ISSN: 1648-6897 / eISSN: 1822-4199

JOURNAL of ENVIRONMENTAL ENGINEERING & LANDSCAPE MANAGEMENT

2024
Volume 32
Issue 1
Pages 57–71
https://doi.org/10.3846/jeelm.2024.20608

STABILITY INDICATOR FOR DEFINING ENVIRONMENTAL AND PROTECTIVE REQUIREMENTS FOR LANDSCAPE ECOSYSTEMS

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Highlights:
- the approach to standardizing the indicator of ecosystem stability is considered;
- the indicator identifies and assesses environmental changes due to human activities;
- the scales, way of complex formation, categories of impact significance are developed;
- the example of constructing the environmental risk matrix is presented;
- division of the compartments allows preventing and reducing of harmful effects.

Article History:
- received 24 April 2022
- accepted 27 October 2023

Abstract. Methodological aspects of assessing harmful impacts on the natural environment are presented, aimed at determining the indicator of ecosystem stability. The use of such an indicator makes it possible to determine environmental changes as a result of anthropogenic activity, as well as to determine the significance of these changes. A system is presented that systematizes the variety of consequences of anthropogenic impact on CLS. A qualitative scale of reducing harmful anthropogenic impact is proposed. It is proposed to conduct assessment of the categories of significance of harmful effects and ecological risk on the basis of a comprehensive evaluation of impacts on individual storeys and subsystems in the compartment from different sources of influence, taking into account their magnitude and intensity. The corresponding scales, a way of complex formation, categories of impact significance have been developed; also, an example of constructing an environmental risk matrix has been presented.

Keywords: ecosystem stability, complex landscape system, ecological regulation, compartment, harmful impact, ecological hazard, gradient of stability change.

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1. Introduction

The hierarchy of the biosphere structure, in turn, determines the hierarchical nature of the systems for regulating the equilibrium (homeostasis) of its landscape systems – a compartment – subsystems – layers. Homeostatic systems are of a genetic nature and evolve together with the structural and functional organization of ecosystems. Life does not exist outside of ecosystems, therefore, the study of natural objects of any taxonomic level is effective only when using a systematic approach (Fränzle, 2010; Shu et al., 2021; Fauzi et al., 2021; Botey et al., 2012).

A complex landscape system (CLS) is a system characterized by the structural and functional unity of interrelated components and the integrity of the biotic and abiotic constituents. The biotic components of the environment are grouped into compartments consisting of hierarchically interconnected subsystems of different levels of organization and a large number of different layers, between which there are close material, energy and hierarchical relationships. A CLS consists of *n* compartments interconnected by flows of matter, each block can receive input flows from the surrounding abiotic environment or other compartments and give off output flows. As a result of the interaction of natural components and anthropogenic factors, a specific network of complex landscape systems of various taxonomic ranks is formed.

In a landscape system, saturated with urban, industrial and agricultural complexes, the specific features of material and energy flows from the aforementioned anthropogenic systems to natural ones, as well as the ability of the latter to overcome these anthropogenic pollution, are of particular functional importance. And this gives rise to the problem of regulating the state of the CLS itself, the basic mechanism of which is ecological regulation – a set of standardization measures aimed at establishing the mandatory norms, rules and requirements for the state, use and environmental safety of the CLS which would not exceed the capability of the CLS for self-regulation and renewal (Obshta et al., 2018).

By the regulatory support of the CLS is meant the development and implementation of sciencebased criteria of the maximum permissible harmful impacts on the CLS, as well as the establishment of norms and rules of nature management based on the established criteria, comprehensive study and analysis of environmental capabilities of the CLS. The result of such activities is the establishment of quantitative values of indicators that make it possible to maintain the anthropogenic impact on the CLS within the permissible limits, at which the mechanisms of its self-regulation in combination with environmental protection measures can ensure the restoration process and will not lead to degradation of the CLS.

The basis for ecological regulation, as a rule, is the national normative documents and regulations (Langlet & Mahmoudi, 2016). Among the most important tasks of standardization is not only the establishment of values, but the definition and optimization of the list of indicators (Dzhumelia & Pohrebennyk, 2021; Pohrebennyk et al., 2019; Pohrebennyk & Dzhumelia, 2020; Chen et al., 2018; Lee et al., 2017; Hu et al., 2017, 2021; Sherameti & Varma, 2015; Štofejová et al., 2021; Ibrahim, 2019; Noviks, 2015; Hof & Hjältén, 2018).

The issue of regulatory support in Environmental Science was dealt with by eastern European scientists such as K. Mäkká, D. Fazekašová, J. Fazekaš, M. Ferretti and others (Mäkká et al., 2021; Fazekašová et al., 2021; Ferretti, 2009); however, to date, unified requirements for the spatial-functional model of CLS organization have not been developed, there is no nomenclature of quality indicators and science-based approaches to their definition, there is no ecosystem classification of CLS components, there is no standard terminology, in particular for the characteristics of the properties of the CLS and various combinations of biogeocoenoses, there are no standardized values of quality indicators of the CLS, which make this work relevant.

The most important for the origin and development of ecological regulation can be considered the provision of S. S. Schwartz (Schwarts, 1976) that the anthropogenic simplification of ecosystems is not necessarily their degradation, but evolution under new conditions. However, not all of the consequences of ecosystem simplification are undesirable. If, in a human-changed environment, the biogeocoenosis maintains itself as a system in optimal condition, this means that the degree of anthropogenic impact does not exceed the adaptive capabilities of this biogeocoenosis (Ruda et al., 2022; De Jong & Dahlberg, 2017).

V. D. Fedorov and A. P. Levych (Fedorov et al., 1982) proposed several approaches to measuring normality (based on a statistical understanding of the norm) and the stability of ecosystems, which is necessary to determine its safety margin (Betts et al., 2017). Similar views on the norm of ecosystems have been expressed by Western researchers within the framework of the concept of ecosystem health (Cairns & Niederlehner, 1995; Costanza, 1992; Rapport, 1995).

D. A. Kryvolutsky, F. A. Tykhomyrov, and Ye. A. Fedorov (Krivolutskiy & Fedorov, 1984; Krivolutskiy et al., 1987) noted that the goals of environmental regulation may be different: protection of the gene pool; maintaining a sanitary state of the environment tolerable for humans; protection of landscape diversity; protection of sources of biological products; protection of recreational resources, etc. An important limiting factor is that all these tasks can and should be solved simultaneously in the same area. Thereby, the multivariance of the standards is set.

The authors' prospective approach to determining the permissibility of changes in ecosystems is to assert that if disturbances in ecosystems under the influence of anthropogenic loads are significantly weaker than possible natural changes and do not lead to irreversible consequences, then such environmental disturbances should be considered as acceptable (Peltola & Tuomisaari, 2016; Michanek et al., 2018; Ali et al., 2017). This implies the following universal criterion – justification of reducing the productivity of the ecosystem by 20–25%. It is also possible to consider to be promising the hypothesis about the universality of the responses of organisms to any adverse changes in the environment.

In general, Israel (1984) understands the permissible environmental load as such its magnitude that does not cause undesirable changes in organisms and ecosystems (primarily in humans) and does not lead to deterioration (any significant) of the quality of the natural environment. In this case, the indication of the high quality of the environment is understood as a value that meets the following criteria: the possibility of sustainable existence and evolution of the historically established ecosystem created and transformed by humans in a given place; the absence in the present and future of adverse effects in any (or the most important) population (in particular, humans, and each person) which is located in this place historically or temporarily (Tihomirov & Rozanov, 1985). Israel (1984) notes that the load tolerance is determined by the nature management objectives. From this point of view, all ecosystems can be divided into three categories: unique (protected); widespread (natural); heavily transformed (artificial). In ecosystems of the first category, the load must exclude the loss of any species; for the second – some changes are allowed, so that the high quality of the environment is maintained; in artificial ecosystems, any reasonable changes in accordance with defined goals are possible.

In the works by Aleksandrova (1998), the problems of ecological regulation are discussed in detail and generalized. The standards must be created to meet three main objectives. The norms should be created to fulfill three main purposes: preservation of the environment (and providing an environment which is favorable for all living things); resource conservation and renewal (with an emphasis on biological resources); preservation of the gene pool and conditions of its existence.

Important is the author's assertion that the norms should be territorially differentiated (that is, they should be different for different types of landscapes), be variant (that is, they should be different for different situations of nature management).

Defining limits for changes in the factors of an ecologically stable environment was proposed in the early 1980s by Canadian researchers, in particular, in the agreement on the control of transboundary pollution with the United States. This concept was further developed in Scandinavia, where the term "critical load" was proposed (Ghadwick & Kuylenstierna, 1991). Attempts have been made to expand the concept of critical loads not only for acid precipitation, but also for heavy metals (Dutta & Singh, 2021; Paul & Saha, 2022; Bubela et al., 2016).

Puzachenko (1992) considers it necessary to examine ecological regulation within the framework of the general problem of ecosystem stability. In this case, the permissible impact should be that which does not lead to a loss of stability.

In the context of the above, it is worth mentioning the environmental impact assessment (EIA). This term is used as a generic concept for all EIA systems/procedures. This term does not refer to any specific national or international procedure. Thus, it affects both the European assessment of the impact on the environment, the EIA according to the national legislation of Ukraine, and the state environmental expertise. The purpose of using this term is to avoid confusion, especially with regard to the term EIA, since it is this term (EIA) that denotes both a certain procedure in the national system and the European EIA system. In Ukraine, there is no effective system for assessing the impact on the environment of potentially environmentally hazardous planned industrial projects (types of activities). In the past, the main role in the assessment of possible environmental consequences was played by the state environmental expertise. With the entry into force of the Law "On Regulation of Urban Development" the state environmental examination was practically canceled. The current system of regulation of economic activity, including EIA as a design stage, cannot provide assessment and prevention of environmental consequences of dangerous types of economic activity and has a number of shortcomings. In particular: processes of determination, forecasting, assessment (EIA) and taking into account the environmental consequences of planned activities (urban planning expertise) are carried out by private individuals; the mechanism (grounds) for determining the obligation to conduct an urban planning examination completely excludes the use of approaches generally accepted in the EU (based on the list of types of activities and threshold values); the EIA procedure, in particular its stages, do not correspond to the international model of environmental impact assessment, in particular the European one; modern environmental impact assessment procedures in Ukraine cannot ensure one of the key principles and elements of the European model: openness and consideration of public opinion. This element is also the subject of Ukraine's obligations under a number of international agreements. This carries a number of risks for Ukraine in the areas of environmental protection, public health, democratic decision-making process, European integration aspirations, international obligations and investment climate. The lack of an effective environmental impact assessment system also creates risks for specific business projects.

The presented analysis indicates the advisability of using the stability indicator to assess the state of any ecosystem. The theoretical foundations of stability are substantiated in the classic works of Poincaré, Lyapunov, Lagrange and others (Leine, 2009; Drever et al., 2006; Yeromenko & Kochan, 2013), which are based on estimates of energy absorption and transformation, and information, that is, the laws of thermodynamics of ecosystem functioning, synergetics, and entropy indexes in open systems. The authors show that, although the natural development of ecosystems is directed towards an equilibrium state, but due to dissipative processes, the systems cannot exist for a long time in such a state and need additional energy for their development. On the whole, this proceeds as fluctuation changes. Thus, ecosystems, as a result of external negative impacts, demonstrate the sequence of phases of equilibrium and, in fact, the conflict of the crisis. The ability of the CLS to overcome the consequences of such external negative influences will be called the resilience of the CLS.

Based on the analysis carried out, the purpose of this study can be defined as follows:

- an attempt to harmonize approaches that use definitions of ecological and protective requirements for landscape ecosystems of both national practice and of world best practices;
- to introduce a clear understanding of the concept of stability as the ability of the CLS to withstand, adapt or resist harmful external influences for a long time without serious violations of its structural and functional characteristics and degradation of the constituent components;
- to present the methodological aspects of establishing ecological and protective requirements for the CLS, based on the determination of the constituent elements of the stability indicator, which are assessed on a certain scale, using the appropriate criteria developed and presented for each gradation of the scale.

2. Materials and methods

The assessment of impact on the CLS was performed using available materials and statistics provided by: the Ministry of Environmental Protection of Ukraine and its regional offices; subdivisions of Ukrmeteocenter; scientific, research and other organizations (United Nations Economic Commission for Europe, 1991). The assessment of transboundary impacts of harmful objects on CLSs can be performed on the basis of an intergovernmental agreement that takes into account the provisions of the Convention on Environmental Impact Assessment in a Transboundary Context, EBPO.

For this work, the CLS of Dniester Precarpathia was chosen and research was carried out on the profile of Pikuy mountain – the Lviv city – Stoyaniv village. As a result, a landscape profile was created, which runs from the southwest to the northeast through the entire studied region. In the landscape structure of the studied CLS of Dniester Precarpathia, the following physical and geographical regions can be distinguished: Stryvigor-Boloziv, Drohobych, Stryi, and Prysvitske foothills. Geostructurally, these natural areas are connected to the Precarpathian Foreland. The landscape structure of the CLS of Dnister Precarpathia makes it possible to clarify the landscape affiliation of negative natural processes and phenomena, and on the other hand, to create prerequisites for a more detailed study of regional territorial units, which is the basis for the further introduction of the sustainability indicator for assessing the state of complex ecological situations that have arisen within the CLS. Anthropogenic activity in the CLS of Dniester Precarpathia is characterized by significant intensity and variety of species. Due to the very rich natural resource and production potential, various branches of industry have acquired considerable development, in particular – mining, agricultural production, forestry, recreation, tourism, etc.

Some section of the CLS of the unit area is selected based on the hypothesis that the CLS can be represented as a collection of compartments that have the properties of the entire CLS. According to the conditions, all such sections are equivalent. The upper boundary of the system under study is drawn parallel to the soil surface at a height H, approximately equal to three times the height of the trees h. At a particular depth R outside the root system placement layer, the lower face is built. The parallelepiped formed in this way will be considered research material. There is no exchange of energy and matter through the side faces since there are no corresponding gradients. Solar radiation and carbon dioxide enter the selected volume through the upper border, and water vapor, for example, is removed. The same exchange processes take place through the lower border. Despite this, everything that enters the system refers to its input influences, and everything that is removed from it – either to losses or to the alienated final product.

During the study of CLS, their ecological impact is considered as some index, which is assumed to be homogeneous and isotropic in the horizontal plane, and the area of CLS is large enough so that the effect of the "edge of the field" can be neglected. In this case, all flows of energy and matter are carried out only in the vertical direction. Moreover, the effect of soil heterogeneity can also be neglected, considering that the described processes can be attributed to any part of the CLS. Of course, homogeneous and isotropic CLS does not exist in nature, but the adopted idealization makes it possible to achieve the necessary corrections for the further analysis.

The upward vertical coordinate is denoted by x, placing its origin (point 0) on the soil surface. The time is marked with t. In this case, all model variables will depend on two arguments x and t. At each moment in time, the system has a vertical distribution of the characteristics of the vegetation cover, as well as various substances – water in the soil, ammonium ions and nitrates in the soil profile, soil temperature, pollution by pollutants and sediments, etc. In the above-ground part of the system, there is also a vertical distribution of various parameters – anthropogenic pollution, radiation, air temperature and humidity, leaf temperature, carbon and nitrogen concentration in phytoelements, etc. Under the action of forces of various natures, these values change.

It is assumed that there are n different components in our system. Each i-th compound from their n total number is characterized by a concentration value c_i $(i = 1, 2, ..., n)$, which can change over time $c_i = c_i(t)$ due to the interaction of the i-th compound with any of the remaining $(n - 1)$ substances. Such an assumption is sufficient so that the described situation could be represented by a mathematical model, which is a system of n differential equations of the first order:

$$\frac{dc_1}{dt} = f_1(c_1, c_2 \ldots c_n \cdot t);$$

$$\frac{dc_2}{dt} = f_2(c_1, c_2 \ldots c_n \cdot t);$$

$$\ldots$$

$$\frac{dc_n}{dt} = f_n(c_1, c_2 \ldots c_n \cdot t), \qquad (1)$$

where $c_1(t)$, ..., $c_n(t)$ – are unknown functions of time, and $\frac{dc_i}{dt}$ $(i = 1, ..., n)$ – is the rate of change in the concentration of the i-th substance.

In model (1), the number of equations n is equal to the number of variables c_1, c_2 ... c_n, substances that change due to interaction. Each f_i $(c_1, ..., c_n, t)$ is a function of the arguments $c_1(t)$, ..., $c_n(t)$, dependent on time and time t itself, and is the algebraic sum of the rates of separate reactions of the formation and removal of the i-th substance in the system.

We will mostly consider systems of first-order equations that contain time derivatives of initial functions. Regarding the form of the right-hand sides (1), depending on the nature of the processes taking place in the system, the functions f_i $(c_1, ..., c_n, t)$ may contain both linear and nonlinear terms with respect to the variables c_1, ..., c_n. Most of the equations under consideration will have right-hand sides that are explicitly independent of time: f_i $(c_1, ..., c_n)$.

This means that these processes occur under constant external conditions.

For a complex landscape system (CLS), the principle of bottleneck is characteristic, according to which the overall rate of substance transformation throughout the reaction chain will be determined by the slowest stage. Therefore, if individual stages of the overall process have characteristic times T_1, T_2, ..., T_n and the slowest stage has a time T_k such that T_k, > T_1, ..., T_{k-1}, T_{k+1}, ..., T_n, then the determining link will be the k-th stage, and the overall time of the process will practically converge to the value of T_k of this bottleneck.

At the same time, the fast stages of the process are characterized by high rates of change in variables, which can be expressed as:

$$\frac{dc_p}{dt} = \frac{1}{\varepsilon} f_n(c_1, c_2 \ldots c_n), \tag{2}$$

where c_p – fast variable, ε <<1 – a small positive parameter.

The appearance of a factor $\frac{1}{\varepsilon}$ >1 in the right part of the equation determines a large value of the speed $\frac{dc_p}{dt} > 0$. The presence of a time hierarchy makes it possible to significantly simplify the initial CLS model, essentially reducing the task of kinetic description of the system to studying the behaviour of the slowest stage. In this sense, the slowest link will be the one that controls, since action on it, rather than on faster stages, can affect the speed of the entire process. This is an objective property of the CLS system, which significantly simplifies the problem of modelling. At the same time, management of this process within the compartment is also simplified. In fact, regulating a complex multistage process is easy to do by acting on one of its key stages, such as changing the parameters of the slowest segment of the entire chain. This increases the reliability of controlling complex multistage ecological processes and is one of the important advantages of ecological systems. In the CLS, this is especially important, since the values of their parameters and initial conditions usually vary and are usually not precisely specified, so it is extremely important to establish the dependence of the behaviour of the system on the values of its parameters.

The qualitative theory of differential equations deals with the study of the behavior patterns of a system based on the form of the right-hand side of the equations, without actually solving the equations themselves: $f_1(c_1, c_2, ..., c_n, t)$ ..., $f_m(c_1, c_2, ..., c_n, t)$.

It should be noted that in order to accomplish the task of determining ecological stability without resorting to finding the solutions $c_1(t)$, ..., $c_n(t)$, it is necessary to somehow exclude the time factor from direct consideration. In fact, by definition, the risks to which the system is subjected over time by the variables $c_1(t)$, ..., $c_n(t)$ in the left-hand sides of (3) are reduced to zero:

$$\frac{dc_i}{dt} = 0, \; i = 1, 2, \ldots n. \tag{3}$$

Hence, by setting the right-hand sides of equal to zero, we obtain a system of algebraic equations:

$$f_1(\overline{c_1}, \overline{c_2} \ldots \overline{c_n}) = 0;$$

$$f_2(\overline{c_1}, \overline{c_2} \ldots \overline{c_n}) = 0;$$

...

$$f_n(\overline{c_1}, \overline{c_2} \ldots \overline{c_n}) = 0. \tag{4}$$

The constant values that the variables $\overline{c_1}(t)$, $\overline{c_2}(t) \ldots \overline{c_n}(t)$ take on when the system reaches a steady state are $\underline{c_1}, \underline{c_2} \ldots \underline{c_n}$.

It should be noted that fast variables, unlike slow variables, are almost always close to their stationary values. This can be easily seen from Equation (5) for the fast variable *sr*. In fact, by moving ε > 0 to the left-hand side, we obtain:

It should be noted that fast variables, unlike slow ones, are almost always close to their stationary values. This can be easily seen from Equation (2) for the fast variable *s*. In fact, by substituting ε > 0 into the left-hand side, we obtain:

$$\varepsilon \frac{dc_p}{dt} = f_p(c_1, c_2 \ldots c_n) \tag{5}$$

at $\varepsilon \to 0$

$$f_p(\overline{c_1}, \overline{c_2} \ldots \overline{c_n}) = 0 \tag{6}$$

this coincides with the algebraic equation for determining the steady-state values of c_p. This means that if the system is divided into fast and slow variables, the change in the fast variables can be neglected, considering them as constant values, and all attention should be focused on the change in the slow variables that determine the "bottlenecks" of the system.

The main approach of the qualitative theory of differential equations is to characterize the state of the system as a whole by the values of variables c_1, c_2, ..., c_n, which they acquire at each moment of time in the process of change according to (1). If we put the values of the variables c_1, c_2, ..., c_n on the coordinate axes in the n-dimensional space, then the state of the CLS will be described by a certain point M in this space with coordinates:

$$M = M(c_1, c_2, ..., c_n). \tag{7}$$

In a stationary state, the point M with coordinates $\{c_1, c_2, ..., c_n\}$ should also be considered stationary, or, otherwise, the point of equilibrium or rest of the system. A change in the state of the system corresponds to a change in the location of point M in n-dimensional space. The space with coordinates c_1, c_2, ..., c_n is called a phase space, the curve described in it by point M is a phase trajectory, and system (1) is a dynamic system with protective properties.

The method of research of stability consists in finding such indicator of a condition and safety of CLS on which it would be possible to find out effectively influence of negative factors on compartments of this CLS. It is assumed that the system in its steady state gets a certain amount of evenly distributed pollutants and can be described by the corresponding distributions of factors. Then stability can be considered on the example of a two-chamber model containing biota – *Z(t)* and water – *Y(t)*. This is a simple and adequate model for describing processes in ecological systems of varying complexity (Poulos, 2021).

Such models are based on the assumption of stable statistical equilibrium in the system: ecosystem – factor – environment. Let the model contain two chambers – *Y(t)* and *Z(t)*, which hold the amount of contaminants, which changes with time t; a_{12} – rate of absorption of pollutants (proportional to the rate of absorption of nutrients such as potassium); a_{21} – the rate of outflow of pollutants.

Assume that the initial stock of radionuclides in the chamber *Y(x)* was Y_0 Bq (^{137}Cs), and their distribution between *Y(x)* and *Z(x)* can be expressed by differential equations:

$$\frac{dy(t)}{dt} = a_{21}z(t) - a_{12}y(t); \tag{8}$$

$$\frac{dz(x)}{dx} = a_{12}z(x) - a_{21}y(x). \tag{9}$$

The solution of two differential equations for this model is:

$$Y(t) = \frac{Y_0}{a_{12} + a_{21}(a_{21} + a_{12}\exp[-(a_{12} + a_{21})t])}; \tag{10}$$

$$Z(t) = \frac{Y_0 a_{21}}{a_{12} + a_{21}(\exp[-(a_{12} + a_{21})t])}. \tag{11}$$

From the solution of differential Equations (3) and (4) describing the course of processes in the model, the stability factor is obtained.

$$\frac{a_{12}}{a_{21}} = \frac{F_b}{F_w} = \frac{1 - F_w}{F_w}, \tag{12}$$

where F_b, F_w are radio capacity factors of biota and water; a_{12} and a_{21} – the rate of absorption and outflow of the pollutant.

In the dynamics of CLS biota, the nature of the interaction of different factors varies from synergism to antagonism. The coefficient of synergism *P* can be defined as:

$$P = \frac{S_{N+onp}}{S_N S_{onp}} S_0, \tag{13}$$

where S_0, S_{N+onp} is the ratio of factors influencing the biota for the control variant and under combined exposure, for example, toxic metal and radiation; S_N and S_{onp} is the ratio of factors for the independent influences of each of them.

If $P = 1$, then there is no synergism in the action of factors. If $P < 1$, it indicates the strengthening of the joint action compared to the individual action of each of them. If $P > 1$, then there is antagonism, i.e., when one factor reduces the negative effect of another.

In general, during the action of *n*-pollutants on the CLS, the formula for estimating synergism through stability parameters will take the form:

$$S_n = S_{\Sigma S_i} S^{n-1} / \prod_{i=1}^{n} S_i, \tag{14}$$

where S_i is the action of a single pollutant, and $S_{\Sigma S_i}$ is the interaction of *n* pollutants.

Then the calculation of the ecological norm for two factors must satisfy.

$$\frac{c_1}{L_1} + \frac{c_2}{L_2} \le 0, \tag{15}$$

where c_1 and c_2 are values of radiation doses and cadmium concentration in water, and L_1 and L_2 are the set environmental limits for the dose of gamma radiation – 4 g/year, and cadmium salts – 20 μMol/dm^3.

The next method is to analyze the mechanisms for obtaining principles for assessing the stability of ecological systems. The most effective and promising for solving research problems is the theory of biotic regulation, the essence of which is based on the laws of organization and functioning of the environment and the restriction of economic intervention, and it is aimed at maintaining ecological balance (Petrosillo et al, 2008). The rate of ecosystem res-toration as a result, for example, of anthropogenic interference, depends on the ecosystem position relative to the equilibrium state. With the strengthening of adverse natural factors, there occur disturbances, increasing deviations from equilibrium to the extent that the system loses stability, which can lead to its destruction.

For adequate mathematical modeling of the CLS stability, it is necessary to clearly rank the hazards that affect environmental processes in the CLS and consider the set of properties that most fully characterize the system in view of the purpose of the study. International standards (ISO 14001:2015; IEC 31010:2019) were used for this purpose. Thus, the process of hazard development can be described by the following logical sequence: disruption of ecological stability → accumulation of factors leading to failures of biological systems → reaction of layers and/or subsystems of the compartment to the action of anthropogenic factors → synergy of the action of factors → reaction of the system to a negative impact.

It is proposed to use the methodology given in (IEC 31010:2019) to evaluate and manage environmental risk. According to (IEC 31010:2019), the risks that may occur for a target group, subjected to a number of environmentally hazardous factors. Risk management is making decisions, including risk assessment and risk management. The process is used to risks for plants, animals, and humans, subjected to such dangerous factors as a man-made impact, industrial emissions, waste, chemicals, microorganisms, etc. Various aspects of the methodology, in particular, analysis of methods of influence of the source of dangerous factors on the target population, should be adapted to a specific area (in our case it is CLS), which will provide useful information to choose methods of risk management and reduction.

To obtain an assessment, it is needed to have significant information about the nature and properties of dangerous factors, and the vulnerability of the target group or populations that these factors are acting. Data on the level of risk associated with the vulnerability of a particular target group to a certain dangerous factor in the established area are initial. Typically get they used in field or laboratory studies.

The next stages should be followed when implementing the evaluation procedure:

- determining the purpose and establishing the scope of risk assessment by determining the boundaries of the target group and classifying types of dangerous factors;
- identifying dangerous factors and their possible consequences for the target group;
- analyzing and finding out the properties of each dangerous factor and the nature of its interaction with the target population;
- analyzing the target group's vulnerability to each dangerous factor;
- characterization of risk.

In the last stage, the information obtained by the results of the analysis of an individual dangerous factor and the vulnerability of the target group is built together to quantify the probability of specific consequences, if you combine influences by all factors. The advantage of analyzing the impact of harmful factors is a detailed study of the nature of the problem and risk factors. It is usually a useful analytical tool for all areas of risk and allows us to identify how and where we can improve our availability or introduce new control and management tools.

The results of the evaluation process are convenient to serve as a risk matrix (Kovačević et al., 2019). It is a matrix to determine the level of risk by combining the probability category of consequences with their severity. The risk matrix is a simple mechanism to increase the obvious risks and facilitate adequate management decisions. Statistically, the risk level can be calculated as a product of the probability that harm will happen to the severity of this harm. In practice, the risk matrix is especially useful when neither the probability nor the severity of the harm can be accurately appreciated.

In the matrix, the risk can be quantitative, semi-quantitative, or qualitative. Semi-quantitative analysis can be used to obtain a risk index for a particular pollutant or pest, and qualitative initial data may be a risk level (eg high, medium, low) or description of probable effects using practical data.

In general, the risk assessment will be considered the process of analyzing the dangerous factor, its source, as well as the ways that this factor can reach a vulnerable target group or population. The information obtained is combined for quantitative assessment of the degree of risk as a product of probability (*probability*) P and the nature or volume of damage (*harm*) H.

3. Results

The purpose of the stability indicator is to describe environmental changes that may occur as a result of planned activities and to assess the significance of these changes. This assessment is based on the following: technical description of anthropogenic impact on the CLS; determination of the layers of the subsystems of the CLS compartment exposed to the impact; experience gained from other projects (Ruda et al., 2021); presented methodology. The impact assessment is carried out for separate layers of the subsystems of the compartments that are part of the CLS.

Depending on the characteristics of the CLS, individual elements of the presented circuit may be absent, and each such event (element) can be assigned a partial indicator in the form of its probability: the probability of failure of the CLS → the probability of accidental loss → the probability of injury, etc. However, the presence of potential hazards in the system is not always accompanied by their negative impact on the object.

Compartment CLS F, can be presented as a set of characteristics and written in the form:

$$F_{ji} = (G_i,\ T_j,\ S_p,\ I), \tag{16}$$

where G – a subset of hygrotopes $G = \{G_i \mid i = 1,\ 5\}$; T – a subset of trophotopes $T = \{T_j \mid j = 1,\ 5\}$; S_p – the set of species diversity of the compartment subsystem; I – the set of integral characteristics, which include the stability of the CLS. The latter set of characteristics may also contain links between components of the ecosystem.

Developing the concept of levels of living matter organization, as the basis for the classification of anthropogenic impacts on living nature, a system was proposed based on the hierarchical structure of the CLS, which puts in order the variety of effects associated with anthropogenic impact on the CLS (Table 1).

A specific feature of the system of criteria displayed in Table 1 is the reduction of a large number of anthropogenic impacts on the biota and the corresponding four levels of biota disturbances into four ordered groups. Most of the traditional toxic effects (increased mortality, impaired ontogenesis and organ pathology, etc.) fall into the group of individual and population responses (level 1).

Change in primary productivity; change of aggregate biomass indicators; changes in the concentration of chlorophyll in the forest ecosystem, other systemic disturbances associated with the accumulation of heavy metals and radionuclides – this is level 2.

Very important and still insufficiently described disturbances are attributed to the level of stability and integrity of ecosystems – level 3.

This system is completed by a group of disturbances in the ecosystems as a part of biospheric processes (level 4), including biogeochemical flows of elements.

The proposed system for the analysis of environmental hazard is the basis for assessing the undesirable impact on the stability and integrity of the ecosystem, an example of

Table 1. Analysis of the levels of environmental hazards caused by anthropogenic disturbance of biota

Item No.	Disturbance level	Examples of disturbances and their consequences (some of them may relate to several levels)
1.	The level of individual and population responses to disturbances	Toxic effects on certain species of organisms (increased mortality, reduced fertility, impaired ontogenesis, pathology, etc.)
2.	Level of aggregate (supraorganismal) responses to disturbances	Change in primary productivity; changes in aggregated biomass indicators; change in chlorophyll concentration in the forest ecosystem; other systemic disorders associated with the accumulation of heavy metals and radionuclides
3.	The level of the stability and integrity disruption of the CLS	Restructuring and/or weakening relationships between soil → moss layer → forest stands → young growth, undergrowth, grass-shrub layer; change of biogeochemical cycles; low capacity for self-regulation and self-regeneration and others
4.	The level of disturbances in the contribution of CLS to biospheric processes	Change of flows (for example, sedimentation of pollutants), flows of N (for example, change of nitrogen fixation level), flows and cycles of other elements, in particular S and P; change of energy flows (thermal, etc.)

which can be the danger of weakening the functional relationships between the compartments in the CLS and abiotic environmental factors, as well as the risk of destruction of compartments. If an anthropogenic impact weakens this relationship in the CLS, then the consequences for it are presented as unfavorable.

The assessment of the CLS stability should be carried out taking into account the synergism of the impact of hazardous factors, which can be represented by the example of a two-chamber model of biota – $Z(t)$ and water – $Y(t)$, which contain a variable with time t amount of radiation pollution. According to the results of the experiment on the model ecosystem, it was found that the value of synergism S (7) for cadmium salts and ionizing radiation ranges from 0.6 to 0.8.

Using a number of key provisions of the theory of biotic regulation, it was found that the main task is not so much to reduce anthropogenic emissions, but to preserve the hierarchical structure of the CLS and provide biotic mechanisms for regulation, functioning and renewal of the CLS. In particular, vegetation is an indicator of diversity, a state of equilibrium, and a disturbance in the CLS, and a compartment acts as a regulatory mechanism for CLS formation, restoration from the initial to equilibrium state, and stabilization. Therefore, the assessment of the CLS stability should be based on a comparative assessment of the successive stages of groupings in a compartment from the initial to a stable climax state. It is performed on the following grounds: the $\Delta Z = Z_2 - Z_1$ difference of the system of one state in relation to another; permissible deviation from the base state or variability of $Z_0 - Z_1 < \Delta Z$; the time interval Δt, within which changes occur or the stability is assessed; the influence of one or more external factors F_i or their synergy.

Two groups of features (characteristics) of a compartment are proposed: the succession rate V and the scope of changes S, that is, their temporal and spatial state – $f(V, S)$. Moreover, both direct and indirect characteristics can be used, for example, the presence of species included in the conservation lists, that is, they are in the zone of greater risk of destruction. To assess the sozological significance of the compartment, 12 main features were used, supplemented by the degree of hemerobity and the ratio between the types of strategies.

It is proposed to evaluate the weight of each feature in points from 1 to 4. The minimum number of points that a compartment can receive for all characteristics is 12 points, the maximum is 48 points; the difference between them is 36 points. Then the degree of risk R, as the loss of each point: 1 point × 100% : 36 = 2.78%. Moreover, the number of analyzed features can be reduced.

Thus, when evaluating all the features, scores are obtained which can be divided into five classes with a range of 7 points: class I (48–42 points) – very rare, having a "narrow" distribution, poor reproduction, very high $R > 83\%$) index of the risk of destruction, very sensitive to changes in environmental factors and require special integrated protection measures; class II (41–35 points) – rare, with limited distribution, poor reproduction, high ($R = 63 - 83\%$) index of the of risk of destruction, sensitive to anthropogenic factors and require certain targeted measures for their protection; class III (34–28 points) – a fragmentary distribution and under the influence of anthropogenic factors, there is a tendency towards a decrease, are characterized by slow recovery, have an average ($R = 43 - 63\%$) index of the risk of destruction and require partial protection; class IV (27–21 points) – have the usual distribution, typical groupings, recover normally in these conditions, have a low ($R = 23 - 43\%$) index of the risk of destruction, resistant to anthropogenic impact, although they do not require protection measures, they can be destroyed by excessive anthropogenic activities; class V (19–12 points) – quite common compartments, sufficiently adapted to the action of anthropogenic factors or formed under their influence, have a very low ($R < 23\%$) index of the risk of destruction and do not need protection.

The assessment of the compartments distribution by stability classes characterizes the gradient of stability change and the rate V of its possible loss, and taking into account the area S occupied by one or another compartment in the CLS makes it possible to assess the scope of these processes. The increase in the risk indexes values indicates the possibility of a catastrophe K. So, the higher the rate of stability loss V_{max} and the increase in risk in a short time, as well as the smaller its area S_{min}, the closer the compartment is to the catastrophic state $K \leftarrow S_{min}V_{max} = (Z_1 - Z_0) / \Delta t$. In other words, the higher the rate of succession, the higher the probability that the compartment of the CLS will reach a critical state and the possibility of catastrophic changes.

Based on the analysis of the diversity of compartments included in the CLS, they can be divided into three categories: P – plastic (hydrophilic, segetal, ruderal, secondary), which are in a state of constant dynamics, easily restored, because the compartment does not change, they have low floristic diversity, serve as centers of establishment of adventive species, have a very low risk of loss; I – inert (forest, steppe), which, when destroyed, are capable of recovery after a long time, pass through the stages of syngenesis, endoecogenesis, phylcoenogenesis (transgenesis processes prevail), which is accompanied by a gradual restoration of the compartment in the structure of the CLS; S – resistant or stable that are in extreme conditions (rock, sandlittoral, raised bogs on the border of the area, under constant anthropogenic pressure), retain their structure well, but if it is disturbed, the compartment is destroyed, which is not restored.

The proposed approach to assessing the stability and the risks of losing a compartment in the CLS makes it possible to obtain quantitative indicators of the stability and risks of compartment loss, which can be used as indicators of the state of the entire CLS. On their basis, it is possible to perform: calculation of those threshold values beyond which negative phenomena occur, predicting and simulating situations, mapping by sources of risks, monitoring and identifying the causes of changes or factors that slow down or restrain the approach of the CLS to a critical state, developing measures to prevent or reduce harmful effects, etc.

In particular, the reduction of harmful anthropogenic impact, in order to achieve its acceptable level, is performed by taking main measures that should be applied in accordance with the scale presented below.

The scale for reducing harmful anthropogenic impact provides:

Reduction of emissions at source. Preventing or reducing the impact at its source requires project solutions in which the causes of the impact are eliminated (for example, changing a pipeline route) or modified (for example, a reduction in the right-of-way for a pipeline). The term "minimization" is also used.

Reducing on-site. It is envisaged to apply modifications to the original project development, for example, taking measures to control environmental pollution. It is often referred to as "on-site cleaning technology".

Reducing at the receptor. If the impact cannot be mitigated at the point of discharge, these measures can be carried out outside the site of the source.

Rehabilitation or reclamation. Some impact leads to inevitable damage to resources (for example, agricultural land during the construction of pipelines). Rehabilitation involves measures to return the resource to its original state.

Compensation by replacement. If other mitigation measures are not possible or not effective enough, compensation for losses, damages and general intrusion may be an acceptable solution. Compensation can be natural (replacement in kind), which is expressed, for example, in planting new plants to replace the lost ones.

The consequences of impacts following mitigation measures are called residual impacts.

Residual impacts are described by experts with relevant work experience. Significance categories of residual impacts are determined by a semiquantitative method, and compared with the initial qualitative expert assessment. An example is presented in Table 2.

Assessing the significance of residual impacts is important for the following reasons: to demonstrate to design engineers the need for appropriate measures to reduce any possible impacts; inform relevant decision-making authorities and stakeholders of residual impacts.

The significance of residual impacts is assessed based on: potential impacts; consequences of exposure. The assessment is based on local, limited, and regional levels of impact. Particular attention in impact assessment is paid to local and limited levels of impact. Similarly, attention is paid to particularly valuable species/resources (for example, species listed in the Red Book).

Comprehensive (integral) assessment of the impact on individual layers and subsystems in a compartment from various sources of influence is a multistage process

Table 2. Residual impact

Initial description of impact, significance of impact (high, medium, low), type of impact (direct, indirect)	Mitigation measures	Residual impact	
		Description of the impact	Significance by layers of subsystems of the CLS compartment (high, medium, low)
Impact of quarry development on forest floor. The forest floor can be damaged or completely destroyed during the works. The significance of the impact is high. Type of impact – direct	Reduce the scope of works in the quarry	Residual impact on forest floor	The significance – high

that involves obtaining an assessment taking into account the following parameters: spatial scale; time scale; intensity, and determines the category of significance of harmful effects and environmental risk (Boyko & Ruda, 2021).

Determination of the spatial scale of the impact is based on the analysis of technical solutions, mathematical modeling, or on the basis of expert assessments and is presented in Table 3. For linear objects, area is mainly used as spatial boundaries; if it is impossible to assess the impact area, linear distance is used.

Table 3. Scale for assessing the area of impact

Graduation level	Spatial boundaries of impact (km^2 or km)		Points
Local impact	Impact area up to 1 km^2	Impact at a distance of up to 100 m from a linear object	1
Limited impact	Impact area up to 10 km^2	Impact at a distance of up to 1 km from a linear object	2
Territorial impact	Impact area from 10 to 100 km^2	Impact at a distance of 1 to 10 km from the linear object	3
Regional impact	Impact area more than 100 km^2	Impact at a distance of more than 10 km from the linear object	4

Determining time-scale impacts on the layers of the subsystems of CLS compartment, is done on the basis of technical analysis, analytical (model) assessments or expert assessments, are presented in Table 4.

Table 4. Scale for assessing the temporal impact

Graduation level	Time scale of impact	Points
Short-term impact	The impact is observed up to 3 months	1
Impact of medium duration	The impact is observed from 3 months to 1 year	2
Long-term exposure to impact	The impact is observed from 1 to 3 years	3
Many-years' (permanent) impact	The impact is observed from 3 to 5 years or more	4

The intensity scale is determined based on the studies described above, as presented in Table 5.

To determine the complex impact on individual layers and subsystems in a compartment, tables with impact criteria should be used (Tables 3, 4, 5). The complex score is determined by the following formula:

$$O^j_{index} = Q^t_i \times Q^S_i \times Q^j_i, \quad (17)$$

where O^j_{index} is complex score for a given impact; Q^t_i is the score of temporal impact on the i-th layer of the compartment subsystem; Q^S_i is the score of the spatial impact on the i-th layer of the compartment subsystem; Q^j_i is the score of the intensity of impact on the i-th layer of the compartment subsystem.

Table 5. Scale of impact intensity

Graduation level	Description of the impact intensity	Points
Slight impact	Changes in the natural environment do not exceed the existing limits of natural variability	1
Weak impact	Changes in the natural environment exceed the limits of natural variability. The natural environment is completely self-regenerated	2
Medium impact	Changes in the natural environment exceed the limits of natural variability, they lead to disruption of individual components of the natural environment. The natural environment retains the ability to self-restoration	3
Strong impact	Changes in the natural environment lead to significant disturbances of the components of the natural environment and/or ecosystems. Some components of the natural environment lose the ability for self-restoration	4

If necessary, the methodology can use the additive definition of the complex impact, in particular, due to the presence of zero values, the equations are canceled during the multiplication action in the complex assessment of the impact on individual layers and subsystems in the compartment.

The significance category is determined by the range of values depending on the score obtained in the calculation of the integral assessment, as shown in Table 6.

Table 6. Categories of impact significance

Impact categories, score			Integral assessment, score	Significance categories	
Spatial scale	Temporal scale	Impact intensity		Points	Significance
Local 1	Short-term 1	Slight 1	1	1–8	Impact of low significance
Limited 2	Medium duration 2	Weak 2	8		
Territorial 3	Long-term 3	Medium 3	27	9–27	Impact of medium significance
Regional 4	Many years' 4	Strong 4	64	28–64	Impact of high significance

For layers of compartment subsystems, the following significance categories are defined: impact on soils and subsoil; impact on surface waters; impact on groundwater; impact on bottom sediments; impact on air quality; impact on biological resources; impact on landscapes; and also for the assessment of physical factors of impact (noise and electromagnetic impacts, vibration, etc.).

Assessment of environmental risks is based on the analysis of the risk source, risk factors, features of a specific ecological situation (biocoenosis or landscape), definition of categories *P*, *I*, *S* of compartments and the above method of risk of compartment loss. When assessing environmental risk, anthropogenic factors, accidental, and cumulative types of risk are singled out as the main factors.

The first – accidental risk – is the result of sudden deviations from the normal functioning of technical or engineering systems with the release of matter and energy, leading to the degradation of the CLS or serious, even irreversible changes in natural processes.

The second type – the cumulative risk is associated with similar consequences that lead to local, regional and even global effects, but it is the result of the accumulation of a number of processes in the CLS in normal operation.

The ecological risk matrix (Table 7) uses an integral impact assessment divided into 5 ranges.

Table 7. Ecological risk matrix

Category	Level of eco-risk	General assessment of CLS
I	$<10^{-8}$	Conditions of ecological well-being
II	$<10^{-6}$	Satisfactory conditions. Normal condition. Man-caused impact on CLS does not exceed the allowable loads
III	10^{-5}–10^{-3}	Unsatisfactory conditions. Technogenic impact on CLS disrupts its stability. Biota degradation tendencies emerge and develop
IV	10^{-3}–10^{-2}	Bad conditions. There is a change in the succession series in the CLS compartment
V	$>10^{-2}$	The state of ecological disaster. The biota is not restored, there is a loss of the CLS compartment

4. Discussion

To formalize the description of the ecosystem, the CLS compartment is presented as a set of characteristics. At the same time, it is advisable to conditionally divide the vegetation variety into layers and subsystems in the compartment. This division is primarily due to the fact that when modeling the migration of radionuclides, pollutants and sediments, it is advisable to distinguish flows not only between individual components of the ecosystem, it is necessary to distinguish flows of biomass and transitions of radionuclides, pollutants and sediments also between forest layers, which will make it possible to assess not only the dynamics of biomass change, but will also allow you to assess the degree of importance of each component. A system based on the hierarchical structure of the CLS was proposed, which organizes the variety of effects associated with anthropogenic impact on the CLS (Table 1).

The use of the model for assessing the combined effect of pollutants on the CLS and the necessary parameters for assessing synergism, antagonism, or additivity, as well as formulas for their calculation based on experimental data, make it possible to classify CLSs depending on the specific structure of pollutants and their type and to assess the resistance of the CLS to anthropogenic impact (Kobza, 2015; Ajman et al., 2021; Kvaterniuk et al., 2020; Zeleňáková et al., 2020; Tang et al., 2018; Yun et al., 2017; Li et al., 2020; Batra, 2021).

The presented assessment of cumulative impacts and synergism of hazards is based on the recommendations of the European Commission (EC) Guidelines (Guidance on EIA, Guidelines for the Assessment of Indirect and Cumulative Impacts as well as Impact Interactions, May 1999), which identifies indirect impacts, cumulative impacts and interactions of impacts and can be divided into two main stages: methods of inspection and identification of impact – aimed at determining how and where indirect and cumulative impacts, or synergism of hazardous impacts may occur; assessment methods – used to measure and predict the magnitude and significance of impacts, based on the study of their intensity and the circumstances of their occurrence and manifestations.

The identification of possible cumulative impacts is made by the construction of a simple matrix which shows the impacts on the layers of the subsystems of the CLS compartments, which have already occurred in the CLS and the impacts that are planned when new objects are put into operation.

With the simultaneous action of several sources of influence, the zones of influence on the individual layers in the compartment may overlap. In these zones, the intensity of impact will be higher than when exposed to a separate source of influence.

According to these features, Grodzynsky (1995) identified three forms of stability – inertness, restorability, and plasticity, which for the CLS can actually be reduced to two – resistibility and plasticity: resistibility – the ability of the K_1 compartment under the influence of factor F_1 during the time Δt_1 not to go beyond certain limits (stability boundaries) Z_1; $\frac{F_1}{\Delta t_1} \leftarrow Z_1$; plasticity – the ability of the K_2 compartment after the termination of the action of factor F_2 during the time Δt_2 to return to the initial stable state Z_2; $\frac{F_2}{\Delta t_2} \leftarrow Z_2$.

Thus, stability can be viewed, on the one hand, as the ability of a compartment to resist the influence of external factors and maintain its characteristics in the Z_1 state (resistant stability according to Lyapunov), and on the other hand, to restore its properties, that is, to be plastic – Z_2.

Tilman (1996) the stronger the resistance of the compartment to the influence of external anthropogenic and abiotic factors, the more difficult it is to break the stability, but if it is broken, then it is difficult to return it to its original state. That is, the higher the plastic resistance, the lower the resistant stability of the compartment.

To interpret these forms of stability, two schemes have been developed with the similar regions of existence of the system *f* (*x, y*). Plastic compartments quickly lose their stability even with a weak action of the *f* factor, which leads to a change in their *SP* state; then their restoration occurs (PS_1). Under a strong influence of the $f_1 > f$ factor, the system, although it undergoes great changes (S_1P_1), does not go beyond the recovery region *Q*. Instead, the resistant system slightly loses stability *SP* under the weak action of the external factor *f*, quickly returning to PS_1; under the strong action of f_1, it gradually enters the post-threshold region of the non-renewable state *U* and loses its stability. High plasticity and low resistance means reduced risk, and low plasticity and high resistance means increased risk. Therefore, the main feature for assessing stability is the degree of resistance, not plasticity (Trishch et al., 2021; Kupriyanov et al., 2022).

Since stability does not have an absolute value, it is incorrect to say that such and such a compartment is stable or unstable, but it can be estimated that in the CLS one compartment K_1 is more stable than another compartment K_2 with respect to the action of a certain factor or their synergistic action F_1, or the Z_1 state of the CLS is more stable than the Z_2 state under certain conditions. Therefore, in general, the stability of the CLS is determined in two ways: on the one hand, the degree of influence of a certain factor *F*, and on the other hand, by the specific feature, location, distance of the K_1 compartment in relation to E_0. That is, the result can be displayed as a vector characterizing the direction and value of the difference between the indexes of the compartments. The assessment of the indications of this vector depends on what is taken as a basis for comparison. For this purpose, it is necessary to choose a compartment as a standard K_0 or to model such a CLS which under the given conditions has the most steady state Z_0. At the same time, CLSs cannot exist in such a state, because taking into account the laws of thermodynamics, a CLS is an open unbalanced system and then has the highest risk of destruction. So, the closer the K_1 system is to the stable, equilibrium, climax state Z_0, the higher the risk of its destruction, and if the system is at the initial stages of the K_2 development, far from the equilibrium state Z_0, then the risk of its destruction is low: $K_1 \rightarrow Z_0$ (*max*); $K_1 \leftarrow Z_0$ (*min*). This conclusion reflects the essence of the method for assessing the stability and risks of destruction of CLS compartments.

In the risk assessment, a prominent place belongs to the study of successional development of the compartment Walker (1995) (Gadow et al., 2021). Succession is seen as an opportunity to rebuild the structure of the compartment in relation to environmental change. Although it is a self-organized and self-sustaining process, it is aimed at improving the mechanisms of energy accumu-lation through the adaptive properties of species, reducing energy costs, and thus reduc-ing entropy, which means approaching a stable but terminal state, and thus increasing the risk of compartment destruction. According to R. Whittaker (Westman & Peet, 1985), succession is not a linear and strictly determined, but a stochastic process. This means that each layer of the compartment subsystem (coenopopulation) can be replaced by another one that is better adapted to existing conditions or preadapted for subsequent possible changes, and such replacement occurs at all stages of the process, in each of the compartment subsystems. Consequently, the indicator of the biotic diversity of those elements that can be interchangeable during the course of the succession is critical, since a decrease in biodiversity narrows the region of stability.

5. Conclusions

The technique of assessment of the CLS, combined with the environmental impact assessment, give important information to support the decision making for investment processes and spatial planning. It is worth considering this practical aspect in our future studies.

The variety of existing approaches and concepts of ecological regulation depends on the intended use of ecosystems and the interpretation of the concepts of "ecological standard", "harmful impact" or "undesirable changes" and is based on the available methods for determining the maximum environmental loads or maximum permissible environmental changes, methods of measuring anthropogenic load, methods for assessing harmful effects or describing the state of biota after such an impact, etc. Therefore, in general terms, the solution to the problem of ecological regulation is reduced to the analysis of relationships and dependencies in the system "anthropogenic load – harmful impact – ecological standard – state of biota – quality of the ecosystem".

The purpose of assessing the indicator of stability is to identify the environmental changes that can occur as a result of planned human activities and to assess the significance of these changes. A system has been proposed that regulates the variety of effects associated with anthropogenic impact on the CLS, where four levels of response to disturbances are identified: individual and population responses to disturbances; disturbance of the stability and integrity of the CLS; aggregate responses to disturbances; disruption of the CLS contribution to biospheric processes.

The assessment of the CLS stability should be carried out taking into account the synergism of the impact of hazardous factors, which are proposed to be determined on the basis of the synergism coefficient *P*. If $P = 1$, then there is no synergism in the action of the factors. If $P < 1$, then this indicates an enhancement in the joint action in comparison with the individual action of each of them. If $P > 1$, then there is antagonism, that is, when one factor reduces the negative effect of another.

Stability cannot be expressed as an absolute value; however it is possible to estimate that in the CLS, one compartment can be more stable than the other with respect to the action of a single factor or the synergistic action of several factors under certain conditions. Therefore, the stability of CLS should be defined as a vector that characterizes the direction and value of the difference between the indicators of the compartments. To assess the stability, it is necessary to model such a CLS, which under these conditions has the most stable state Z_0.

At the same time, the CLS cannot exist in the Z_0 state, since it is an open unbalanced system, otherwise, taking into account the laws of thermodynamics, there is a high risk of its destruction. Therefore, the closer the individual system is to the state Z_0, the higher the risk of its destruction, and if the system at the initial stages is far from the equilibrium state Z_0, the risk of its destruction is minimal.

Accordingly, the assessment of the distribution of compartments by stability classes is characterized by the gradient of stability change and the rate V of its loss, and taking into account the area S occupied by the compartment in the CLS allows assessing the proportion of these processes. Thus, the higher the rate of loss of stability V_{max} and the increase in risk in a short time, as well as the smaller its area S_{min}, the closer the compartment is to a catastrophic state K. In other words, the higher the rate of succession, the greater the probability that the compartment of the CLS will reach a critical state and the possibility of catastrophic changes.

The presented analysis of the diversity of the compartments included in the CLS made it possible to divide them into three categories: P – plastic, I – inert, S – resistant or stable. This division, in particular, will allow the development of measures to prevent or reduce harmful effects, etc. For this purpose, a qualitative scale of reducing harmful anthropogenic impact is presented, which will take into account: reduction of emissions at the source; reduction at the point of exposure; weakening at the receptor; restoration or reclamation; compensation by replacement. The residual impact is proposed to be assessed by experts using a semiquantitative method.

An integral assessment of the impact on individual layers and subsystems in the compartment from various sources of exposure is proposed to be assessed taking into account the spatial and temporal scales and intensity of impacts. Such an assessment will determine the category of significance of adverse effects and environmental risk. The corresponding scales, a method of integration, categories of impact significance and approaches to the construction of an environmental risk matrix have been developed.

The developed methodology will make it possible to do the following: to assess the impact on the CLS under the exposure to various sources of pollution; to determine the significance of environmental impact; to form an assessment of the cumulative impact and synergism of hazardous factors; to construct environmental risk matrices; also this will provide an opportunity to draw specific conclusions regarding the environmental and protective requirements for the CLS.

Acknowledgements

This paper is supported by the National Research Foundation of Ukraine, project number 0123U103529 (2022.01/0009).

Author contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Chengjun Zhou, Mariia Ruda and Alla Shybanova; methodology, Chengjun Zhou, Mariia Ruda and Taras Boyko; software, Orest Kochan, Mariana Levkiv; validation, Elvira Dzhumelia, Alla Shybanova and Taras Boyko; formal analysis, Orest Kochan, Mariana Levkiv; investigation, Chengjun Zhou, Elvira Dzhumelia; resources, Mariia Ruda, Mariana Levkiv; data curation, Taras Boyko; writing–original draft preparation, Mariia Ruda; writing–review and editing, Elvira Dzhumelia, Orest Kochan, Mariana Levkiv; visualization, Elvira Dzhumelia; supervision, Chengjun Zhou, Alla Shybanova; project administration, Orest Kochan; funding acquisition, Chengjun Zhou, Mariia Ruda and Taras Boyko. All authors have read and agreed to the published version of the manuscript. Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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