Water Code of Ukraine (in particular, Section Four on water protection), is logically structured using integrated criteria K1 to K7.

The criteria cover all critical aspects of the evaluation objective, while striving to minimize their number: K1 – Compliance with the conditions for the use of water fund lands; K2 – Compliance with the conditions for establishing water protection zones and sanitary protection zones; K3 – Compliance with the conditions for using WB in protected natural areas; K4 – Implementation of measures to prevent water pollution, littering, and depletion; K5 – Compliance with conditions for the placement of enterprises and related requirements; K6 – Implementation of measures to avoid damage to WB; K7 – Prevention of harmful effects of water and accidents at WB, as well as elimination of their consequences.

Each criterion from K1 to K7 jointly forms a generalized integral (emergent) contribution toward achieving the defined goal and reflects the full range of scientific and applied regulatory requirements established in the legal framework of Ukraine. The use of the AHP allows for expert-analytical determination of the contribution of each of these elements to the prioritization of the stated comprehensive objective.

The AHP methodology requires the formulation of verbal question blocks addressed to expert analysts for pairwise comparison of elements at each level. These comparisons evaluate each criterion's dominance, priority, and relative contribution compared to others using the specific Saaty scale.

The questions are formulated for the level of elements K1 to K7: *"Which criteria K is more important, essential, or desirable, compared to each of K1 to K7, in achieving the hierarchical goal?"*. After conducting pairwise comparisons, the assessment and *CI* of expert opinions are determined. These must align with the matrix dimensions or number of elements being compared, which are mathematically justified and experimentally confirmed by T. Saaty [5]. This requirement is one of the fundamental ideological premises for applying AHP correctly.

The criteria for sources of natural and anthropogenic formation of the current state of WB include the following: FIP1 – Impacts of processes in the abiotic environment of WB; FIP2 – Impacts of processes in the biotic environment of WB; FIP3 – Impacts of processes associated with anthropogenic (technogenic) pressure of WB (Fig. 3).

For the FIP1–FIP3 criteria level, the questions are formulated as: *"How is the influence of element FIP more important, more probable, more significant, etc., compared to each of the elements FIP1 to FIP3 as sources of natural and anthropogenic formation of the state of WB, within the aspects of compliance with*

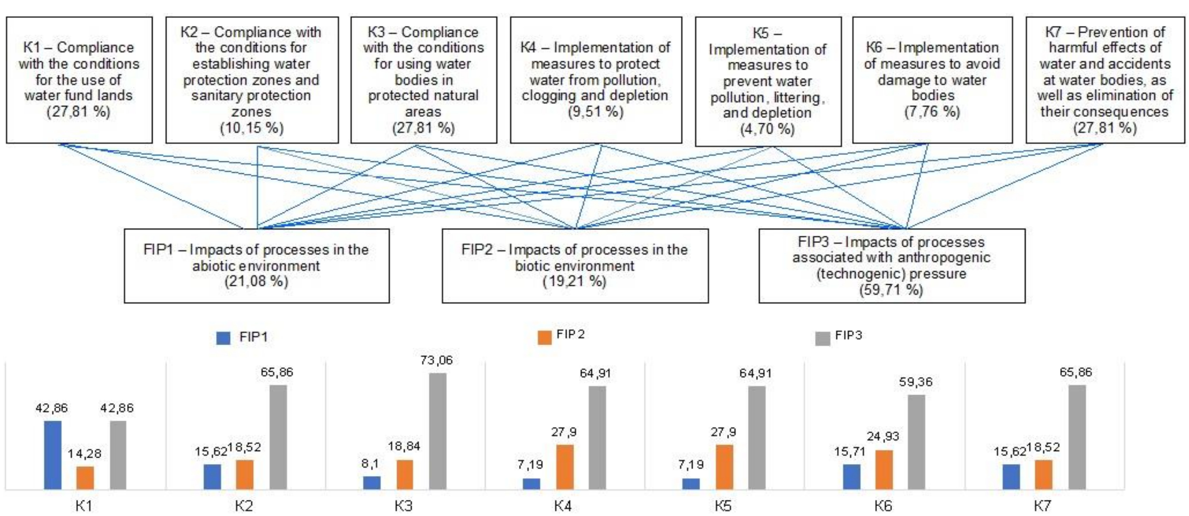

Fig. 3. Weight contribution of each of the elements of the FIP level in each criterion of the K level

each criterion of the higher level K1 to K7?”. Which, in turn, as characteristic parameters of the predicted impact on a WB in the aspects of each element of the higher level FIP1, …, FIP3 can be generally described as sources of impact, taking into account all the necessary elements with characteristic parameters of the predicted impact on WB CP1, …, CP4. The following are taken as characteristic parameters of the predicted impact on WB: CP1 – Quantitative characteristics of the predicted impact; CP2 – Qualitative characteristics of the expected impact; CP3 – Conditions for the accumulation of risks of the impact hazard; CP4 – The possibility of regulating the safety of the impact (Fig. 4) [9].

For the CP1–CP4 level, the evaluation questions are posed as: *“How does the assessed criterion CP dominate the identified FIP processes, and to what extent is it more significant, more probable, more influential, etc., in comparison with each of the listed CP1 to CP4 elements?”.* The most difficult to systematize is to substantiate the necessary and sufficient elements to summarize all the negative impacts on the environment that should be selected as the resulting types of consequences of natural and anthropogenic loading (NAP1, …, NAP7), which are already enshrined in regulatory legal acts on environmental safety, in particular in references to the Water Code of Ukraine, and have been studied by scientists before, are being studied now and will be studied in the future to assess and minimize such impacts effectively. The following negative consequences of natural and anthropogenic loading on WB are defined in the general structural and logical scheme: NAP1 – Landscape change (dams, canals, reservoirs, ponds, etc.); NAP2 – Destruction of soil cover (beams, washouts, mudflows, etc.); NAP3 – Deformation of the Earth’s crust layers (landslides, sinkholes, etc.); NAP4 – Chemical pollution of territories and WB; NAP5 – Violation of the water regime of territories (drainage, flooding, waterlogging, desertification); NAP6 – Risk of increased morbidity among the population; NAP7 – Loss of biodiversity of territories and WB (Fig. 5).

For the criteria level NAP1 to NAP7, evaluation questions are posed as follows: *“How do the identified processes associated with the evaluated NAP element dominate, and to what extent are they more significant, more probable, more impactful, etc., compared to each of the NAP1 to NAP7 elements, in the context of each of the higher-level criteria CP1 to CP4?”.*

The final level of the systematic hierarchical approach to achieving water safety in terms of environmental security of the state is divided into four directions of generalized assessment components (GC), designated as GC1 to GC4: GC1 – Justification of the environmental status of water safety components; GC2 – Justification of the level of anthropogenic pressure and its influence on WB; GC3 – Justification of the composition of typical pollutants in WB; GC4 – Justification of the level of background pollution in WB (Fig. 6).

For the lowest level elements GC1 to GC4, the comparative evaluation questions are formulated as: *“What is the contribution and priority of each GC element in pairwise*

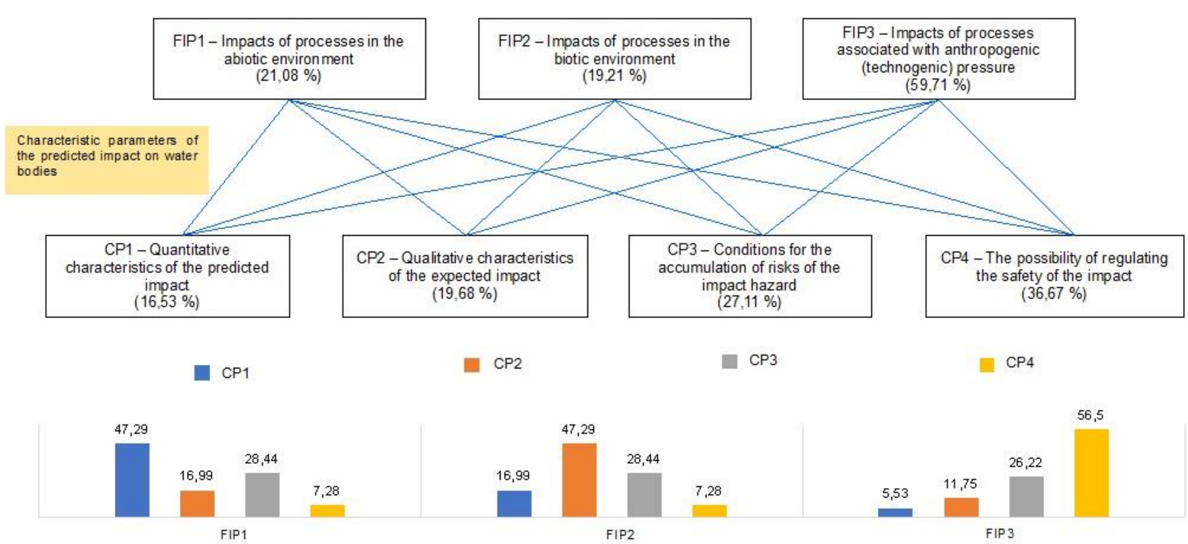

Fig. 4. Weight contribution of each of the elements of the CP level in each of the criteria of the FIP-level

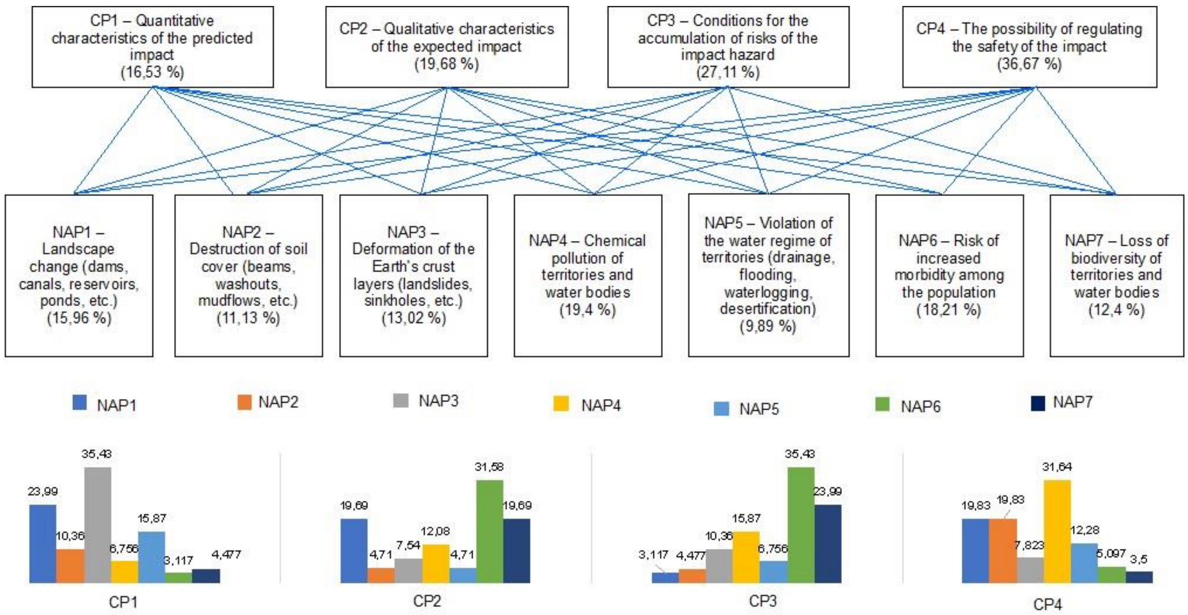

Fig. 5. Weight contribution of each of the elements of the CP level in each criterion of the FIP level

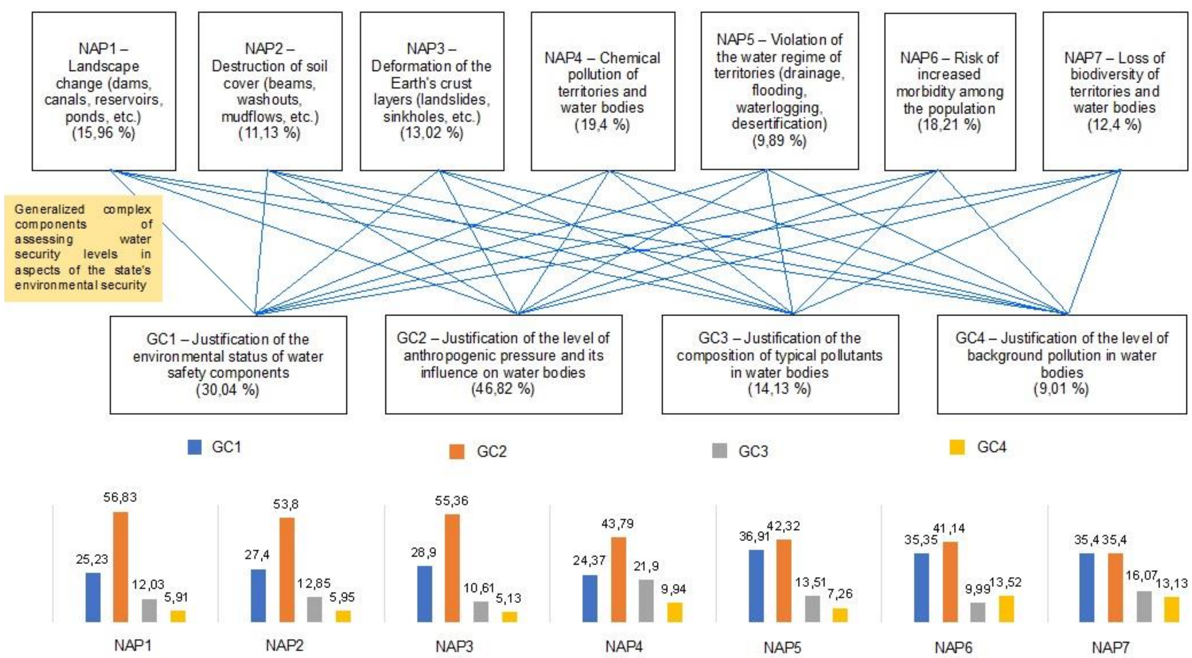

Fig. 6. Weight contribution of each of the elements of the GC level in each criterion of the NAP level

comparison with the other GC1 to GC4 elements, in evaluating the influence of each of the previously defined criteria NAP1 to NAP7, which describe the negative consequences of natural and anthropogenic pressure on the state's WB?". The objectivity of solving the task of identifying the environmental safety level of WB is conditioned by the requirements of the Water Code of Ukraine on water protection and by the adequacy of the criteria in covering the whole chain of evaluation factors and their characteristics [9].

In the developed structural and logical model shown in Figure 7, pairwise comparisons are conducted regarding the dominance of one element over another. These comparisons are then expressed in integers according to the Saaty scale (Table 2). Standard statistical point estimation methods can be applied to process the evaluation data based on the assumption that differences in expert responses are caused by random, independent fluctuations around specific "true" values.

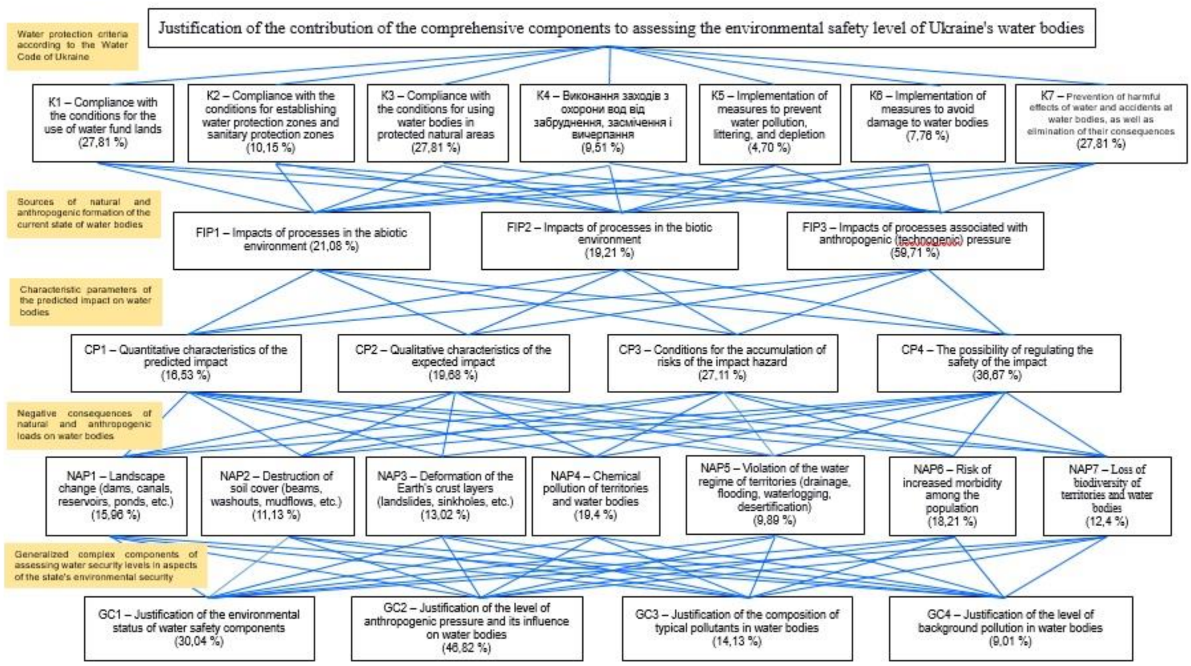

Fig. 7. Hierarchical structural and logical scheme for identifying the level of ecological safety of water bodies

During the identification procedure, the values of indicators and indices of the respective characteristics are projected onto corresponding scales. The arguments of the identification objective function e_i, which represent the features of evaluation factors according to the relevant components of the criteria, are expressed as dimensionless score values.

Thus, the task of identifying WB's environmental safety level is reduced to comparing the obtained score-based assessments and ranking them according to a set of partial or integral criteria (index).

The definition of a set of environmental protection measures without analyzing the rationality of economic use of the catchment area of watercourses based on the assessment of the impact of negative factors that accelerate degradation processes, and positive factors that may lead to stabilization and improvement of the ecological status of river basins is costly and inefficient. Selecting the most effective and economically feasible environmental protection measures is necessary to reduce the intensity of degradation processes in small river basins. The water-protection effectiveness of these measures is evaluated based on: the level of protection from dissolved and sorbed agrochemicals; the duration and rate of manifestation of the protective effect; their universality and the number of additional effects (e.g., increased agricultural productivity, additional yields due to increased moisture reserves, prevention of water erosion, gully formation, and bank abrasion, reclamation of low-productivity lands, reduction of reservoir siltation, increase in base river flow, and improvement of meadow-forest landscapes and microclimate conditions); and the economic costs of implementing each environmental protection measure [13].

It is important to note that researchers studying the protection of water resources during armed conflicts have emphasized that, despite international legal norms for protecting WB during armed conflicts, such norms have failed to safeguard this critically important resource [13] adequately. As demonstrated by the war in Ukraine and other military conflicts [14], international legal norms for protecting WB under such conditions are neither functional nor practical.

Conclusions. A method for identifying the level of ecological safety of WB under conditions of uncertainty has been developed, which is solved by methods of system analysis using a multicriteria approach. With this approach, identifying WB's environmental safety level is reduced to comparing the obtained score estimates and ranking them by a set of partial or integral criteria (index).

Using the hierarchy analysis method to substantiate the contribution of complex components in assessing the ecological safety of WB in Ukraine is a key element that allowed the best solution to be chosen for applying the assessment methodology. First of all, it is based on the terms: “usefulness”, “limitations”, “opportunities” and “risks”, which are first assessed separately as components of the requirements of the Water Code of Ukraine, and then, through a comparative assessment, are combined on a single scale and synthesized into an analytical solution, where each element has its priority and weight, and in general – combines a single holistic approach to achieve a specific result, namely the ecological safety of WB – where the first of the management measures is a substantiated scientific assessment.

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МЕТОД ІДЕНТИФІКАЦІЇ РІВНЯ ЕКОЛОГІЧНОЇ БЕЗПЕКИ ВОДНИХ ОБ'ЄКТІВ

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Анотація. *Розроблено метод ідентифікації рівня екологічної безпеки водних об'єктів в умовах невизначеності, що розв'язується методами системного аналізу з використанням багатокритеріального підходу. Вирішення задачі підвищення адекватності ідентифікації полягає не тільки в пошуку адекватнішого критерію, але й у використанні декількох критеріїв, що описують різносторонньо мету ідентифікації рівня екологічної безпеки водних об'єктів і доповнюють один одного. Визначення екологічної безпеки водних об'єктів в аспектах вимог Водного Кодексу України доцільно структурувати за комплексними критеріями. Метод ідентифікації рівня екологічної безпеки водних об'єктів використовує прийоми обчислення бальних оцінок різних факторів, що характеризують окремі складові конкретних критеріїв. Об'єктивність вирішення задачі ідентифікації рівня екологічної безпеки водних об'єктів обумовлюється забезпеченням критеріями достатньо повного ланцюга оцінювання ознак загроз. Процедура проведення ідентифікації базується на підходах багатокритеріальної оцінки з подальшою згорткою її до інтегрального індексу, який буде визначати рівень екологічної безпеки водного об'єкту. При проведенні процедури ідентифікації значення індикаторів і індексів відповідних характеристик проектуються на значення відповідних шкал. Аргументи цільової функції ідентифікації, які є ознаками чинників оцінювання за відповідними складовими критеріями, виражаються балами в безрозмірному вигляді. Задача ідентифікації рівня екологічної безпеки для природних чи техногенних об'єктів в умовах невизначеності розв'язується методами системного аналізу з використанням багатокритеріального підходу і зводиться до порівняння отриманих бальних оцінок і ранжування їх за сукупністю часткових критеріїв чи інтегральним критерієм (індексом). Використання методу аналізу ієрархії для обґрунтування вкладу комплексних складових оцінювання рівня екологічної безпеки водних об'єктів України є ключовим елементом, що дозволило вибрати найкраще рішення щодо застосування методології оцінювання.*
Ключові слова: *антропогенне навантаження, водні об'єкти, екологічна безпека, природно-технічні геосистеми*