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SYSTEMATIC APPROACH FOR ENSURING THE RESILIENCE OF ECOLOGICAL-ECONOMIC SYSTEMS OF THE RUSSIAN ARCTIC (PART 2. ASSESSMENT PROCEDURE AND CRITERIA)

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Abstract. *Background*. The study is aimed at design and development of methods and approaches to ensuring, assessment and regulation of the ecological robustness of Arctic regions in order to resilience and management efficiency enhancement of the ecological-economic systems performance of the Arctic. To date, this problem is of particular importance under conditions of intensive industrial development of the resource base of Arctic territories, which reduces the stability of Arctic ecosystems and negatively affects the health and life quality of the population. *Materials and methods*. The research work consists of two parts. In the first part the proposed principles of resilience management and criteria for ensuring the environmental safety of the Arctic region, based on the postulates of the theory of sustainable development and the concept of acceptable risk, are considered. In the second part the environmental safety metrics and systematic approach to assessing the level of ecological robustness of the Arctic ecosystems, based on expert methods for resilience analysis of organizational and technical systems, are discussed. *Results and conclusions*. The fundamental principles and a set of criteria for ensuring environmental safety for various types of economical activity in the Arctic region have been developed. A general systematic approach to the ecological robustness analysis of the Arctic region according to selected principles and criteria, based on the joint application of a hierarchical multi-level decomposition scheme "principle – criterion – indicator – index" and models for quantitative and qualitative assessment of the complex system resilience, is proposed. The use of developments provides the formation and advance of the legal regulatory framework (national public standard) for governing various types of economical activity in the Arctic region, as well as improving the quality of managerial decisions made by state, regional and enterprise authorities in the field of environmental safety and environmentally friendly, responsible nature management.

Keywords: ecological-economic system, resilience management, safety principles and criteria, estimation procedure, environmental quality control, sustainable development, acceptable risk concept, Arctic region

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МЕТОДИЧЕСКИЙ ПОДХОД К ОБЕСПЕЧЕНИЮ ЖИЗНЕСПОСОБНОСТИ ЭКОЛОГО-ЭКОНОМИЧЕСКИХ СИСТЕМ РОССИЙСКОЙ АРКТИКИ (ЧАСТЬ 2. МЕТОД И КРИТЕРИИ ОЦЕНКИ)

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Аннотация. *Актуальность и цели*. Работа направлена на создание и развитие методов и подходов обеспечения, оценки и регулирования экологической устойчивости арктических регионов для повышения жизнеспособности и эффективности управления функционированием эколого-экономических систем Арктики. Особую значимость эта задача приобретает сегодня в условиях интенсивного промышленного освоения ресурсной базы арктических территорий, что снижает устойчивость арктических экосистем и негативно влияет на здоровье и качество жизни населения. *Материалы и методы*. Работа состоит из двух частей. В первой части рассматриваются предложенные принципы управления устойчивостью и критерии обеспечения экологической безопасности Арктики, основанные на постулатах теории устойчивого развития и концепции приемлемого риска. Во второй части обсуждаются система показателей безопасности и методический подход к оценке уровня экологической устойчивости арктических экосистем, базирующийся на экспертных методах анализа жизнеспособности организационных и технических систем. *Результаты и выводы*. Разработаны основополагающие принципы и система критериев обеспечения экологической безопасности для различных видов хозяйственной деятельности в Арктике. Предложен общий методический подход к анализу экологической устойчивости Арктики по выбранным принципам и критериям, основанный на совместном применении иерархической многоуровневой схемы декомпозиции «принцип – критерий – индикатор – показатель» и моделей количественной и качественной оценки жизнеспособности сложных систем. Использование разработок обеспечивает формирование и развитие нормативно-правовой базы (национального общественного стандарта) для регулирования различных видов хозяйственной деятельности на территории арктических регионов, а также повышение качества принимаемых управленческих решений органами государственного, регионального и корпоративного управления в области экологической безопасности и экологически ответственного природопользования.

Ключевые слова: эколого-экономическая система, управление жизнеспособностью, принципы и критерии экологической безопасности, методика оценки, контроль качества окружающей среды, устойчивое развитие, концепция приемлемого риска, Арктика

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Introduction

Ecological resilience is an integral part of the country's national security, the development of its economy and the social welfare of the state. Thereby, in this regard the problems of ecological resilience are as so important as the issues of ensuring military, economic and international security. Overcoming the consequences of global challenges and threats (climate change, loss of biodiversity, increase in consumption of natural resources, increase in volume of waste, etc.), which are the main causes of environmental quality loss and ecosystem degradation in general, requires availability of updated standards and state-of-the-art effective tools for ecological resilience management. These standards and means should provide the technical-organizational framework of a system focused on maintaining stable characteristics of the robustness of ecological-economic systems performance and minimizing the risks of negative impact on the environment as a result of making unreasonable managerial decisions, through the implementation of mechanisms for regulating and standardizing ecological security target indicators, the adoption of environmentally appropriate and best available technologies, as well as ecological efficiency enhancement programs. Though, the legal-regulatory framework adopted in our country to ensure ecological security does not fully take into account the specificity of management processes in this problem domain, unlike a number of leading foreign countries. This circumstance along with resource intensity and high initial cost of engineering integrated automated control systems for management of ecological security greatly complicates the large-scale implementation of such tools in real practice.

The imperfection of the models, methods and tools currently used for analysis, assessment and organizational management of the ecological-economic systems resilience, as well as the need to mutual agreement and link these means with the basic provisions of the pursued public policy in the field of environmental protection predetermine the focus and relevance of this study. A special attention should be paid to solving the ecological security and resilience problems at the sectoral and regional levels and, as local quality targets are achieved, shifted towards the implementation and strategic planning of sustainable development policies at the state level. In addressing these issues, one cannot do without integrated interdisciplinary research based on a systems approach and allowing a comprehensive analysis of socio-political, economic, technological, environmental and administrative processes and the relationships between them in order to evaluate the trajectories for ensuring simultaneous economic growth, social stability and improvement the state of natural environment.

The subject of inquiry is the Arctic zone of Russia (Russian Arctic), which is a strategic macro-region of the Russian Federation and forms a fifth of the country's federal budget revenues. According to normative documents [1, 2, 3], ensuring the ecological resilience and security of the Russian Arctic is an indispensable priority when conducting any economic activity in this area in terms of maintaining the quality of the natural environment acceptable for the favorable life of the population and sustainable development of the regional economy, eliminating accumulated damage and recreating the environment due to the increasing economic activity in the development of the resource base of the Northern territories and the impact of global climate change. To achieve these goals, a fundamentally novel concept of ecological security based on the natural science backlog developed over the past 30 years, modern risk management practices, the principles of sustainable development and resilience management of complex systems, is needed. Research along these lines will provide new knowledge-producing on the matter and nature of relationships between various aspects of ecological security, which are necessary for an integral estimation of the resilience level of the Arctic ecological-economic systems and the generation of evidence-based well-grounded guidelines to decision makers (public authorities and business entities) to enhancing the efficiency and effort of environmental policy in the Russian Arctic.

The work is divided in two parts. The first part is discussed in [4]. In the second part we examine the environmental safety metrics and a general methodological approach to the ecological robustness analysis of the Arctic region according to principles and criteria selected and explicit in the first part of our study. The second part consists of three main sections. The background of the study and related work are discussed in the first section. The second section provides a framework of the systematic approach to aggregated assessing the level of ecological robustness of the Arctic ecosystems based on expert methods for resilience analysis of organizational and technical systems. The ecological resilience assessment procedure based on application of the hierarchical multi-level decomposition scheme "principle – criterion – indicator – index" and its formal representation are proposed in the third section. In conclusion, the summary and contributions of the study are given.

Background

Environmental protection and ecological resilience ensuring along with socio-economic and infrastructural development problems are among the main state imperatives for the development of the Russian Arctic. This thesis determines the need to prioritize environmental issues, both in terms of monitoring the climate policy impact on the performance of ecological-economic systems, and the generation of managerial decisions that enhance the ecological security of the Arctic regions of Russia taking into account up-to-date urgent challenges.

Any managerial decisions made in the field of industrial development of the Russian Arctic should be made taking into account the understanding of the basic principles of the concepts of ecological security [5, 6], ESG (Environmental, Social, and Corporate Governance) [7, 8], green and circular economy [9, 10]. To generation and validation of such decisions, comprehensive interdisciplinary ecological-economic research should be carried out. Therefore, at present it is especially urgent to develop models of potential actual threats to ecological security of critical facilities of the regional ecological-economic systems, a list of countermeasures to ensure the ecological resilience of natural-industrial systems in the Arctic regions, including novel standards for classifying industrial facilities according to the degree of environmental impact and assessing systemic risks of natural and man-made critical situations origination in these systems. The course towards toughening the climate policy and national economy decarbonization, as well as the expanding adoption of friendly international environmental standards require, on the one hand, the new technologies development that meet the specified criteria, and, on the other hand, the impact assessment and analysis of the managerial decisions made on the performance of ecological-economic systems in the Arctic region and compliance with ecological security criteria.

Along these lines, tools for situational management of ecological resilience of the Russian Arctic critical infrastructures (by the example of the Northern Sea Route) [11], as well as a set of ecological security metrics [4] to estimating and analyzing the integral index of ecological resilience of the natural-industrial system facilities operating in this territorial district, have been developed. In addition, the Russian legislation in the field of ecological security and well-known practices of managing the resilience of natural-industrial systems are also examined. It has been revealed that the Russia's concept of ecological security in comparison with the leading world powers (USA, China) and the EU countries has a pronounced anthropocentric nature, since it is designed to ensure and protection the environmental interests of individuals from various external and internal threats (personal ecological security). Thus, within the bounds of this concept ecological security ensuring consists in overcoming the consequences of climate change, the growth of resource consumption, the environmental deterioration and degradation of the all natural components (water, air, soil, biodiversity, etc.), the increase in waste and is carried out by the state represented by all authorities, including local governments, and public associations of privy citizens through the organization and implementation of appropriate environmental protection measures, as well as the environmental awareness and education. At the same time, the estimation models for evaluating threats (damages) vested in departmental methodologies and tools for regulating ecological security enshrined in the federal laws are often based on adaptation the global concept of sustainable development with the response connotation. Such a way is not always acceptable in domestic practice and does not take into account the Russian specificity of business keeping and management, since the known liberal governance mechanisms inherent in foreign policies are either not agreed-upon the rules, or completely contradict game directive adopted in our country in problem area under consideration. Thereby, the efforts of researchers should be focused on the development of scientifically well-grounded guidelines to decision-makers for improving Russian approaches to the organizational management of ecological resilience (robustness) and ensuring the environmental safety of natural-industrial systems. An overview of key trends and characteristics of the state-of-the-art ecological security studies is in detail represented in research [12].

Historically, the traditional approach to ensuring the ecological security in our country was based on the concept of "absolute security" [13]. According to study [14], its essence boiled down to the desire of making technology and the technosphere absolutely safe for people and expected the introduction of all kinds of protection measures that are practically feasible. Practice shows that the concept of absolute security is inadequate to the laws of the technosphere, unattainable or associated with exceeding, sometimes unjustified financial expenditure for the society. In addition, the demands of absolute security captivating with its humanity can turn into a tragedy for people, because it is impossible to ensure zero risk in existing complex systems, and an individual must be oriented towards the possibility of critical situations emergence. Therefore, starting from the late 70s – early 80s of the 20^{th} century in industrialized countries a transition settled in the studies and research related to ensuring and managing the ecological security from the concept of absolute security to the concept of acceptable (tolerated) risk [15] based on the general provisions of the theory of economic risk [16]. The essence of this concept lies in the desire to create such a small danger that society is ready to put up with in case of the emergence and development of critical situations in terms of the quality of life, the level of socio-economic development, geopolitical position and other essential factors. The principle of acceptable risk has become known as the ALARA principle (As-Low-As-Reasonably-Achievable).

The concept of acceptable risk integrates technical-organizational, technological, socio-economic and military-political aspects and is a certain compromise between the level of security in general and the possibilities of achieving it. As shown in [17], the magnitude of acceptable risk can be estimated using the cost-based mechanism, which allows distributing the society's expenditure of achieving a given level of security between the natural, man-made and social spheres. That is, it is necessary to maintain an appropriate ratio of costs in these areas, since the imbalance in favor of one of them can cause a sharp increase in risk level and it will go beyond the permissible values. With an increase in the costs of ensuring the security of natural-industrial systems, the technosphere risks decrease, but meanwhile, socio-economic ones increase. Spending excessive funds on improving the security of natural-industrial systems in conditions of limited economic opportunities can simultaneously cause implicit damage to the social sphere [18].

In real practice, one has to combine and choose between different risk management concepts as stated in [19]. Since the measures to reduce environmental risks are quite expensive, the concept of acceptable risk can be suitable for solving urgent problems of ensuring ecological security. This is the optimal principle of risk management, when the costs of environmental protection measures are comparable to the amount of potential losses and the degree of possible negative consequences of the implementation of these risks. The concept of acceptable risk can be effectively applied to any field of activity, branch of production or organization. Undoubtedly, there is no absolute security, since there will always be some level of residual risk. How much risk is acceptable or unacceptable following [20] is resolved and established by public authorities (regulators), oversight bodies, administrations and management of specific enterprises. The degree of introduction of this concept into the practice today is varied in different countries and in some of them it has already been successfully embedded and adopted into active legislation as laid down by [21].

Estimation methodology and Related work

State-of-the-art methodology for assessing the ecological resilience of socio-economic systems includes the following methods:

1. The method of environmental indicators analysis provides evaluation of ecological indices such as water, air, and soil pollution levels, waste volume, etc.
2. The method of environmental impact assessment provides quantification of the resources used by the system and the waste it produces, and comparison with the capacity of the environment.
3. Ecological footprint method provides the impact assessment of the system on the environment by measuring the amount of biologically productive land and water resources needed to sustain a specific level of resource consumption, emissions to the environment and waste disposal.
4. Environmental cost accounting method allows assessing the impact of production activities on the environment in monetary terms taking into account all costs of water, air, and soil cleaning, as well as compensation for ecosystem damage.
5. Life-cycle assessment method allows evaluating the environmental consequences of the entire product life-cycle from raw material extraction to waste disposal.
6. Environmental risk assessment method allows estimating the probability of negative consequences for the environment and human health as a result of production activities, as well as to determine the most effective measures to reduce risks.
7. Environmental audit method allows assessing the compliance of production activities with the requirements of environmental legislation, identifying problem areas and proposing measures to eliminate them.
8. Environmental transparency method makes it possible to ensure the availability of information on the impact of production activities on the environment to the general public, which contributes to increasing awareness and citizen participation in decision-making.
9. Environmental compensation method allows taking into account biodiversity losses and other negative consequences for ecosystems when developing new projects and proposing measures for their compensation, such as creating new nature reserves or restoring destroyed forests.
10. Ecological design method allows taking into account environmental aspects when designing new facilities and developing new products, which contributes to reducing negative impact on the environment.
11. Environmental responsibility method makes it possible to hold companies and organizations responsible for their negative impact on the environment and take measures to reduce it, such as introducing environmental certificates or standards.
12. Viability assessment method provides evaluation of the system's ability to survive and develop in the long-term outlook.
13. Economic assessment method provides evaluation of the economic efficiency of the system taking into account its impact on the environment.
14. Multi-criteria assessment method provides evaluation of the environmental sustainability of the system taking into account several criteria, such as economic efficiency, social responsibility, and environmental impact.

Within this methodology, three main classes of ecological security assessment methods can be distinguished:

1. Environmental monitoring methods provide collection and analysis of data on various ecological parameters, including measurement of air, water, soil pollution levels, biodiversity and radiation. Environmental monitoring involves systematic and regular observation of the environment to assess its quality and safety. The data obtained from environmental monitoring is analyzed using statistical methods and models

that allow for the assessment of environmental and human health risks. Based on the results of the analysis, measures are developed to enhance ecological security, such as reducing harmful emissions and improving water quality.

2. Environmental modeling methods intend the use of mathematical models to forecast the impact on the environment, such as calculating air pollution levels or climate change.

3. Environmental impact assessment methods allow the estimated probability of environmental risks and their consequences for the environment and human health. These methods include risk analysis of various types of pollution, such as chemicals, radiation and climate change, and also allow for the identification of possible negative impacts on the environment and human health resulting from new projects or construction.

The analysis of domestic and foreign scientific literature also allows for the conditional classification of known methods for assessing the ecological security and resilience of territories into three complementary groups: qualitative, quantitative, and combined. Quantitative methods are based on the measurement and analysis of quantitative parameters, such as air, water and soil pollution levels. Qualitative methods are vice versa based on the analysis of qualitative ecosystem characteristics, such as biodiversity, plant and animal life conditions, etc. Combined methods use both quantitative and qualitative parameters to obtain a more complete and accurate assessment. The difference between these approaches lies in the fact that quantitative methods provide precise numerical values, which are convenient for comparing and analyzing data; qualitative methods allow for the assessment of ecosystem conditions with consideration for its complex structure and interrelationships between elements, and combined methods integrate the advantages of both approaches and allow for a more complete and accurate assessment of the environmental situation.

Quantitative methods are effectively applied to identify specific sources of pollution and determine necessary measures for improving the environmental situation, but may be limited by data availability and measurement methods and may not always consider the structure of interrelationships between ecosystem elements. Qualitative methods are successfully used to identify problems that cannot be measured quantitatively, but are highly subjective depending on the experience and knowledge of experts, and may not always be used for data comparison and analysis. Combined methods, despite their inherent advantages of qualitative and quantitative approaches, can be labor-intensive and costly compared to single methods.

Known combined methods for assessing the ecological security and resilience of the region include:

1. Matrix method, which involves integrating qualitative assessments of probability and importance of environmental risks using a matrix, where each risk is evaluated on a scale of probability and importance.

2. Analytic hierarchy process method, which uses a combination of expert assessments and mathematical models to determine the importance and probability of environmental risks.

3. Multiple criteria method, which involves using several criteria to assess environmental risks, such as expert assessments, statistical data and mathematical models.

4. Bayesian statistical methods that use a combination of data from different sources, such as expert assessments, statistical data and modeling results, for more accurate assessment of environmental risks.

5. Multi-criteria optimization methods that provide the determination of the best combination of measures for preventing or reducing environmental risks based on several criteria, such as cost, effectiveness, system performance and environmental efficiency.

6. Fuzzy-set methods that involve determining the degree of risk based on fuzzy inference rules and linguistic variables, and also allow for considering not only point values of individual parameters, but also their uncertainty and fuzziness, resulting in more accurate and realistic outcomes considering multiple factors and conditions.

The next proposed method for assessing and analyzing the resilience of regional ecological-economic systems belongs to the class of multi-criteria combined methods and is positioned among known methodological approaches as a tool for environmental safety (sustainability) analysis based on the use of a hierarchical multi-level decomposition scheme "principle – criterion – indicator – index". Most related work (e.g., [22, 23]) to our study examining the same class of methods are based on the reliability theory fundamentals [24] and the use of computational operations with a multi-dimensional data cube (OLAP-cube) [25] in the aggregated assessment procedures of system and critical infrastructure resilience. The key principles, criteria and indices of ecological security used in our assessment procedure of ecological-economic system resilience were in detail discussed in [4] and [26].

The method for assessing and analyzing the resilience of ecological-economic systems must adequately meet the following functional requirements:

1. Compliance with the basic provisions and criteria of the national public standard for ensuring ecological security in the Arctic [26], as well as norms and rules established by the legislation of the Russian Federation in the field of environmental protection.

2. Applicability to all structural elements, critical infrastructures and resilience types of regional ecological-economic systems.

3. The ability to operate with all the resilience components (domains) of the ecological-economic systems either individually or in the aggregate.

4. The ability to derive quantitative, semi-quantitative and qualitative estimates of the ecosystem resilience and their aggregation into a generalized assessment.

5. The ability for self-verifying and audit, i.e., solving the inverse problem, and interpreting the results of the assessment.

6. Supplement of the potential of already existing risk and security management practices.

7. The ability to joint use (integration) other assessment tools for the analysis of various types of threats, safety indicators and optimization of target resilience functions taking into account the peculiarities of the life-cycle of objects in ecological-economic systems.

8. Consideration of cascade effects and the ability to obtain relative resilience estimates for critical elements of ecological-economic systems, e.g., through continuous monitoring of their resilience over time or by comparing their own resilience characteristics with other critical elements of these systems.

9. Variability in adjusting assessment parameters to balance the resilience level of the critical elements and infrastructure in ecological-economic systems subject to multiple threats with the level of resilience achieved through anti-crisis measures taken by risk managers and operators managing the development of these systems, and which society is willing to accept under current conditions.

10. Usability, low cost, ease of implementation and application for solving both specific and more general problems of managing and maintaining the resilience of complex systems.

Assessment procedure framework and formal representation

The systematic approach to ecological security and resilience assessment and analysis corresponds a hierarchically organized four-level decomposition of environmental safety indices, focusing mainly on the socio-economic and natural-industrial resilience domains. The holistic and easy-to-use structure of the method for estimating integral environmental safety index adopted from study [22] is shown in Figure 1, illustrating the four-level scheme "principle – criterion – indicator – index" and different steps in the assessment procedure (selection of the generic indicators and influencing factors, quantification, expert’s judgments aggregation, defuzzification, calculations of the weighted average crisp scores, bottom-up synthesis of the total ecological resilience index, interpretation of the results in radar charts, etc.).

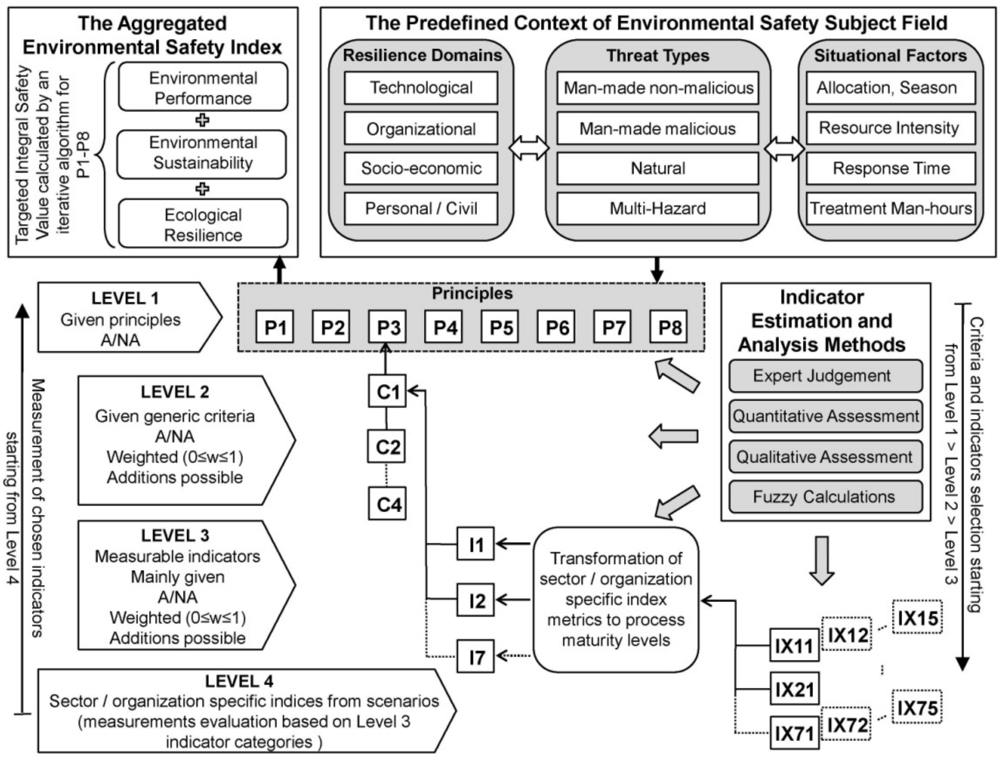

Fig. 1. The overall hierarchical scheme of Environmental Safety Index systematic assessment (adopted from [22])

The backbone for environmental safety index is ecological security ensuring principles (*P1 – P8*) described in the first part of our study [4] and reflecting the different strategies of resilience management of the regional ecological-economic systems. These eight principles form the first level (Level 1) of integral indicators in resilience assessment procedure. Level 1 remains given. Each integral indicator (principle) at Level 1 is decomposed to a subset of given generic criteria correspond the second level (Level 2) indicators ($C^1{}_i \ldots C^1{}_N - C^8{}_i \ldots C^8{}_M$). In tote, we have extract 43 criteria at Level 2. Level 2 is tailorable. Similarly, each criterion at Level 2 is further decomposed to the next subset of mainly given measurable indicators ($I^{1i}{}_j \ldots I^{1i}{}_K - I^{8i}{}_j \ldots I^{8i}{}_L$), which are comprised at the third level. Therein, we have assigned 271 indicators. Level 3 is also tailorable. In turn, each indicator at Level 3 is additionally decomposed to a subset of sectoral (organizational) indices specific to the critical facilities or infrastructures of ecological-economic systems, taking into account critical situation scenarios selected for analysis under given conditions. We have primarily specified 1156 indices at fourth level. Thus, the bottom of the resilience scoring system hierarchy is Level 4, which consists of different quantitative, semi-quantitative and qualitative metrics and measures referred to sector-specific characteristics of ecological-economic systems. Indices represented at Level 4 ($IX^{1ij}{}_p \ldots IX^{1ij}{}_Q - IX^{8ij}{}_p \ldots IX^{8ij}{}_R$) are transformed to a quantitative measurement scale using fuzzy calculations and normalization technique. The weights are assigned by experts to the indicators defined at levels 2, 3 and 4 according to their significance and interest to measure. When fuzzification and weighting factors determination of all indices at Level 4 is done, the overall ecological security and resilience index estimation is implemented through weighted aggregation of the indicators going upwards the hierarchy from Level 4 to Level 1 (meanwhile, each indicator at given levels get a concrete assessment). Alternatively, it is also possible to focus on some single indicators at various levels that seem more suitable to identify gaps in environmental safety and resilience in terms of flexibility of applying the proposed assessment procedure. At once, the selection of criteria and indicators, which are interesting to measure, is starting from Level 1 downwards the bottom, and the very measurement of chosen indicators is starting from Level 4 upwards to the top, i.e., the levels 1, 2, and 3 are aggregations of level 4 indices, rather than genuine measurable indicators as such. Finally, the defuzzification of operationalized fuzzy scores should be carried out until the crisp estimates of the all aggregated indices are obtained. Thereupon, an interpretation of the resulting assessments is given in graphical or tabular form.

Subsequently, the selection of relevant specific criteria and indicators at levels 2, 3 and 4, as well as the data acquisition for estimation procedure depend on the initially predefined context and detailed specification of scenario, including resilience domains, security threat types and situational factors. Establishment of the weighting coefficients for measured indices importance is a prerogative of expert's judgments.

Based on the research results [27], a formal representation of the described multi-level hierarchical assessment procedure of ecological-economic system resilience can be written with the following formulas:

$$ESR = f\left(ESR_{Org}, ESR_{Tech}, ESR_{Pers}, ESR_{SoEc}, t\right) \xrightarrow{\gamma} opt, \quad (1)$$

$$ESRI = \frac{1}{8}\prod_{p=1}^{8}\left[\frac{1}{l}\prod_{c=1}^{l}u_c\left[\frac{1}{n}\prod_{i=1}^{n}v_i\left[\frac{1}{m}\prod_{j=1}^{m}w_j IX_{c,i,j}\right]\right]\right], \quad (2)$$

$$\sum_{c=1}^{l}u_c = \sum_{i=1}^{n}v_i = \sum_{j=1}^{m}w_j = 1, \quad (3)$$

where ESR is the resilience of ecological-economic system; ESR_{Org} is the organizational resilience; ESR_{Tech} is the technological resilience; ESR_{Pers} is the individual (personal) resilience; ESR_{SoEc} is the socio-economic (cooperative) resilience; $ESRI$ is the aggregated environmental safety index calculated on the basis of indicator values at levels 2, 3 and 4 of the evaluation system decomposition, respectively; $IX_{c,i,j}$ are the drawn resulting estimates of the particular resilience and safety indicators at levels 2, 3 and 4, respectively; l, n, m are the number of estimating safety and resilience indicators at levels 2, 3 and 4, respectively; u_c, v_i, w_j are the agreed weighting coefficients (weights) stated by experts for particular indicators at levels 2, 3 and 4, respectively, possessing the values in the range [0, 1] subject to the relative measure of significance of the indicators involved in the assessment; γ is a degree of concordance between integral environmental performance and environmental sustainability indexes characterizing the state variation in time of ecological resilience domains; t is a time parameter conditionally reflecting the dynamics of changes in the security and resilience indicators under consideration.

The proposed integral estimation model (1)–(3) of the overall environmental safety index uses an original system of ecological security and resilience indicators designed as a result of the generalization of existing indicated systems and the formation of aggregated indicators obtained by convolving a series of groups of the generally accepted standard security indices. As well, the model also implicates several individual resilience indicators reflecting the specificity of critical elements and infrastructures of the ecological-economic systems.

The choice of a multiplicative convolution of criteria in formula (2) is due to the need to comply with the principle of "equitable compromise" between the key ecological security and resilience indicators, taking into account their equal significance. In addition, the selected criteria we have initially defined are interdependent, and changing the characteristics of one of them can significantly affect the assessment of the parameters of others. In some cases, when evaluating and analyzing specific groups of ecological security or resilience indicators, additive convolution of criteria can be also applied. This is allowed when the criteria can be evaluated independently of each other, i.e., when assessing the environmental safety of the commercial introduction of various prospective technologies in the industrial sector of regional economy.

In fine, it should be noted that the designed method is in some way an omnibus technique for the workflow implementation of the overall security and resilience analysis of ecological-economic systems. Since it is mostly intended for self-assessment, it can be in some cases not fully objective, but, however, the estimation results are sufficiently indicative for strategic decision-making support to enhance security and resilience of the regional ecological-economic systems in various emergency situations by leveling the highlighted strengths and weaknesses of the performance of critical facilities and infrastructures operating in these systems. Improving the objectivity and adequacy of the method to obtain better results from the different perspective can be further achieved through its use in combination with other well-known methodologies for situational management and assessment of the system robustness, such as methods for in-depth analysis of the technological and organizational resilience of critical infrastructures [28, 29].

Conclusion

With the worsening of the environmental situation in the Arctic regions, which is caused by the aggravation of regional and global environmental problems, as well as the emergence of natural and man-made critical situations, the resilience and security of ecological-economic systems play a vital role in the sustainable development of these territories and are at the forefront of world science, being the subject of many state-of-the-art studies around the world, both in the field of the humanities (political, economic, social, etc.), as well as technical and natural sciences. Thus, the issues and goals of developing standards and models for organizational management (regulation) of ecological security, principles and methods for assessing the resilience of ecological-economic systems come to the foreground. The problem-solving of these objectives is utterly necessary for the preparation of scientifically grounded evidence-based guidelines and scope for the greening of regional and national policies in the Russian Arctic and effective implementation of the sustainable development strategy for this macro-region. Along the lines of solving these problems in the course of the study, the following main results were drawn:

1. The fundamental principles and a set of criteria for managing and ensuring ecological security and resilience for various types of economical activity in the regions of the Russian Arctic have been developed. The proposed principles and criteria are based on the postulates of the theory of sustainable development and the concept of acceptable risk. The set of key indicators of ecological security and resilience can be expanded and deepen subject to the changing legislation, preferences of experts and the current state of affairs in the socio-economic sphere.
2. A generic methodological approach to assessing the overall level of ecological robustness (security and resilience integral index) of Arctic ecosystems according to selected principles and criteria is proposed. The approach is based on the joint application of a hierarchical multi-level decomposition scheme "principle – criterion – indicator – index", methods of expert analysis and models for quantitative and qualitative assessment of the resilience of organizational and technical systems.

The contribution of our findings to the development of the theory and practice of managing ecological-economic systems lies in the interdisciplinary scientific study of the goals and objectives of the conceptualization and institutionalization of ecological security and in the adaptation of quantitative and qualitative methods for assessing the resilience of critical infrastructures for a prescriptive analysis of the ecological robustness of regional systems. The application field of the research results is the methodical-organizational support of information and analytical decision support systems for the preventive management of ecological security. In addition, the combination of the proposed developments with well-known advanced solutions can be efficiently used under implementation of the key provisions of the Strategy for Environmental safety of the Russian Federation for the period up to 2025 [3] and the Strategy for the Development of the Arctic zone of the Russian Federation and ensuring national security for the period up to 2035 [1] in the Murmansk region in terms of the design and adoption of environmentally friendly ESG and CSR behavioral models of business entities, as well as new standards governing the public domain of environmental safety for elements of industrial-natural systems.

Further research in the problem area under consideration will be continued in the direction of developing advising (recommending) intelligent systems and decision support tools for managing ecological security and resilience, which will provide accounting both quantitative information and non-formalizable qualitative aspects that describe the state of regional ecosystems and influencing factors in the integral assessment of the ecological robustness level and ecological-economic system performance for the subsequent generation of guidelines formulated in natural language (in verbal form) to decision makers and the synthesis of adequate situational control models in the face of constantly growing volumes of diverse data that require operational analytical processing, control, verification and interpretation.

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