CHAPTER 2

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INNOVATIVE GEOECOLOGICAL RISK ASSESSMENT IN TECHNOGENESIS FOR GREEN ECONOMY PROGRESS

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The green economy represents oneself the direction in economic science within which it is considered that the economy is a dependent component of the environment within that it exists being as its part. It agrees (Zakharova, 2015), the green economy is considered today as a base of sustainable development, and the innovative green technologies allowing economy to develop without damage to the environment are considered as its main tools. These technologies are based on power- and resource-saving, reduction of technogenic emissions, alternative energy sources, organic agriculture and many other components. Meanwhile an important role for green economy progress can play the innovative geoecological risk assessment in technogenesis, as which it is necessary to understand the following. So, if risk or possible danger, in the general sense of the words, is a combination of the probability and the consequences of adverse events, geoecological risk is the probability of environmental degradation and its transition to an unstable state, mainly due to man-made impact, as well as the probability of the impact of these environmental changes on the industry. Quantitative assessment of geoecological risk is a fundamental element of preservation of life for society as a whole. Taking into account the current statistics of natural and man-made disasters, as well as the state of environmental pollution in Russia and worldwide, there is an urgent need to predict geoecological risk for public and private structures

1. INTRODUCTION

Quantitative assessment of geoecological risk is used in geoecological design in different countries of the world, but often without knowledge and understanding of the mechanisms that lead to the risk, and accompanied by high uncertainty in its assessment. Here, geoecological design is understood as an engineering solution for a project that provides the most efficient use of environmental conditions and resources while maintaining their quality.

It is known that the stability of technoecosystems (i.e., ecosystems formed under the influence of technogenic factors) is largely determined by the natural biogeochemical cycles of chemical elements transformed to various degrees by technogenic activity (Bashkin, 2008). Understanding of the fundamental mechanisms regulating the flow of substances in biogeochemical chains allows us to quantify geoecological risk and to determine technological solutions for its management in various technoecosystems.

Modern industrial production uses a huge number of different chemicals, as both raw materials and intermediates, and as final products for consumers. Many chemicals in waste end up in landfills and in wastewater, causing ever-increasing environmental pollution. In this regard, the question arises as to the quantitative aspects of the stability of various components of the environment, as well as the possibility of irreversible destruction of the biogeochemical structure of the human habitat - the biosphere.

In addition, it is necessary to be able to predict the probability of negative effects of a pollutant, as well as the scale of the necessary remediation of ecosystems (their purification and restoration), the various components of which are contaminated and disturbed as a result to technogenesis (Bashkin, Galiulin, 2019c). When we are trying to answer these questions, there is uncertainty associated with insufficient or inaccurate knowledge of the interaction of pollutants and the environment.

To solve the problem of interaction of pollutants and the environment, a number of approaches have been developed on the basis of assessment of geoecological risk, which is used in cases where it is impossible to give a clear answer about the impacts of man-made pollution on the environment and human health. However, since harmful effects are almost always present and only the level of damage varies, the required response should include an assessment of the likelihood of geoecological risk. In addition, the question of the risk tolerance of different ecosystems and humans needs to be answered. There is also an inverse problem: how much the changing environment affects the stability of the industry.

The innovative geoecological risk assessment in technogenesis for green economy progress including assessment of geoecological risk in the «technogenesis-environment» system and influence of uncertainty on this process, and also assessment of technogenic impacts on ecosystems are presented. The essence of present work is illustrated by means of eight relevant figures (Bashkin, Galiulin, 2019a).

2. ASSESSMENT OF GEOECOLOGICAL RISK IN THE "TECHNOGENESIS-ENVIRONMENT» SYSTEM

Assessment of geoecological risk in the "technogenesis-environment" system is a process of analysis of the probability of reversible or irreversible changes in the biogeochemical structure and functions of ecosystems in response to man-made impact, as well as the impact of environmental changes on the functioning of the industry. Man-made exposure often refers to an agent (substance) of a chemical, biological, or physical nature, i.e., a stressor.

The effects of stressors can be observed at all levels of the biogeochemical chain, from microorganisms to humans (including the individual) to the population or ecosystem (Bashkin, Galiulin, 2018). Consequently, industrial components are examples of stressors; they are constantly or periodically released into the environment and cause negative effects on organisms that may be reversible or irreversible (lethal).
Assessment of geoecological risk makes it possible to determine the probability of reversible or irreversible effects in ecosystems in response to the arrival of stressors, and to take certain measures to prevent their negative impact. It also allows assessment of the impact of the environmental changes on the functioning of the industry. In past decades, the direct or indirect negative impacts on the environment and human health associated with technogenesis have been under close

scrutiny by specially authorized bodies, international organizations, and society as a whole. This has led to the formation of various mechanisms to solve the problem of interaction in the "technogenesis-environment" system. Now, several procedures have been developed to predict, assess, and mitigate the geoecological consequences of technogenesis. The main tool, the so-called ecologization of technogenesis, is assessment of geoecological risk (Bashkin, Galiulin, 2019b).

Assessment of geoecological risk has been recognized worldwide as a complex, scientifically based methodology for assessing the consequences of technogenesis, characterized by a high degree of uncertainty and significant potential danger to the environment and human health. Wide application of approaches to assessment of geoecological risk in assessment of environmental design is recommended to obtain more reliable and adequate conclusions about the consequences for ecosystems and human health associated with environmental degradation. It is important to assess the risk of changes in natural processes for the sustainability of industrial facilities, especially in polar regions.

Assessment of geoecological risk is particularly useful when we are considering design alternatives - including the "zero" option (abandonment of the planned economic activity) - and selecting the optimal design solutions. The interpretation of risk impacts is intended to facilitate assessment of their significance and ranking, and, consequently, to simplify the process of prioritization in the selection of measures to prevent and/or reduce the importance of possible negative geoecological consequences of implementation of a project.

In other words, the conclusions of the assessment of geoecological risk should become the basis for its management, i.e., the determination of the most significant geoecological consequences associated with a particular investment project, as well as the development, justification, and implementation of measures to reduce the risks to the environment, human health, and sustainability of industrial production.

One of the methods of geoecological risk management is a comparative risk analysis, which is a process of comparison and ranking of different types of risks aimed at determining the most significant component of them. Comparative risk analysis is designed to help optimally allocate the necessary resources for the implementation of environmental and human health measures, which should be provided in the investment project.

In the light of the above, it seems necessary to improve the methodology and practice of determining the anthropogenic impact on the environment through the systematic use of methods for assessing geoecological risk. What is especially important is the introduction of risk assessment in the geoecological justification of industrial facilities, characterized by increased danger to the environment, taking into account the reverse effect of this environment on the operation of industrial facilities.

Many foreign and domestic classifications of geoenvironmental engineering objects include large projects in mining with high geoecological risk. It is known that the development of mineral deposits, especially in the open way, leads to a significant transformation of landscapes due to changes in the material-energy flows in ecosystems.

It is important to note that the few examples of application of methods of geoecological risk assessment in the "technogenesis-environment" system in Russian practice relate to the oil and gas industry - namely, projects for the development of oil and gas fields, as well as the construction of pipelines for transportation of hydrocarbon raw materials. At the same time, for example, in the conditions of the polar regions, the changes in environmental parameters due to man-made impact (soil-ground warming) have a reverse effect on the infrastructure of gas fields and gas pipelines, violating their mechanical stability.

3. SCHEME OF GEOECOLOGICAL RISK ASSESSMENT

Assessment of geoecological risk is a complex scientific and practical process using iterative approaches, i.e., actions that improve the results of this assessment by repeatedly improving the quality of the necessary initial information about the risk, which is the result of scientific research in various fields of knowledge - from biogeochemistry and ecotoxicology to chemical technology and engineering geology. As seen in **Fig. 1**, the scheme of research in the process of assessing the geoecological risk in order to manage this risk includes three blocks of sequentially performed procedures - geoecological studies, assessment of the geoecological risk, and management of the geoecological risk - each of which contains its own set of tasks.

Figure 2 presents a typical scheme of a step-by-step assessment of geoecological risk, which is reduced at the final stage to the management of this risk. In particular, the hazard identification stage is aimed at qualitative prediction of negative impact.

As a rule, at this stage it is possible to identify the potentially negative impacts of certain pollutants on the environment, as well as the influence of environmental changes on industrial facilities. This could draw on existing experience in assessment of similar pollutants in other conditions. Already at this stage, certain decisions can be taken for the management of geoecological risk, using financial or administrative methods.

The process of hazard quantification includes consideration of the maximum possible flow of the substance and the spatial boundaries of the possible effects of a pollutant. In other words, there is a need to consider the step-by-step life path of a hypothetical chemical, from the stage of its state as a raw material to the stage of waste formation of the substance, **Fig. 3**.

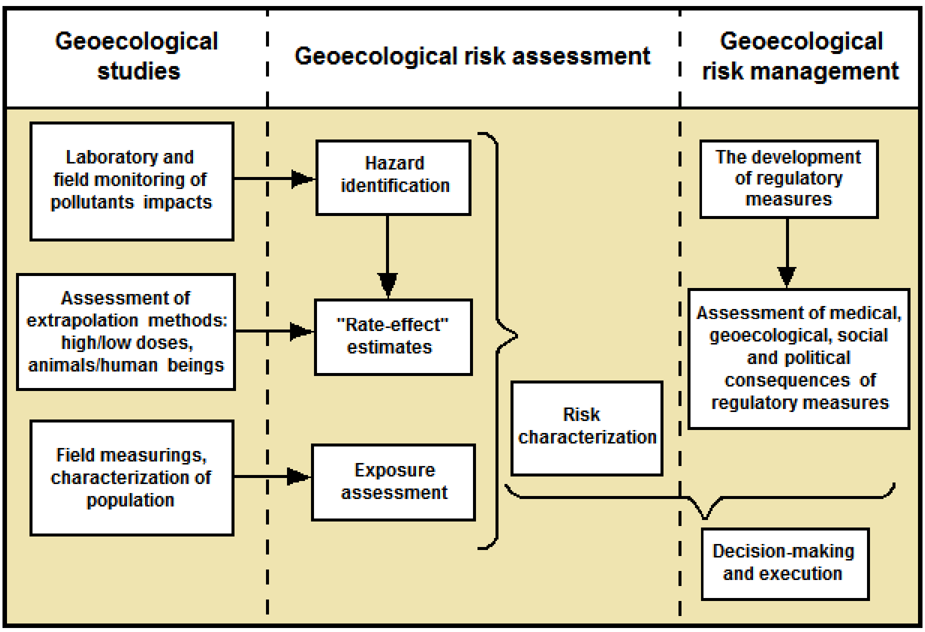

Fig. 1: Scheme of research in the process of geoecological risk assessment and management

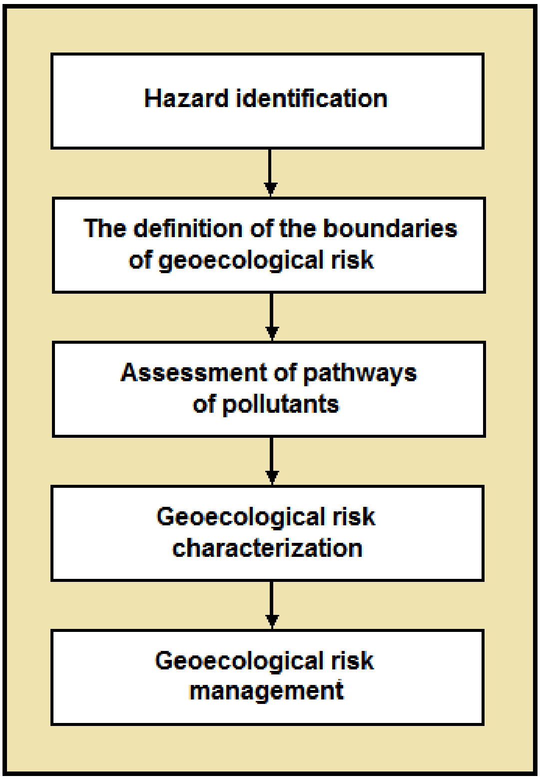

Fig. 2: Scheme of stage-by-stage assessment of geoecological risk, which comes down to management of this risk

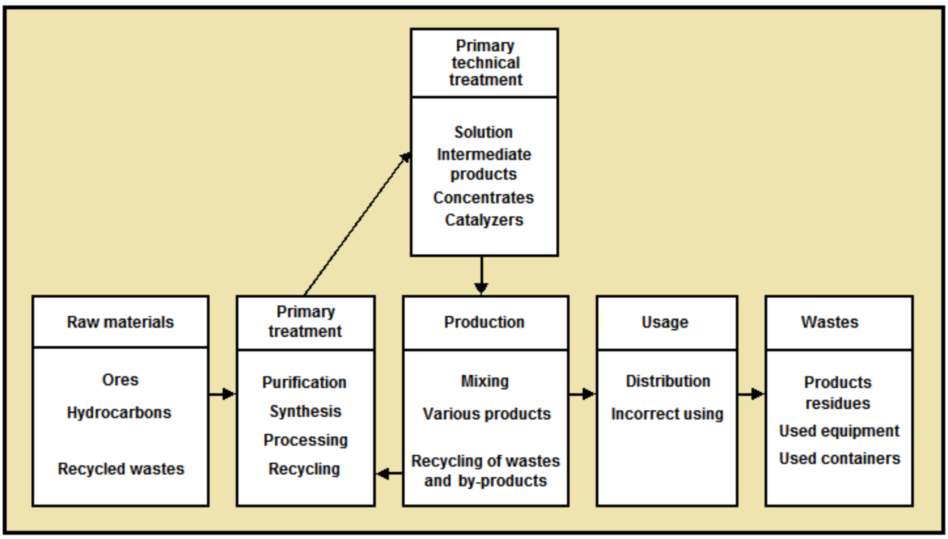

Fig. 3: Stage-by-stage life path of a hypothetical chemical substance

The process of evaluating routes of exposure to the stressor involves consideration of a general pattern of pollutant impacts on biota. At this stage, the effects of the chemical on human health from the moment of its emission into the environment in the event of an emergency are also investigated, **Fig. 4**.

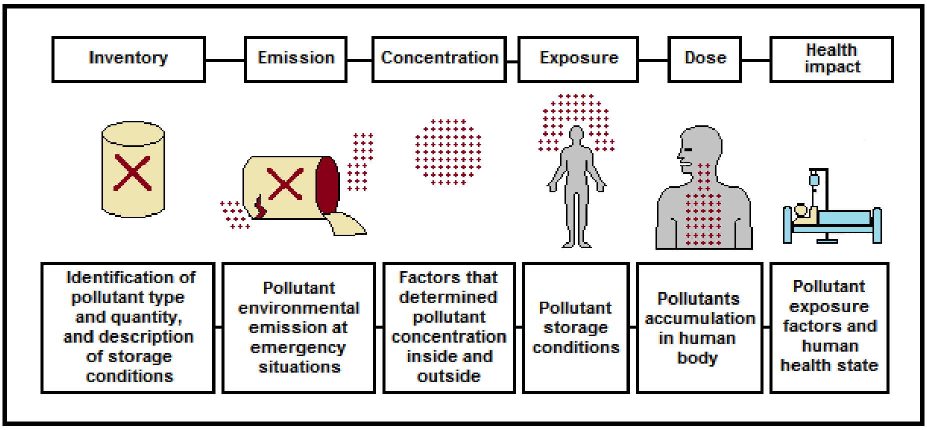

Fig. 4: Impact of a chemical substance on the health of humans from the moment of its emission into the environment in an emergency situation

As can be seen, the starting point in this assessment is an inventory of the chemical to identify its type, quantity, and storage conditions, which should determine the possibility of its emission into to the environment in the event of an accident, which, ultimately, through certain stages, would lead to a negative impact on human health.

4. INFLUENCE OF UNCERTAINTY ON THE PROCESS OF GEOECOLOGICAL RISK ASSESSMENT

In a general sense, uncertainty, as a measure of information, should be understood as the absence or lack of information about something, and inequality is a formal expression of uncertainty. As for the process of geoecological risk assessment itself, the need for its implementation arises when a direct and unambiguous response is difficult to obtain because of a large number of uncertainties in the description of the life cycles of chemicals from extraction and processing of the relevant raw materials to their use as products and waste generation.

Very rarely can a definite answer be given about all of the stages and processes occurring during the life cycle of products, as in the vast majority of cases our knowledge is either insufficient or incorrect, or it relates to the chemical in question only indirectly. At the same time, the sources of uncertainty can be:

- lack of understanding of cause-effect interactions and lack of satisfactory scientific theory - for example, knowledge of the processes of bioaccumulation of chemicals in biogeochemical food chains, mechanisms of pharmacokinetics, and effects of air pollutants on the development of flora, as part of the biota;
- use of models that do not correspond to real conditions, because of lack of data and the need to simplify them;
- unreliability of experimental data due to the difficulties encountered in field monitoring (problems of sampling and chemical analyses), lack of long-term series of observations, and the huge spatial variability of most environmental parameters;
- insufficient data due to their fragmentary nature, both temporal and spatial, especially at the local and regional levels;
- insufficient information content of toxicological data on substances during their extrapolation from experimental animals to humans and from high experimental short-term doses to low but long-acting doses in the environment;
- variability of many natural parameters that determine the transformation and migration of pollutants in the environment (weather, climate, natural disasters, etc.);
- necessary assumptions on which the analysis of geoecological risk is based and the resulting changes in which these assumptions are reflected;
- absence or lack of scientific history related to the study of the behavior of many specific newly synthesized chemicals in various environmental components;
- scarcity of data on the influence of the changing environment on industrial facilities, especially in polar areas.

In accordance with these sources of uncertainty, the following examples of information support can be given, showing the need to perform assessment of geoecological risk when one or another part of the necessary information is uncertain or contains uncertainty:

- potential emissions of hazardous chemicals into the environment: their sources, speed and quantity;
- possibility of fires and explosions;
- migration and fate of pollutants in the environment;
- mechanisms and rate of atmospheric dispersion or dilution processes in natural waters;

- exposure to pollutants: their doses, exposure of sensitive organisms, durations of exposure;
- determination of dose-response interactions for humans by extrapolation of information obtained in experiments with experimental animals;
- industrial accidents related to wear and tear of equipment;
- industrial accidents related to errors of made by workers;
natural disasters; earthquakes, tsunamis, typhoons, hurricanes, etc.;
- changes in the hydrogeological, soil and plant characteristics of landscapes: for example, changes in the depth of groundwater and land use, soil erosion, ground melting (Galiulin et al., 2020).

Consequently, the behavior of chemicals during their life cycle in one form or another includes uncertainty, and, accordingly, their fate in the environment should be determined using methods for assessing geoecological risk. In other words, the probability of adverse effects of pollutants on the environment and humans should be quantified. Hence, there is undoubtedly great interest from specialists working in the field of environmental chemistry and ecotoxicology in methods for assessing geoecological risk.

5. PROCESS OF GEOECOLOGICAL RISK ASSESSMENT

A detailed step-by-step process of geoecological risk assessment, allowing the researcher or practitioner to give a full-scale description of this phenomenon - which greatly facilitates its perception and, consequently, the understanding of the possibilities of risk management - is presented in Fig. 5.
As can be seen from the starting points, this process leads to a full-fledged characterization of geoecological risk - such as the "impact" and "receptor" - consistently through separate stages, and further to the concept of "danger", while all three starting points are ultimately summarized in a "dose-response" state as key provisions of the characteristics of the geoecological risk.

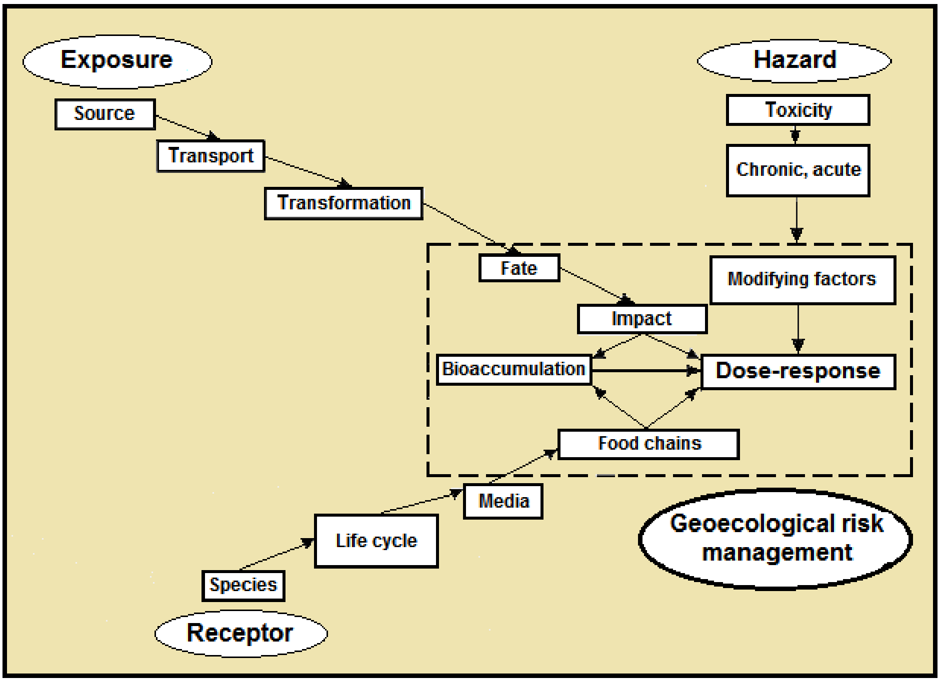

Fig. 5: Step-by-step process of assessment of geoecological risk for its management

5.1. Identification of the problem of geoecological risk

The first step in the process of geoecological risk assessment, as in the determination of the hazard of chemicals, is identification and formulation of the problem. For example, it is necessary to assess some classes of chemicals (industrial components), their toxicity, and their possible scope of distribution. This step includes a preliminary characterization of exposure and toxic effects. Mandatory points in the formulation of the problem are planning and discussion of the process of assessing geoecological risk between experts in the field of risk assessment, i.e., risk assessors and managers. Managers include those interested in the production or use of chemicals, production managers, and financiers providing investment, as well as representatives of the local administration.

Both the process of assessment of geoecological risk and its financing are discussed. An important point of such discussions in the formulation of the problem is definition of the types and sizes of uncertainties allowed in

the process of assessing geoecological risk, as these assumptions will determine the risk management scheme.
Key factors in the process of geoecological risk assessment, such as the relationship between expert assessments of the effects of chemicals on biota and humans and experimental observations, as well as the effects of a transformed polluted/degraded environment on the industry, are also discussed at the problem formulation stage. A preliminary conclusion about the availability of the data is made, the necessity and duration of field observations are formulated, and the type of experimental test objects is considered. The understanding reached at this stage between risk assessors and managers is essential for further work in the process of assessing geoecological risk.

5.2. Identification of the adverse effects of chemicals

Identification of the adverse effects of chemicals can be considered in the process of discussion with managers and in the formulation of the problem. At the same time, this may be a separate section of the geoecological risk assessment process, since, as already noted, this phase provides a qualitative hazard assessment based on existing literature data by comparison with similar chemicals and natural conditions or by extrapolation of other results.

If the phase of identification of the negative effects of chemicals is singled out as an independent one, its tasks include definition of the characteristics of stressors and the impacts on ecosystems and humans. Definition of the characteristics of stressors includes a complete description of the chemical and physical properties of the pollutant: its chemical structure, solubility in water and organic solvents, octanol coefficient, melting and boiling points, volatility, reactivity, period of existence in different environments, and ability to migrate and immobilize.

Special attention should be given to the effects associated with a negative impact on the environment (and a reverse effect on industrial facilities) and humans, and this is a significant part of the whole process of risk assessment. At this step it is necessary to assemble all available information on the effects, including the toxicological properties of the chemical substance (such as its doses causing mortality of 50% or 95% of infected animals (LD_{50}, LD_{95}, respectively)); bioaccumulation potential;

the presence of carcinogenic, mutagenic, or teratogenic effects; and the overall degree of toxicity. It is necessary to assess the ability of the substance to move through biogeochemical chains, from the lower links to the higher ones, including humans as a closing link.

At the same stage, the choice of parameters by which the toxicity of the pollutant is estimated should be considered. These parameters can include:

- the content of the chemical in various media: in the atmosphere, soil, water, and biota (Radojevic & Bashkin, 2006);
- changes in the activity of various biochemical parameters in animals and humans;
- general violation of reproductive functions and survival of various test objects.

These parameters are determined either by laboratory and field observations or by expert assessments. Although experimental observations significantly increase the duration of the process of assessing geoecological risk and its cost, this approach allows collation of reliable data and improvement of the quality of hazard assessment.

Expert assessments are applicable when there is already a certain set of studies with similar substances, the results of which allow a conclusion to be drawn about the behavior of the pollutant in the environment with some approximation. At the same time, the use of expert assessments significantly accelerates the process of assessing geoecological risk and reduces its cost.

The result of the identification of the negative impact of the pollutant is the development of a conceptual model that includes various blocks consisting of the above steps in the process of assessing geoecological risk: characteristics of the stressors, their impact on ecosystems and humans, and the parameters of the assessment, as well as the time and spatial subordination. The conceptual model may also include an appropriate computer calculation algorithm.

5.3. Analysis of the negative effects of chemicals

On the basis of all collected information on the impact of chemicals on the environment and the conceptual model that is created, a quantitative analysis of the negative impact is carried out. Such an analysis is carried

out, as a rule, by computer calculations because it is necessary to process large volumes of different kinds of data, including the characteristics:
- physical and chemical properties of the pollutant;
- effects of the pollutant on biota and humans;
- geochemical and biogeochemical fluxes of the pollutant in the studied landscapes in comparison with the background areas;
- toxic effects of the pollutant;
- durations of exposure to the pollutant;
- how this chemical could change the environmental characteristics related to stability of industrial facilities.

All of these data are processed on the computer using the appropriate algorithm. An obligatory element of the calculations is analysis of input data uncertainty and its impact on the final or intermediate results of the calculations.

At the stage of the analysis, it is possible, and often necessary, to carry out different types of iterations, i.e., performing repeated calculations based on the refinement of input information and its impact on the results. In general, the stage of analysis of the negative effects of chemicals is fundamentally similar to any other analytical study based on receipt of certain quantitative conclusions on the basis of the available material.

5.4. Characteristics of geoecological risk

The characterization of geoecological risk represents the final phase of its assessment, when all of the data obtained at the previous stages are integrated and discussed. Using quantitative indicators obtained at the stage of analysis of the negative impact of the chemical, and on the basis of the expertise of the risk assessors, a conclusion is reached on the degree, size and probability of danger for a particular individual, population, or ecosystem as a whole.

One of the most common methods used for such assessments is comparison of the data with data from other similar projects or studies. The risk from exposure to the studied pollutant is compared with the risk from other factors by comparison with different chemicals or natural parameters.

The presence of such comparative conclusions greatly facilitates the next phase: management of the geoecological risk. However, if such a comparison cannot be made, the causes are identified and the uncertainty associated with the lack of comparative risk assessments of the various factors is analyzed. At this stage, the involvement of independent experts from other organizations to verify the reliability of the results is also highly desirable. The data obtained in the phase of definition of the characteristics of the geoecological risk should be clearly defined to exclude ambiguous interpretation of them.

It is necessary to avoid use of narrow scientific terms that are incomprehensible to a wide range of managers in formulation of the conclusions of the process of geoecological risk assessment. A broad discussion between the risk assessors and the managers responsible for managing the geoecological risk will help to clarify all issues and resolve misunderstandings.

5.5. Geoecological risk management

Characterization of the geoecological risk leads directly to the management phase, providing a basis for discussion between the risk assessors and managers in the presence of the industrialists, financiers and administrators. In this debate, measures are discussed for the protection of the environment/industry and protection of the population from chemical or other influences.

At the same time, risk management is primarily a decision-making process to minimize geoecological risk without serious prejudice to the interests of society or its individual groups. For example, in the case of emissions of pollutants into the atmosphere and their subsequent release into the soil, the discussion may lead to a decision to limit production and reduce emissions at the same level of production and/or remediate the soil. In this case, economic costs should be taken into account, and decisions are made on the basis of the results of ecological and economic optimization modeling.

Figure 6 shows a scheme of categorization of geoecological risk depending on the frequency of exposure to the chemical, economic damage from environmental pollution, and the impact of pollution on the ecosystem, leading to acceptable effects, effects necessitating application of measures to reduce geoecological risk, or unacceptable effects.

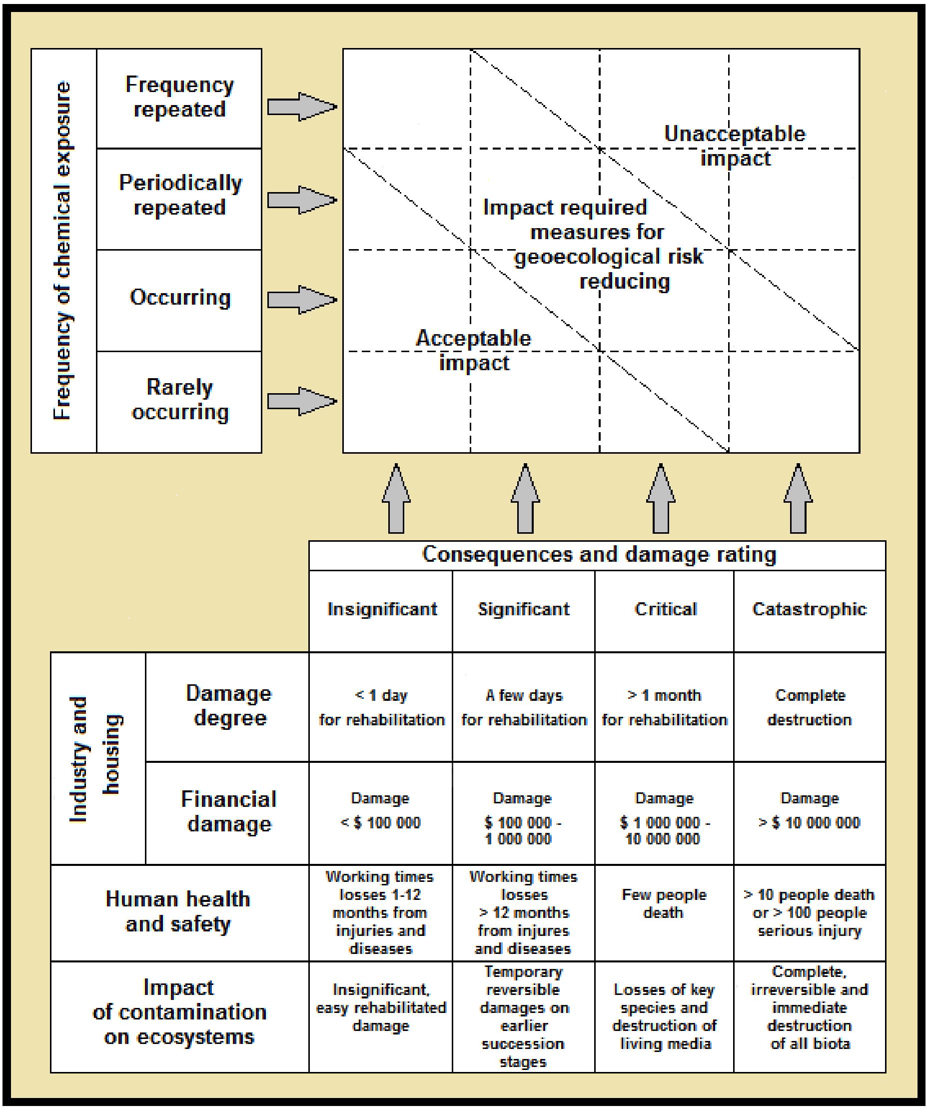

Fig. 6: Scheme of categorization of geoecological risk depending on the frequency of chemical exposure, economic damage from environmental pollution, and impact of contamination on ecosystems

Also, the impact of the chemical leads to economic damage, resulting, in particular, from the degrees of violation and financial damage to the industry, housing, human health, and safety, and the impact of the pollution on ecosystems, as well as the adverse effects of a polluted/degraded environment on industry functioning.

5.6. Sequence of steps in geoecological risk assessment

Below, we summarize all of the stages that various chemicals, including industrial components, necessarily pass in the process of assessment of geoecological risk, namely:

1. Collection of information of a general nature, which implies:
- familiarization with legislation on environmental protection;
- contact with representatives of local legal and environmental organizations;
- familiarization with databases of toxicological data on chemicals;
- information on the physical, chemical, and toxicological characteristics of chemicals.

2. Determination of chemical exposure, which implies:
- collection of existing information for all blocks of the conceptual model of geoecological risk assessment;
- determination of the value and reliability of the information collected and initial uncertainty analysis;
- conduct of additional pilot studies if they are necessary to fill existing information gaps;
- use of quantitative and structural relationships for the primary evaluation of new chemicals;
- selection of the most sensitive test objects to determine the level of toxicity.

3. Characteristics of geoecological risk, which implies:
- comparison of actual and potential concentrations of chemicals with existing sanitary standards (Radojevic & Bashkin, 2006);
- identification of the level of danger for the population, through the use of LD_{50} and LD_{95} values;
- identification of adverse influences of environmental changes on industrial facilities.

4. Management of geoecological risk, which involves:
- adoption of measures to regulate the emission of pollutants, i.e., prohibition, restriction, selection of the most toxic substances, and prevention of pollution;
- implementation of continuous and periodic monitoring;
- environmental-economic optimization modeling to determine the direction of investment;
- repetition of the process of assessment of geoecological risk for chemicals with increasing production and new information about accidents and high levels of local and regional environmental pollution;
- rehabilitation of ecosystems to avoid adverse effects.

Thus, the process of geoecological risk assessment begins with familiarization with legal documents from the sphere of environmental legislation related to tests, descriptions, and regulation of production of new and existing industrial components both in the whole country and in certain regions where these substances are produced, sold, or used. The next step is to collect information on the physical and chemical properties of substances, especially those that determine their migration along biogeochemical chains and bioaccumulation.

Also, information on the production, use, and disposal of the chemical waste that is most dangerous from the geoecological point of view, including data on its acute and chronic toxicity to test objects, is needed. It should be emphasized that there is sufficient information on the toxicological properties of chemicals produced over a number of years. However, similar information on newly released substances is limited or not available. In such circumstances, a preliminary conclusion on toxicity can be reached on the basis of the quantitative and structural characteristics of similar chemicals. In the absence of even these data, laboratory and field toxicity screening should be carried out.

At the stage of risk characterization, it is necessary to take into account that many existing maximum permissible concentration (MPC), LD_{50} and LD_{95} values have been obtained long ago and in many cases do not reflect the current picture of both the composition of the produced and used chemicals and their levels in various environmental objects. In this case, it is recommended to use international standards - for example, those of the World Health Organization (WHO).

Finally, it is important to note that measures for the management of geoecological risk must take into account the existing legislation on the protection of the environment. Development of alternative options using ecological and economic optimization modeling is the most real step in risk management schemes on local and regional scales. The key point of the whole process of the need to assess geoecological risk is analysis of the probability of its manifestation in the man-made sphere of human activity and, in particular, under the influence of specific chemicals on the environment.

6. ASSESSMENT OF TECHNOGENIC IMPACTS ON ECOSYSTEMS

The world practice of geoecological substantiation of investment projects in the man-made sphere of human activity shows that assessment of the impacts on biota is one of their weak points. Russia is no exception to this rule: despite regulatory requirements for assessment of man-made impacts on the environment, the quality of research of this nature is generally low. Among the main reasons for this situation are the limitations of the traditional methodology used for assessment of anthropogenic impacts on biota. Among its main disadvantages is the lack of an ecosystem approach, as well as the prevalence of qualitative methods of assessment over quantitative methods. The way out of this situation is to develop a concept of quantitative approaches to the analysis of the probability of geoecological risks, which is performed using the method of assessment of anthropogenic impacts on ecosystems on the basis of ecosystem MPCs, i.e., critical loads of pollutants on ecosystems.

6.1. Methodology of assessment of technogenic impacts on ecosystems

To characterize anthropogenic impacts on ecosystems and the resulting geoecological risks, the following criteria should be used:
- extent of exposure: local, territorial, regional, transboundary, or global;
- duration of exposure: single, periodic, permanent, short term, medium term, or long term;
- nature of the impact: its reversibility or irreversibility;
- intensity of exposure: absolute or relative;
- probability of exposure: high, medium, or low;
- exposure uncertainty: high, medium, or low.

It should be noted, in particular, that because of the structural and functional complexity of ecosystems, the results of assessment of anthropogenic impacts on ecosystems, forecasting changes in their state, are characterized by a high degree of uncertainty. This is due to inevitable simplifications in the modeling of various processes in the environment and the lack of input data for predictive calculations, as well as the lack of reliability or scientific validity of the algorithms that are used.

The procedure for assessing the geoecological risks arising from the technogenic impact includes the following steps:
- hazard identification, i.e., identification of sources of exposure; characterization of chemical, physical, biological, and radiological risk factors; and determination of potential recipients of exposure in the form of environmental components, as well as possible negative changes in their state;
- assessment of exposure, i.e., determination of the intensity of the anthropogenic load on the selected recipients of exposure;
- assessment of effects, i.e., determination of threshold levels of the anthropogenic load (in the form of reference doses or concentrations) on the recipients of exposure;
- characteristics of risk, i.e., assessment of individual geoecological risks, determination of their degree of acceptability, and uncertainty analysis of the results of the studies.

The most detailed studies on assessment of geoecological risks are associated with analysis of the effects of pollution of ecosystems. To date, approaches to quantitative assessment of risks to ecosystems have already been developed, but they are limited to studies of population and species composition. Moreover, little is known about the adverse influences of changed ecosystem characteristics on the stability of industrial facilities, especially in polar areas.

6.2. Conception of critical loads of chemicals on ecosystems

To improve the methodology for assessing anthropogenic impacts on ecosystems, it is advisable to turn to the concept of the critical load of a chemical substance. Figure 7 presents a schematic representation of the concept of critical chemical loading on ecosystems, based on the level of its impact, when exceedance of the dose of a pollutant causes increases in the degrees of the anthropogenic impacts on ecosystems and, conversely, on the industry.

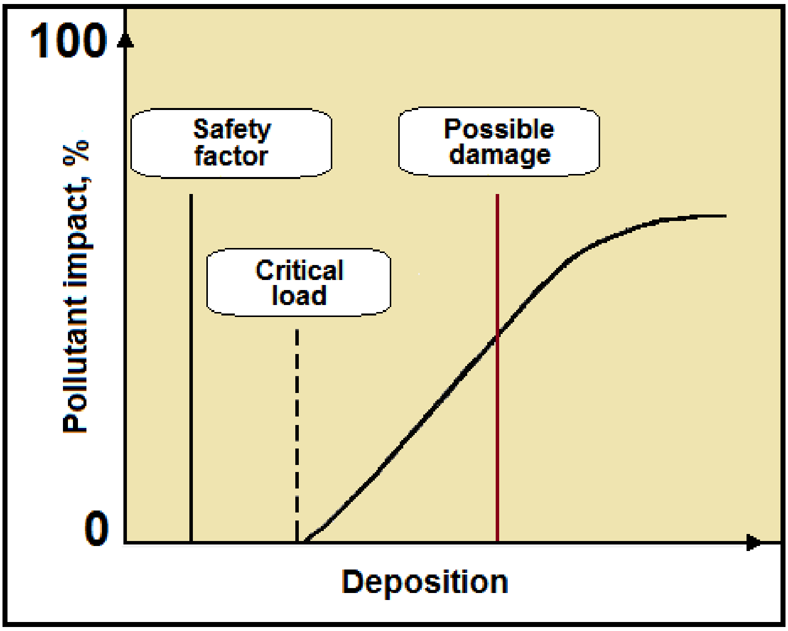

Fig. 7: Schematic image of the concept of the critical load of a chemical substance on ecosystems

As seen, the critical load is an intermediate state between the safety factor and the possibility of damage in the ecosystem. It should be noted that the concept of the critical load does not in itself determine the nature of the response to such effects; it only identifies the permissible threshold of pollutant intake. The concept of the critical load of chemicals is based on an assumption regarding the threshold of pollutant intake, exceedance of which will lead to irreversible changes in the structure of ecosystem functioning. Below this threshold, no significant adverse effects on ecosystems should occur. If the pollutant input falls below the limits, conditions are created for normal development of ecosystems. If the pollutant input exceeds the safe level, it is necessary to estimate this excess in order to reduce the negative impact, to ensure the safety of ecosystems.

In general, the concept of critical loads of chemicals and the related methodology are focused on atmotechnogenic depositions and their effects, i.e., occurring by deposition of substances from the atmosphere, sedimentation, and precipitation on ecosystems. Methods for calculating critical loads of the main pollutants contained in industrial emissions - including sulfur (S), nitrogen (N), and heavy metals - have now been developed and are being applied. Land and freshwater ecosystems are considered recipients of anthropogenic impacts. Although the methodology mentioned above was initially global- and national-scale research oriented, there has been a considerable amount of work on the calculation and mapping of critical loads of pollutants at the regional level in recent years.

In addition, as part of the work to improve the reliability of the initial data for calculations and testing of new techniques, such studies have been carried out at the local level. It should also be emphasized that the concept of critical loads of chemicals on ecosystems is based on the idea of the threshold effect of technogenic factors on ecosystems. The value of the critical load is the maximum amount of the pollutant to which the ecosystem can be atmotechnogenically exposed annually for a long period (50-100 years) without causing irreversible changes in its structure and functions. This indicator characterizes the carrying capacity of ecosystems and is analogous to the reference doses or concentrations of pollutants - the generally accepted standard for impact studies on the estimation of geoecological risks.

In contrast to the sanitary and hygienic quality standards for natural environments (i.e., the MPC, temporarily permissible level (TPL), etc.), the critical load values are the standards that establish the importance of anthropogenic impact on ecosystems as a whole, not on their individual components (air, soil, water, etc.). The calculation algorithms provide for selection of a limited number of biogeochemical parameters, the threshold values of which guarantee the safety of the anthropogenic load on the recipients.

On the basis of biogeochemical principles, the methodology of critical loads allows the internal heterogeneity of the area of influence - for example, the projected industrial facility - to be taken into account. The magnitude of the critical loads is assessed on the basis of internally homogeneous receptor sites, i.e., the sites of ecosystems.

The main criteria for determining the latter are the indicators characterizing the peculiarities of the migration of pollutants in the environment: soil conditions, vegetation cover, and other relevant features of the catchment area. Consequently, the critical load values can be calculated for each recipient ecosystem, which makes them local ecosystem standards of anthropogenic impact.

6.3. Conception of ecosystem risk assessment

Ecosystem risk is defined as a two-dimensional indicator, which firstly characterizes the probability of negative changes in the state of ecosystems as recipients of the impact and secondly characterizes the magnitude of such changes. The quantitative assessment of ecosystem risks is based on calculation and spatial analysis of exceedances of critical loads of pollutant X ($Ex(X)$) within the limits of the zone of influence of the designed industrial facility.

Exceedances of critical loads reflect the ratio between the value of the exposure (i.e., the actual or predicted load of the pollutant) and the safe level of exposure as the magnitude of the critical load of the pollutant. The magnitude of anthropogenic impacts on ecosystems can be calculated as a percentage, which expresses the area of exceedance of the critical load as a proportion of the total area of this group of cells, for example, of the sanitary protection zone of the designed industrial facility.

The choice of criteria for the acceptability of expected changes depends on the nature of the technogenic ecosystems. For the latter with the status of particularly valuable or vulnerable ecosystems, the critical load should not be exceeded in any percentage of their territory. In other cases, it is proposed to follow the principle of "95% protection" of ecosystems, according to which the level of the anthropogenic load is considered acceptable when $Ex(X) \leq 0$, for 95% of the study area.

The calculation of ecosystem risk is proposed to be carried out using probabilistic modeling of critical load exceedances on the basis of the Monte Carlo method. In contrast to the traditional calculation of critical load exceedances, the input data for model calculations are not single values of biogeochemical parameters (i.e., default values or average values) but arrays of their values. The input data arrays can be prepared on the basis of field research data and the results of analysis of objects-analogs.

As a result of modeling for each individual receptor site, a set of $Ex(X)$ values is obtained. The frequency distribution of these values allows us to calculate the probability (P; from 0% to 100%) of achieving positive $Ex(X)$ values for each of the selections within the computational site.

Each value of $P(Ex(X) > 0)$ will correspond to the value of $M(Ex(X) > 0)$ as the total area of the selections exceeding the critical load. The ecosystem risk function ($R(X)$) is derived from arrays of values (M; P):

$$R(X) = \{M, P\},$$

where M is the area of selections (sampling) with exceedances of the critical load ($Ex(X) > 0$) and P is the probability of exceedance of the critical load.

Figure 8 presents a schematic representation of the ecosystem risk functions, consisting of a step distribution function and a continuous normal distribution function.

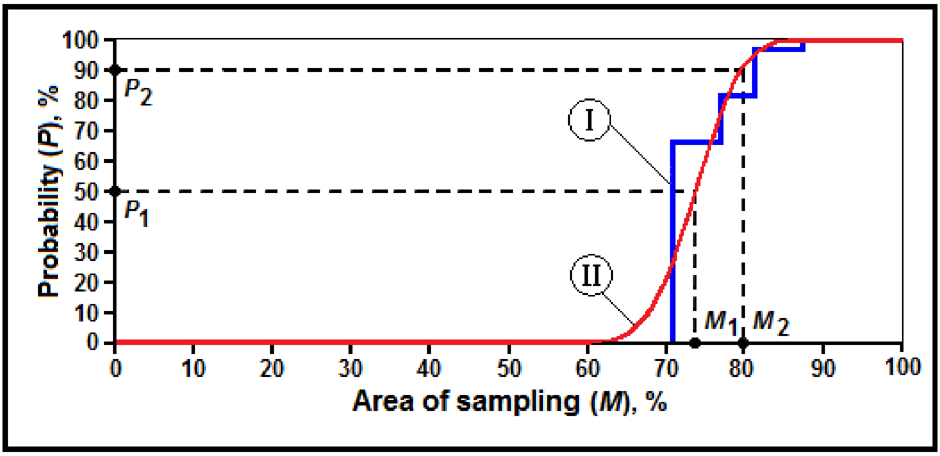

Fig. 8: Scheme of functions of ecosystem risk ($R(X)$), consisting of a step distribution function (I) and a continuous normal distribution function (II). P_1 and P_2 denote the 50% and 90% levels of probability, respectively, and M_1 and M_2 denote the areas of sampling

As can be seen, the function of ecosystem risk is a distribution function and, with a large number of receptor sites, the array of values (M; P) is well approximated by the continuous function of normal distribution. If the number of selections is small, then transition to the normal distribution is impossible and the function will have a step-by-step form.

The normal distribution function allows calculation of:

- with what probability P_1 (50% level) will be marked exceedance of the critical load in the territory less than M_1;

- the probability of exceeding the critical load for a given range of values M ($M_1 \leq M_i \leq M_2$): $P = P_2 - P_1$, where P_2 corresponds to the 90% probability level.

It is proposed to follow a formal procedure or risk assessment procedure when assessing ecosystem risks based on critical loads of pollutants.

6.4. Step-by-step assessment of ecosystem risks

First of all, the hazard identification phase should identify the sources of emissions, identify possible anthropogenic impact scenarios, and compile a complete list of pollutants contained in the emissions of the designed industrial facility. In addition, it is necessary to outline the range of potential recipients of the impact (i.e., ecosystems within the zone of influence of the designed industrial facility) and to rank them.

On the basis of the available information on hazards and recipients, it is necessary to carry out a qualitative characterization of anthropogenic impacts and to determine the list of pollutants for which a detailed risk assessment as priority pollutants is appropriate.

The exposure assessment should include a detailed description of the recipients, including subdivision of the recipient ecosystems into receptor sites and establishment of a current or projected load level of priority pollutants - the magnitude of their deposition (in grams per hectare per year or in equivalents per hectare per year). At the stage of ecosystem risk assessment, calculation and mapping of critical loads of priority pollutants characterizing the maximum permissible load on the selected recipients should be carried out.

The characteristics of ecosystem risks should include calculation of changes in the state of recipients and the probability of their occurrence, as well as determination of the degree of acceptance of such changes in accordance with the selected criteria. Risk characterization is proposed to be carried out in two stages. At the first stage it is necessary to perform deterministic calculation of critical load exceedances on the basis of averaged input data. In case of detection of receptor sites with $Ex(X) > 0$ at the second stage, it is advisable to assess ecosystem risks by using modeling methods.

Studies on assessment of ecosystem risks should be completed with an analysis of the uncertainty of the results. To do this, it is necessary to describe the sources of uncertainty at each stage of risk assessment and assess the reliability of the results of calculations. The results of the ecosystem risk assessment can be used to rank individual industrial construction projects and develop approaches to mitigate man-made environmental impacts. Quantitative assessment of ecosystem risks is advisable in the preparation of geoecological justification of the above projects, the implementation of which may be accompanied by ecosystem risks with a high degree of uncertainty.

7. CONCLUSION

Geoecological risk is the probability of environmental degradation or transition to an unstable state mainly as a result of man-made impact, as well as assessment of the probability of the reverse impact of the transformed environment on the state of industry. The quantitative assessment of geoecological risk is a fundamental element of the functioning of natural and anthropogenic systems.

Geoecological risk assessment is the process of analyzing the likelihood of reversible or irreversible changes in the biogeochemical structure and functions of ecosystems in response to man-made impacts. Assessment of geoecological risk is a complex scientific and practical process using iterative approaches, i.e., actions that improve the results of this assessment by repeatedly improving the quality of the necessary initial information about the risk.

The need for a geoecological risk assessment arises when a direct and unambiguous response is difficult because of a large number of uncertainties in the description of the life cycles of chemicals, from the extraction and processing of the relevant raw materials to their use as products and waste generation. The process of assessing the geoecological risk of chemicals includes the stages of collecting general information, determining the impacts of chemicals and the characteristics of the geoecological risk *per se*, and managing this risk.

Ecosystem risk is defined as a two-dimensional indicator that firstly characterizes the probability of negative changes in the state of ecosystems as recipients of impact and secondly characterizes the magnitude of such changes. The quantitative assessment of ecosystem risks is based on calculation and spatial analysis of exceedances of critical loads of the pollutant within the limits of the zone of influence of the industrial facility.

Ecosystem risk assessment can be considered as a part of geoecological risk assessment.

Thus, the received conclusions convincingly prove the important role for green economy progress considered here the innovative geoecological risk assessment in technogenesis.

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