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PECULIARITIES OF MULTI-CRITERIA ASSESSMENT OF ECOSYSTEM RISKS

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The growth of anthropogenic impact on the environment, caused by population growth, urbanization and intensification of industrial and agricultural production, leads to ecosystem degradation and climate change. This, in turn, creates significant ecosystem risks – the likelihood of negative changes in ecosystems under the influence of natural or anthropogenic factors, which leads to biodiversity loss, disruption of ecosystem functioning and negative impact on people and the economy. However, the complexity of ecosystems and the interaction of numerous factors complicate the assessment process and require the use of a comprehensive multi-criteria approach. The article considers the concepts of ecosystem risk assessment through the prism of multi-criteria, analyzes existing models (qualitative and quantitative) and demonstrates the practical application of this approach. Ecosystem risk assessment is carried out using various methods, including: analysis of historical data, modeling of ecological processes, expert assessments and monitoring. Multi-criteria assessment is one of the most common methods, since it takes into account a wide range of interrelated factors.

Keywords: *ecosystem risk, modeling of ecological processes, multi-criteria assessment, environmental monitoring, anthropogenic factors*

Хлєстова Ольга, Бурко Вадим, Єлістратова Неллі. Особливості багатокритеріальної оцінки ризиків екосистеми

Зростання антропогенного впливу на довкілля, спричинене зростанням населення, урбанізацією та інтенсифікацією промислового та сільськогосподарського виробництва, призводить до деградації екосистем та зміни клімату. Це, зі свого боку, створює значні екосистемні ризики – ймовірність негативних змін в екосистемах під дією природних або антропогенних факторів, що призводить до втрати біорізноманіття, порушення функціонування екосистем і негативного впливу на людей та економіку. Проте складність екосистем і взаємодія численних факторів ускладнюють процес оцінки та потребують застосування комплексного багатокритеріального підходу. У статті розглянуті концепції оцінки екосистемних ризиків через призму багатокритеріальності, аналіз наявних моделей (якісних та кількісних) і демонстрація практичного застосування цього підходу. Оцінка екосистемних ризиків здійснюється за допомогою різних методів, що передбачають: аналіз історичних даних, моделювання екологічних процесів, експертні оцінки та моніторинг. Багатокритеріальна оцінка є одним із найбільш поширених методів, оскільки вона враховує широкий спектр взаємопов’язаних факторів.

Ключові слова: *екосистемний ризик, моделювання екологічних процесів, багатокритеріальна оцінка, моніторинг довкілля, антропогенні фактори.*

Introduction. Population growth, urbanization, industrial and agricultural development lead to an increase in anthropogenic impact on the environment, accompanied by ecosystem degradation, climate change and other negative consequences. Ecosystem risk is the probability that a certain ecosystem will undergo negative changes due to natural or anthropogenic factors [1]. This can lead to loss of biodiversity, disruption of ecosystem functioning and, as a result, negative impacts on people and the economy. Many countries have signed international agreements that provide for the assessment and management of ecosystem risks. For example, the Convention on Biological Diversity and the Paris Agreement. There is an urgent need to understand what threats exist for natural systems, identify risks and develop effective strategies for their preservation. The study of the features of ecosystems is accompanied by problems associated with their complexity, interaction and influence of various factors. To assess ecosystem risks, it is necessary to take into account a large number of criteria, such as climate change, pollution, biodiversity loss, etc., which complicates the analysis process and requires the use of special methods.

The need for informed management decisions: Ecosystem risk assessment is an important component of the decision-making process for natural resource management. The results of such an assessment allow for the development of effective measures for environmental protection, climate change adaptation and sustainable development.

Multi-criteria ecosystem risk assessment is a necessary tool for ensuring sustainable development and conservation of natural resources. It allows for the identification of potential threats, assessment of their consequences and development of effective management strategies.

The purpose of this work – Applying the concept of ecosystem risk assessment through the prism of multi-criteria, qualitative and quantitative models, to demonstrate the practical application of this approach.

Materials and methods. Various methods are used to assess ecosystem risks, including: analysis of historical data on ecosystem changes, modeling of ecological processes, expert assessments, monitoring of ecosystem status. Multi-criteria assessment is one of the most common methods, as it allows taking into account a wide range of factors that affect the state of ecosystems.

Analysis of the literature shows that contradictory approaches are used to define the concept of “ecosystem risk”. It is often identified with man-made hazard. In [1], risk is understood as the conditional probability of a dangerous event occurring in the natural environment in numerical reproduction.

Therefore, an important element in the study of environmental risk (including the anthropogenic component) is the establishment of criteria for functional dependencies on the relevant parameters and the assessment of its magnitude [2; 3]. There are different approaches. Thus, in, potential environmental risk is expressed as a function of the following parameters:

- type of land use (economic use of land);
- management technologies (territorial concentrations of industrial and agricultural production, transport, construction);
- dangerous technogenic processes and phenomena;
- population density;
- landscape sustainability potential.

In [4] there is a formula for determining the values of potential environmental risk, which takes the form:

$$R = \frac{1}{(1 - X)^{\alpha}}, \tag{1}$$

where R – the value of the eco-risk;

X – the corresponding anthropogenic load on the ecosystem ($0 \le X \le 1$);

α – the indicator of the susceptibility of a given type of ecosystem to a certain type of anthropogenic load (the value of the system’s stability), $\alpha \ge 1$.

The author [5] proposes to determine the ecological risk potential (E) of a territory using the formula:

$$E = \frac{T}{C} + H, \tag{2}$$

where T – potential of man-made environmental impact;

C – potential of the natural environment’s resilience to man-made impacts;

H – potential of adverse natural-anthropogenic processes.

In this case, the stability potential C is expressed as a simple algebraic sum of the following quantities: the meteorological potential of the atmosphere, the stability potential of natural waters and soils, and the biotic potential. There is no doubt about the correctness of the qualitative nature of the dependence of risk on the specified parameters (the risk is greater, the higher the degree of technogenic load and the influence of natural and anthropogenic processes on the formation of danger and the lower the level of environmental stability). However, some parameters included in formula (1) are functionally dependent on others. This does not make it possible to adequately assess the degree of ecological danger. A number of researchers [3] are based on the fact that the study of natural variability of ecological processes under the influence of biotic and abiotic factors is quite successfully used to predict the eco-risk of small (closed) natural systems.

When studying ecosystem risks in open natural systems, as a rule, there is no possibility of studying "pure ecological structures" [5], and it is necessary to take into account the criteria associated with material, energy, biological processes occurring in the natural environment.

In recent decades, a direction has developed in which theoretical models of complex systems "nature" and "society" are created, taking into account the criteria that determine the dynamics of ecosystems under the influence of parameters of the state of the environment, the level of pollution, resource supply conditions, and the recreational capacity of ecosystems. The authors of many studies note that to assess the risk of ecosystems, it is necessary to study dynamic phenomena of a critical order – the ability to enter an unstable equilibrium state of self-oscillations or bifurcation.

At the same time, the direction of creating matrices for determining quantitative criteria for the risk of environmental safety and the complex ecological impact of production processes on the environment is developing.

However, the implementation of these methods is hindered by the lack of specific indicators and the possibility of transitioning from qualitative criteria to quantitative ones to determine the degree of environmental safety [5].

The definition of ecosystem risk is based on ecological risk, but requires the use of a wider range of criteria and indicators, because although ecological risk and ecosystem risk are closely related, they have important differences. Ecological risk focuses on the impact of a particular factor on a single component of the environment (for example, oil pollution of water, the impact of pesticides on a bee population). Ecosystem risk, in turn, considers the impact on the entire ecosystem, including the complex interactions between its components and the consequences for the functioning of the entire system. It takes into account not only direct impacts, but also cascading effects, as well as consequences for the services that the ecosystem provides to people. Key differences include the scale of assessments that determine whether ecological risk is local or regional, while ecosystem risk can be local, regional or global, depending on the characteristics of the biome. Also, ecological risk is generally easier to assess because it focuses on one or a few indicators, while ecosystem risk is much more complex because it needs to take into account the many interactions between different components of the ecosystem. Another difference is that ecological risk can cause local damage (e. g., fish kills in a polluted river), while ecosystem risk can lead to irreversible changes in the functioning of the entire ecosystem (e.g., coral reef collapse, desertification). They also manifest themselves differently over time: ecological risk can manifest itself quickly (e. g., oil spills), while ecosystem risk can develop gradually over a long period of time (e. g., climate change). Finally, ecosystem risk always takes into account impacts on ecosystem services (clean water provision, pollination, climate regulation), which are not central to the assessment of ecological risk [6; 7].

Ecosystem risk assessment is a complex and multi-step process that typically includes the following criteria. In accordance with the key differences between the concepts of "ecological" and "ecosystem" risk, it is necessary to define criteria for assessing ecosystem risk (Table 1).

Ecosystem risk assessment is carried out using models that take into account complex interactions between ecosystem components. The assessment results are used to develop risk management strategies and make decisions on environmental protection. It is important to note that the development of a single universal methodology for assessing ecosystem risk is difficult due to the diversity of ecosystems and stressors.

To ensure the requirements considered, a methodology has been proposed that will allow, taking into account quantitative and qualitative indicators, to simultaneously determine the level of ecosystem risk.

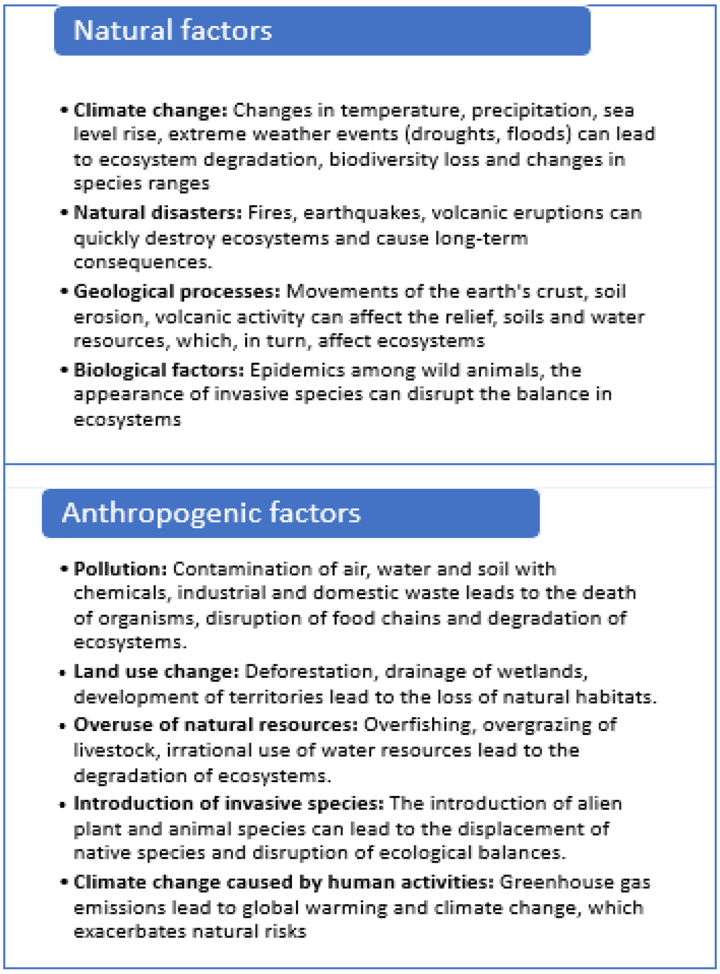
Results. When studying the features of ecosystem risk, the potential impact of various factors (natural and anthropogenic) on ecosystem risk was determined (Fig. 1) [7].

To understand the limits of sustainable development and find ways to achieve balanced interaction between humanity and nature, the concept of ecosystem capacity was studied – the ability of an ecosystem (be it a forest, ocean, river or even the planet Earth as a whole) to constantly absorb the negative impact of anthropogenic activity and provide resources for human activity without harming its functioning and preserving biodiversity, the amount of technogenic resource consumption that a given ecosystem can support without exceeding its ability to recover. Ecosystem capacity

Table 1

Key criteria for ecosystem risk assessment

Stages of ecosystem risk assessment	Purpose of assessment	Ecosystem risk factors
Identifying ecosystem stressors	Identifying factors that can negatively impact an ecosystem	Pollution, climate change, overexploitation of resources
Assessment of stressor exposure in an ecosystem	Assessment of level and duration of exposure	Contaminant concentration Duration of exposure
Ecosystem Sensitivity Assessment	Determining the susceptibility of an ecosystem to a stressor based on its structure, function, and resilience	Changing ecosystem structure Changing ecosystem function Changing ecosystem resilience
Ecosystem Impact Assessment	Determining the Probability and Scale of Negative Consequences of a Stressor's Impact on an Ecosystem	Probable Negative Consequences (Minor, Minor, Moderate, Significant, Catastrophic) Scale of Negative Consequences
Uncertainty assessment of ecosystem indicators	Accounting for uncertainty in data and models used for risk assessment	Incomplete data Model imprecision
Assessment of socio-economic impacts associated with changes in ecosystem services	Assessment of the impacts of ecosystem degradation on societal well-being	Deterioration of public health Economic losses Loss of recreational opportunities
Determining ecosystem status indicators	Selecting appropriate biological, chemical and physical indicators for monitoring ecosystem status	Chemical, physical, biological indicators
Scenario development	Forecasting possible scenarios for future events, taking into account different levels of stressor impact	Pessimistic, Optimistic Moderate



Natural factors

- **Climate change:** Changes in temperature, precipitation, sea level rise, extreme weather events (droughts, floods) can lead to ecosystem degradation, biodiversity loss and changes in species ranges
- **Natural disasters:** Fires, earthquakes, volcanic eruptions can quickly destroy ecosystems and cause long-term consequences.
- **Geological processes:** Movements of the earth's crust, soil erosion, volcanic activity can affect the relief, soils and water resources, which, in turn, affect ecosystems
- **Biological factors:** Epidemics among wild animals, the appearance of invasive species can disrupt the balance in ecosystems

Anthropogenic factors

- **Pollution:** Contamination of air, water and soil with chemicals, industrial and domestic waste leads to the death of organisms, disruption of food chains and degradation of ecosystems.
- **Land use change:** Deforestation, drainage of wetlands, development of territories lead to the loss of natural habitats.
- **Overuse of natural resources:** Overfishing, overgrazing of livestock, irrational use of water resources lead to the degradation of ecosystems.
- **Introduction of invasive species:** The introduction of alien plant and animal species can lead to the displacement of native species and disruption of ecological balances.
- **Climate change caused by human activities:** Greenhouse gas emissions lead to global warming and climate change, which exacerbates natural risks

Fig. 1. The impact of various factors on ecosystem risk

(or ecosystem capacity) is the maximum possible number of living organisms that a given ecosystem can support over a long period of time, taking into account its resources and ability to recover.

To take these factors into account when assessing the level of ecosystem risk, the ratio of the ecosystem capacity under study and anthropogenic impact was determined, and ecosystem stability coefficients were calculated. As a method for such an assessment, the creation of a balance model "Consumption – Reproduction" of matter and energy was proposed, which allows determining the magnitude of the impact on the ecosystem and predicting the boundary conditions of its stability. Accordingly, the methodology for determining ecological capacity is reduced to calculating the main production functions of the ecosystem and the natural level of fluctuations of its ecologically significant parameters. Exceeding this level occurs as a result of anthropogenic impacts in the ecosystem, which has reached the limit of stability, and can lead to its degradation. Taking this approach as the basic one, it was determined according to the following algorithm:

1. Ecological capacity of the ecosystem, conditions. t/year:

$$T_{ej} = \sum_{n=1}^{n} E_i X_i \tau_i, \qquad (3)$$

where T_{ei} – ecosystem capacity, conditions t/year:

E_i – ecosystem capacity of the atmosphere, hydrosphere, lithosphere ($I = 1, 2, 3$) t/year;

X_i – coefficient of variation for natural fluctuations in the content of the main substance in the i-environment ($i = 1, 2, 3$).

For example, the coefficient of variation for atmospheric air is the natural oxygen content, $X_1 = 3 \cdot 10^{-6}$. Coefficient of variation for water – the volume of water inflow into the inlet of a water body: rivers, lakes, bay $X_2 = (4 \pm 0,2) \cdot 10^{-5}$ [4].

There are no universal values of the coefficients of variation for biota, but based on data on the dispersion of the values of the production of biocenoses (depending on the type of biocenose), we accept for the city – $X_3 = 0.05$, for a nature reserve $X_3 = 0.15 – 0.5$,

τ_i –mass conversion factor into conventional tons ($\tau_1 = 0.46$ conditional t/t,

$\tau_2 = 0.3$ conditional t/t, $\tau_3 = 0.37$ conditional t/t).

When calculating the ecological capacity of the ecosystem environment, the basic methodology [1] uses empirical values of ecologically significant parameters in each environment. In order to eliminate inaccuracies in the calculations of the ecosystem capacity of the environment, it is proposed to introduce additional calculations of these parameters.

2. The ecological capacity of atmospheric air is calculated by the volume of atmospheric oxygen reproduction, as the main parameter of the intensification of biotic processes of natural decomposition of pollutants, t/year:

$$E_1 = V_1 \cdot C_1 \cdot F_1, \qquad (4)$$

where $V_1 = S_T \cdot h_z$ – extensive parameter, which is determined by the size of the ecosystem's territory, km^3;

S_T – ecosystem area, thousand km^2;

$h_z = 0.5$ km – the height of the air layer exposed to man-made pollution is given, taking into account the height of the hilly terrain;

F_1 – the rate of multiple renewal of the mass of oxygen in the atmosphere, year^{-1}:

$$F_1 = \frac{5589{,}6 \cdot v}{\sqrt{V_1}}, \qquad (5)$$

where C_1 –oxygen reproduction in atmospheric air, $C_1 = 21.1$ t/km^3;

v – average air velocity in the ecosystem region [4].

Total oxygen reproduction is calculated as the sum of reproduction in the context of biogeocenoses of the ecosystem [4].

$$C_1 = \sum_{n=1}^{n} Y_n = \sum_{n=1}^{n} S_n^{bgc} \cdot P_n, \qquad (6)$$

where S_n^{bgc} – area of the n-th biocenosis;

P_n – amount of oxygen released per unit area of ecosystem biomass for vegetation in the ecosystem zone, $P_n = 1.0–10.0$ t/km^2 [4].

3. Calculation of the ecological capacity of the hydrosphere ($i = 2$) and lithosphere ($i = 3$) is determined according to the formula:

$$E_i = V_i \cdot C_i \cdot F_i, \qquad (7)$$

where V_i – an extensive parameter determined by the size of the ecosystem,

F_i – the rate of multiple renewal of the volume of water and plant biomass, respectively, year^{-1};

C_i – the content or concentration of the main ecologically significant substances in the aquatic environment or lithosphere, t/km^2 или t/km^3.

For example, for surface waters, t/year

$$E_2 = V_2 \cdot C_2 \cdot F_2, \qquad (8)$$

where V_2 – the total average annual volume of all surface watercourses: rivers or water area (10 km^2) of the sea, which are included in the ecosystem territory.

For the aquatic environment, the biomass concentration, parameter $C_2 = 10^9$, t/km^3 [4].

F_2 – the rate of multiple renewal of water in the aquatic ecosystem:

$$F_2 = \frac{0{,}0315 \cdot f + 3 \cdot 10^{-6} \omega S}{V_2}, \tag{9}$$

where f is the sum of water flows in watercourses,

$$f = \frac{V_{los} \cdot K}{\tau}, \tag{10}$$

where V_{los} – volume of water inflow, catchment area, м^3

τ – period, year;

ω – average annual precipitation, mm/year;

S – total surface water catchment area, m^2;

K – coefficient of multiple water renewal in a water body. The rate of multiple water renewal (sea, bay area) is assumed to be 50–60 times natural renewal [8].

Calculation of ecological capacity for the earth's surface ecosystem

$$E_3 = V_3 \cdot C_3 \cdot F_3, \tag{11}$$

where V_3 – equals the total area of the ecosystem ($V_3 = S_1$), km^2;

$C_3 = 1{,}5$ – the density of distribution over the surface of dry matter biomass in the ecosystem (adopted taking into account the coefficient of specific greening of the territory);

$$F_3 = \frac{P_B}{B}, \tag{12}$$

where F_3 – biomass renewal rate, 1/year,

P_B – average annual dry matter productivity $P_B = 3–10$ t/year for the reserve [8];

B – average annual biomass of organic matter, determined by absolute dry weight, $B = 0.05–0.03$ t/km^2.

The studies assessed the anthropogenic impact (Ui) by ecosystems: atmosphere, hydrosphere, lithosphere ($i = 1, 2, 3$).

Anthropogenic impact on the atmosphere is proposed to be determined by the actual consumption of oxygen used to neutralize emissions from pollution sources. The total annual amounts of pollutants $Wn(j)$ entering the atmosphere that bind oxygen are taken into account. The most common of them are carbon oxides ($j = 1$), nitrogen oxides ($j = 2$), sulfur dioxide ($j = 3$).

The annual amount of oxygen consumption for production and economic purposes is calculated by the formula:

$$U_1 = \sum_{n=1}^{n} W_{1(j)} I_{za\,j} \delta_j, \tag{13}$$

where U_1 – annual oxygen consumption by major pollutants (enterprises or transport), thousand tons;

$W_{1(j)}$ – annual volumes of pollutants entering the atmosphere for each j-substance, standard tons;

δ_j – conversion factor into conventional volumes of oxygen consumption, depending on molar masses. For carbon monoxide 0.571, nitrogen oxide 0.696, sulfur dioxide 0.5 [9];

I_{zaj} – individual pollution index for the jth substance in the air environment.

The authors proposed that when determining the annual levels $Wn(j)$ of pollution from the nth source for industrial (gaseous, liquid, solid), as well as household waste, their complex pollution indices should be taken into account. For the atmosphere, (I_{zaj}) is calculated – the relative hazard of impurities, and their toxicity:

$$I_{za} = \sum_{j=1}^{n} \left(\frac{C_j}{MPC_{sd}} \right)^{a_j}, \tag{14}$$

where MPC_{sd} – maximum permissible average daily concentration of the substance, mg/m^3;

C_j – average concentration of the jth substance in a given environment, mg/m^3;

a_j – the coefficient of reducing the degree of harmfulness of a substance to the degree of harmfulness of sulfur dioxide, which depends on the hazard class of the pollutant [9].

Based on statistical data and the proposed calculation method, the anthropogenic impact on the atmosphere was determined for further assessment of ecosystem risk (Table 2).

5. Anthropogenic impact on surface water bodies is characterized by the volume of water required to dilute harmful substances (considered as liquid waste), polluted effluents to their MPCs in water bodies of fishery importance, as well as the volume of irreversible water consumption.

The total annual volume of water required to "compensate" for pollution:

$$U_2 = V_n I_{2(j)} + V_b, \tag{15}$$

where U_2 – the level of pollution of surface water bodies of the ecosystem, expressed in standard tons/year of clean water required for wastewater dilution;

V_n – volume of contaminated effluent, thousand m^3;

$I_{2(j)}$ – individual pollution index for the jth substance of the most dangerous pollutant in the

Table 2

Anthropogenic load on the air environment of the ecosystem

No.	Indicator	Years					
		2008	**2010**	**2012**	**2014**	**2016**	**2018**
1	Emissions from stationary and mobile sources: total, thousand tons, W	445.0	454.2	430.0	449.7	386.9	310.4
2	By substance: nitrogen oxides, W_{NOx}, thousand tons	28.6	28.6	16.0	15.9	23.6	18.1
3	Dioxide and other sulfur compounds, thousand tons	30.2	28.5	24.7	24.8	20.1	16.5
4	Carbon monoxide, thousand tons	342.8	355.7	342.0	359.3	308.8	245.0
5	Total emissions by substance (NO_x, SO_x, CO)	401.6	412.8	382.7	400.0	351.1	261.5
6	The volume of oxygen consumed, per molar mass: $U_i = W_i \cdot B_i$, including: (at = 0,696) (if at = 0,5) U_{CO} (at $B_{CO} = 0{,}571$)	20.0 15.1 205.7	20.02 14.25 213.4	11.2 12.35 205.2	11.13 12.4 215.6	14.4 10.61 86.7	10.9 8.8 148.4
7	Conditional volume of oxygen consumption per: NO_x, SO_x, CO, thousand tons	240.8	247.7	228.8	238.9	211.1	168.1
8	Oxygen consumption in terms of total emissions, $U_2 = U_B \cdot 0{,}9$, thousand tons	216.7	222.9	251.7	215.9	189.9	151.3
9	The potential for atmospheric resistance to man-made loads at $T_{e1} = 4272{,}6 \cdot 10^2$ t/year	0.5	0.52	0.58	0.5	0.44	0.35
10	By substance nitrogen oxides, W_{NOx}, thousand tons dioxide and other sulfur compounds, W_{SOx}, thousand tons carbon monoxide, W_{CO}, thousand tons	23.4 24.2 274.0	22.8 24.1 273.8	23.6 25.6 292.0	26.8 28.5 325.5	16.0 30.2 342.8	15.9 28.5 355.7

effluent (MPC of the pollutant in a fishery reservoir), mg/l;

V_b – volume of irreversible water consumption, thousand m^3.

6. The technogenic load on the lithosphere (U_3) is calculated based on determining the degree of depletion of the land fund, i.e., the reduction in the bioproductivity of the ecosystem due to the withdrawal of the territory. The total area of land where bioproductivity is disrupted as a result of economic activity and has a total soil pollution index Z_C = 32–128 and more (pollution category hazardous and very hazardous), areas for storing toxic waste, areas with soil pollution (places of accumulation of household waste) is calculated as:

$$U_3 = \sum_{j=1}^{n} S_{ar} Z_{Cj}, \qquad (16)$$

where S_{ar} – area of the territory with disturbance or absence of biocenosis, km^2;

Z_{Cj} – indicator of total chemical pollution of soils,

$$Z_{Cj} = \left(\sum_{j=1}^{j} K_{Cj} \right) - (n-1), \qquad (17)$$

where K_{Cj} – element concentration coefficient, $K_{Ci} = C_j / MPC_j$;

n – number of chemical elements with $K_C > 1$.

7. When calculating the level of ecological risk of an ecosystem, a comparison of the anthropogenic load on the territory (Ui) and its ecological capacity (Ti) was made. The coefficient of ecosystem stability (Eif) to the influence of factor (f) was determined for each natural environment (i):

$$E_{if} = \frac{U_i}{T_i}, \qquad (18)$$

For a comprehensive assessment of the ecosystem risk of the entire ecosystem, the integral ecological risk coefficient is calculated as the sum of the environmental coefficients. The obtained value is used to rank the ecological risk for the ecosystem as a whole.

The study calculated the ecosystem [10] stability coefficient (Eif) on the territory of the landscape reserve (Vinogradne settlement, Mangushiv district, Donetsk region), which is located in the coastal zone of the Sea of Azov (hereinafter abbreviated as the Reserve).

A balance model was compiled using the method of multi-criteria impact factors (f) for each natural environment using formulas (7)–(18).

The calculation results were used as input data for a qualitative analysis of the probability of ecosystem risks in the reserve.

The calculation results determined the potential for the stability of the ecosystem of the atmosphere (*Z*), which has an average level of ecological risk, Eif = 0.4–0.58. The "average significance" of ecosystem risk (Table 3) was determined from the risk priority scale.

Table 3

Risk priority scale

Risk Priority Scale	Ecosystem resilience potential, *Eif*, conditional, t/year			Probability of impact on
	≤ 10	≤ 60	≤ 100	
Low	1–3			Negligible, Low
Medium	5–6			Moderate
High	7–10			Significant, Catastrophic

Further research into the qualitative model allowed for the creation of an ecosystem risk assessment matrix that can be used for practical purposes [11; 12].

Conclusions. Ecosystem risk assessment is critically important for sustainable development. It is necessary for the development of effective strategies for biodiversity conservation and adaptation to climate change.

The assessment of ecosystem risks is complex due to the multifactorial nature and interaction of various processes. It is necessary to take into account a large number of criteria (climate change, pollution, biodiversity loss, etc.), which requires the use of special analysis methods. Multi-criteria assessment is a necessary tool for making informed management decisions. It allows you to identify potential threats, assess their consequences and develop effective natural resource management strategies.

The developed methodology allows you to take into account the peculiarities of ecosystem functioning, takes into account the impact of biotic, abiotic and anthropogenic factors on the recipients of the natural environment – the atmosphere, hydrosphere, lithosphere, taking into account weighting factors, and allows you to make a transition from qualitative to quantitative criteria.

The assessment of ecosystem risks is a complex task that requires taking into account many factors and their interaction. Simplified models do not always provide an adequate picture. Modern approaches are focused on modeling complex systems, taking into account dynamic processes and developing quantitative assessment criteria. However, the lack of a unified methodology and specific indicators hinders the widespread implementation of these methods.

Table 4

Ecosystem risk criterion assessment matrix

		The severity of the impact				
		Minor (1–2)	**Low (3–4)**	**Moderate (5–6)**	**Significant (7–8)**	**Catastrophic (9–10)**
Probability of atmospheric impact	Very rarely (1–2)	🟩 .	🟩 .	🟩 .	🟩 .	🟩 .
	Rarely (3–4)	🟩 .	🟩 .	🟩	🟩	🟩
	Occasionally (5–6)	🟩 .	🟩 .	🟨 Z^1	🟨	🟨
	Often (7–8)	🟩 .	🟨	🟥	🟥	🟥
	Very often (9–10)	🟩 .	🟨	🟥	🟥	🟥

LITERATURE:

1. Системи екологічного управління. Вимоги та інструкції щодо застосування : ДСТУ ISO 14001:2006 [Чинний з 15.05.2006]. Київ : Держстандарт України. 2006. 16 с.

2. Ribas J.R., Arce M.E., Sohle F.A. Multi-criteria risk assessment: Case study of a large hydroelectric project. *Journal of Cleaner*, 2019. Vol. 227. Is. 1. P. 237–247. URL: https://www.sciencedirect.com/science/article/abs/pii/S09596526193111

3. Скилодімов Н. Моделювання оцінки множинних небезпек за допомогою батокритеріального аналізу та GIS : практичний посібник. *Екологічна планета Земля*. 2019. № 78. С. 25–34. URL: https://link.springer.com/article/10.1007/s12665-018-8003-4/78_25_34.pdf/

4. Акімова Т., Кузьмін А., Хаскін К. Екологія. Природа – людина – технології. Київ : Основа, 2010. 120 с.

5. Semenzin E., Critto A., Carlon C., & Rutge M. (2017). Development of a site-specific ecological risk assessment for contaminated sites. Part II. A multi-criteria based system for the selection of bioavailability

assessment. *Science of the total*. Vol. 379. No. 1. P. 34–43. URL: https://www.sciencedirect.com/science/article/abs/pii/S004896970700290/379_34_43.pdf/

6. Zabeo I., Pizzol L., Agostini P., Critto A., Giove S. Regional risk assessment for contaminated sites. Part 1. Vulnerability assessment by multicriteria decision analysis. *Environment-Elsevier*, 2020. Vol. 37. P. 1295–1306. URL: https://www.sciencedirect.com/science/article/abs/pii/S016041201100131/37_1295_1306.pdf/

7. Лінков І., Сежер Т. Поєднання багатокритеріального аналізу рішень, оцінки життєвого циклу та оцінки ризиків для нових загроз. *Публікації ACS*. Київ, 2011. № 45, С. 321–331. URL: https://pubs.acs.org/doi/full/10.1021/es100959q/45_321_331.pdf/

8. Дорогунцов С., Ральчук О. Управління техногенно-екологічною безпекою в контексті парадигми сталого розвитку: концепція системно-динамічного рішення. Kyiv : Наукова думка, 2012. 200 с.

9. Топуз Е., Талинин І., Аудін К. Інтеграція оцінки ризиків для довкілля та здоров'я людини для виробництв, що використовують небезпечні матеріали: Кількісний багатокритеріальний підхід до оцінки екологічного ризику. *Екологія. Право. Людина.* Київ, 2012. № 37 (2). С. 393–409. URL: https://www.sciencedirect.com/science/article/abs/pii/S0160412010002291/37_393_409.pdf/.

10. Хлєстова О. А., Єлістратова Н. Ю., Кальянов А. В., Волков Д. В. Використання математичної теорії катастроф у промисловій екології. *Екологічні науки*. Харків, 2020. № 30. С. 15–19. URL: http://ecoj.dea.kiev.ua/archives/2020/3/4/30_15_19.pdf

11. Raaijmakers R., Krywkow J., A. van der Veen. Flood risk perceptions and spatial multi-criteria analysis: an exploratory research for hazard mitigation. *Natural hazards*, 2017. Vol. 46. P. 307–322. URL: https://link.springer.com/article/10.1007/s11069-007-9189 z/46_307_322.pdf/

12. Barquet K., Cumiskey L. Using participatory Multi-Criteria Assessments for assessing disaster risk reduction measures. *Coastal Engineering*, 2018. Vol. 134. P. 93–102. URL: https://doi.org/10.1016/j.coastaleng.2017.08.006/134_93_102.pdf/

REFERENCES:

1. Systemy ekolohichnoho upravlinnia. Vymohy ta instruktsii shchodo zastosuvannia [Environmental management systems. Requirements and instructions for use] (2006). ISO 14001:2006 from Ist april 2006. Kyiv : Derzhstandard Ukrainy [in Ukrainian].

2. Ribas, J. R., Arce, M. E., & Sohle, F. A. (2019). Multi-criteria risk assessment: Case study of a large hydroelectric project. *Journal of Cleaner*, 227 (1), 237–247. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S095965261931 1138/227_237_24.pdf/

3. Skilodimov, H. (2019). Modeliuvannia otsinky mnozhynnykh nebezpek za dopomohoiu bahatokryterialnoho analizu ta HIS: praktychnyi pryklad [Multi-hazard assessment modeling via multi-criteria analysis and GIS: a case study]. *Ekolohichna planeta Zemlia – Environmental Earth,* 78(1). Retrieved from: https://link.springer.com/article/10.1007/s12665-018-8003-4/78_25_34.pdf/ [in Ukrainian].

4. Akymova, T., Kuzmin, A., & Haskin. K. (2010). Ekolohiia pryroda-liudyna-tekhnolohii [Ecology nature-man-technology]. Kyiv : Osnova [in Ukrainian].

5. Semenzin, E., Critto, A., Carlon, C., & Rutge. M. (2017). Development of a site-specific ecological risk assessment for contaminated sites. Part II. A multi-criteria based system for the selection of bioavailability assessment. Science of the total, 379, 34–43. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S004896970700290/379_34_43.pdf

6. Zabeo, I., Pizzol, L., Agostini, P., Critto, A., & Giove, S. (2020). Regional risk assessment for contaminated sites. Part 1. Vulnerability assessment by multicriteria decision analysis. *Environment-Elsevier*, 371295–1306. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S016041201100131/37_1295_1306.pdf

7. Linkov, I., & Seager, T. (2011). Poiednannia bahatokryterialnoho analizu rishen, otsinky zhyttievoho tsyklu ta otsinky ryzykiv dlia novykh zahroz [Coupling multi-criteria decision analysis, life-cycle assessment, and risk assessment for emerging threats]. *ACS Publications*, 45(12), 321–331. Retrieved from: https://pubs.acs.org/doi/full/10.1021/es100959q/45_321_331.pdf/ [in Ukrainian].

8. Doroguntsov, S., & Ralchuk, O. (2012). Upravlinnia tekhnohenno-ekolohichnoiu bezpekoiu v konteksti paradyhmy staloho rozvytku: kontseptsiia systemno-dynamichnoho rishennia [Management of technogenic and ecological safety in the context of the sustainable development paradigm: the concept of a system-dynamic solution]. Kyiv : Naukova dumka [in Ukrainian].

9. Topuz, E., Talinli, I., & Aydin, K. (2012). EIntehratsiia otsinky ryzykiv dlia dovkillia ta zdorovia liudyny dlia haluzei, shcho vykorystovuiut nebezpechni materialy: Kilkisnyi bahatokryterialnyi pidkhid do otsinky ekolohichnoho ryzyka [Integration of environmental and human health risk assessment for industries using hazardous materials: A quantitative multi-criteria approach to environmental risk assessment].

Mizhnarodna ekolohichna orhanizatsiia – Environment International, 37, 393–409. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0160412010002291/37_393_409.pdf/ [in Ukrainian].

10. Khlestova, O. A., Yelistratova, N. Y., Kalyanov, A. V., & Volkov, D. V. (2020). Vykorystannia matematychnoi teorii katastrof u promyslovii ekolohii [The use of mathematical theory of catastrophes in industrial ecology]. *Ekolohichni nauky – Ecological Sciences*, 30, 15–19. DOI: http://ecoj.dea.kiev.ua/archives/2020/3/4/30_15_19.pdf/ [in Ukrainian].

11. Raaijmakers, R., Krywkow, J., & A van der Veen. (2017). Flood risk perceptions and spatial multi-criteria analysis: an exploratory research for hazard mitigation. *Natural hazards*, 46, 307–322. Retrieved from: https://link.springer.com/article/10.1007/s11069-007-9189 z/46_307_322.pdf/ [in English].

12. Barquet, K., & Cumiskey, L. Using participatory Multi-Criteria Assessments for assessing disaster risk reduction measures. *Coastal Engineering*, 134, 93–102. Retrieved from: https://doi.org/10.1016/j.coastaleng.2017.08.006/134_93_102.pdf/