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Original paper

# Natural and Technogenic Risks Assessment of Arctic Nature Use for the Murmansk Region Coastal Zone

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**Abstract**
Intensification of economic development of the Arctic coast of Russia increases the vulnerability of its coastal territories and coastal eco-socio-economic systems, exposed to a complex impact of natural and anthropogenic factors. Facing climatic changes and an increasing anthropogenic load, these Arctic territories require a comprehensive scientific system for analysing environmental and socio-economic risks of nature management to ensure their sustainable development. The study aims to develop a model of risk assessment that combines quantitative and qualitative indicator methods with a matrix method. The paper proposes an innovative matrix method of risk assessment based on a three-component structure (risk-source, risk-factor and risk-object). Each component of the system is characterised by a unique set of classification attributes, and the relationships between them are quantitatively assessed by the method of expert assessments on a five-point scale. The developed model of coastal management risks in the Russian Arctic contains two key matrices of risk components: risk-factor – risk-source and risk-object – risk-factor. This allows for a comprehensive analysis of risk formation processes. The model was applied in practice to 17 local coastal municipalities in the Murmansk Region. Using the developed methodology and model as a tool enables a thorough evaluation of the effectiveness of measures aimed at reducing environmental and socio-economic risks related to the Arctic coastal management. This approach provides a scientifically sound basis for improving territorial planning and forecasting the sustainability of Arctic coastal eco-socio-economic systems as an integrated whole, thus contributing to the sustainable development of Arctic coastal territories. Integrating the proposed model into management decision-making processes allows the dynamics of changes in the natural environment and socio-economic conditions to be taken into account in the mid- and long-term. This is particularly important for maintaining the balance in complex Arctic ecosystems.

**Keywords**: nature-use risks, social and economic risks, ecological and economic risks, coastal eco-socio-economic system, Arctic, integral risk indicator, nature-use ecology

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# Оценка природных и техногенных рисков арктического природопользования для береговой зоны Мурманской области

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**Аннотация**
Интенсификация хозяйственного освоения арктического побережья России приводит к росту уязвимости прибрежных территорий, береговых эко-социо-экономических систем Арктической зоны Российской Федерации, подверженных комплексному воздействию природных и антропогенных факторов. В условиях климатических изменений и увеличения антропогенной нагрузки возникает необходимость в разработке комплексной научной системы анализа экологических и социально-экономических рисков природопользования для устойчивого развития прибрежных территорий Арктической зоны Российской Федерации. Цель исследования состоит в разработке такой модели оценки рисков, которая сочетает количественные и качественные индикаторные методики с матричной методикой. Предложена инновационная матричная методика оценки рисков, основанная на трехкомпонентной структуре (риск-источник, риск-фактор и риск-объект). Каждый компонент системы характеризуется уникальным набором классификационных признаков, а взаимосвязи между ними количественно оцениваются методом экспертных оценок по пятибалльной шкале. Разработанная модель рисков природопользования на побережье Российской Арктики содержит две ключевые матрицы составляющих риска: риск-фактор – риск-источник и риск-объект – риск-фактор, что позволяет проводить комплексный анализ рискообразующих процессов. Практическое применение модели проведено на примере 17 локальных приморских муниципальных образований Мурманской области. Применение разработанной методики и модели в качестве инструмента позволяет осуществлять комплексную оценку эффективности мер по снижению экологических и социально-экономических рисков, связанных с береговым арктическим природопользованием. Такой подход обеспечивает научно обоснованную базу для совершенствования территориального планирования и прогноза устойчивости арктических береговых эко-социо-экономических систем как единого комплекса, способствуя устойчивому развитию прибрежных территорий Арктики. Интеграция предложенной модели в процессы принятия управленческих решений дает возможность учитывать динамику изменений природной среды и социально-экономических условий в среднесрочной и долгосрочной перспективе, что особенно важно для сохранения баланса в сложных арктических экосистемах.

**Ключевые слова**: риски природопользования, социально-экономические риски, эколого-экономические риски, береговая эко-социо-экономическая система, Арктика, интегральный показатель риска, экология природопользования

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## Introduction

Economic development in the Arctic has increased the vulnerability of coastal ecosystems to natural and technogenic threats [1–5]. There is an urgent need to establish a scientific basis for analysing the risks associated with the nature use and their impact on the eco-socio-economic systems of the Arctic Zone of the Russian Federation (AZRF). One approach to such an analysis is to use a matrix in combination with quantitative and qualitative indicators. In the context of the Arctic, this approach can be implemented [1)] by using modern methodological tools, particularly cartographic and geoinformation methods [6–8] as well as marine spatial planning [9].

The concept of risk has many definitions in general, primarily relating to spheres of human activity that require assessment [2)] [5, 10]. In terms of nature use in Arctic conditions, risks are associated with the probability of a negative event occurring within a given timeframe, as well as the potential extent of damage. This damage can be measured in monetary terms or other absolute values, e. g. the area of exposed territory, volume of atmospheric emissions or the number of victims. A year is typically used as the time period for assessing nature-use risks.

A number of Arctic-specific issues need to be considered and addressed in risk assessment methodology [11–14]:

– creation of complex technical systems and the increased risk of nature use in the Arctic should be seen as the result of technological progress and increased use of natural resources;

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1) Gogoberidze, G.G., Shilin, M.B. and Rumiantceva, E.A., 2020. [Principles of Classification of Nature Management Risks and their Interaction with Elements of the Coastal Eco-Socio-Economic System of the AZRF]. In: Rumiantceva, E.A., ed., 2020. *Regularities of Formation and Impact of Marine and Atmospheric Hazardous Phenomena and Disasters on the Coastal Zone of the Russian Federation under the Conditions of Global Climatic and Industrial Challenges (“Dangerous Phenomena – II”) in memory of Corresponding Member RAS D.G. Matishov: Proceedings of the International Scientific Conference*. Rostov-on-Don, pp. 318–320 (in Russian).

2) Buyanov, V.P., Kirsan, K.A. and Mikhaylov, L.A., 2003. [*Riskology: Risk Management*]. Moscow: Ekzamen, 381 p. (in Russian).

– Arctic coastal nature use has a complex structure and is subject to unique risks that should be considered when developing territories and water areas;

– the impact of natural and anthropogenic risks on Arctic coastal eco-socio-economic systems poses a significant threat of cascading disasters and hierarchic systems catastrophes.

The coastal AZRF is characterised by two types of risk influencing nature-use processes: natural risks (as a consequence of natural hazards) and anthropogenic risks (including man-made disasters). While these types of risk to Arctic nature use are fundamentally different, they often occur together. This makes the Arctic region and its coastal zones unique in terms of the vulnerability of all components of coastal eco-socio-economic systems [15–17].

The study aims to develop a risk assessment model for Arctic nature use in coastal areas of the AZRF based on a risk assessment matrix in a sustainable nature use system. This will enable the spatial distribution of risk assessments to be obtained and the most important risk factors to be identified. The model will also be tested in seaside municipalities in the Murmansk region.

The article uses materials from conferences [1), 3)].

**Methods**

*A matrix approach to the risk assessment of Arctic coastal nature use*

Considering risk as infliction of harm with a certain probability, we can present it as a chain of three links [5, 16, 17].

1. Risk source.

The Arctic coastal zone is a complex eco-socio-system in which economic activity and nature use take place, and it contains potential sources of risk. The emergence of threats influences the region's sustainable development.

2. Risk factor.

The occurrence of negative factors transforms potential risks into specific events that threaten the objects and practices of nature use within the Arctic coastal system. Such threats originate from the risk source.

3. Risk object.

As an integral part of the Arctic coastal system, risk objects are exposed to negative factors that jeopardise their stable functioning and sustainability. An integrated

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[3)] Gogoberidze, G.G. and Rumiantceva, E.A., 2023. Integrated Model of Risks of Arctic Nature-Use Management for the Russian Arctic Coastal Zone Based on the Interrelationship of Natural, Geomorphological and Technogenic Risk Factors. In: E. A. Rumiantceva, ed., 2023. [*Prevention and Elimination of Emergency Situations in the Arctic Zone of the Russian Federation : Proceedings of the Scientific-Practical Conference, 4–7 April 2023*]. Murmansk: MAGU, pp. 96–98 (in Russian).

approach to risk management is therefore required to ensure the long-term sustainability of the Arctic coastal zone.

It should be emphasised that the risk source and risk object in the Arctic coastal zone are closely bound, forming a sequence of interrelated risk incidents. Multi-stage accidents can be forecasted by applying the scenario method, whereby an initial hazard source initiates a risk factor that affects a vulnerable object. This object then becomes a generator of new risk factors, and the process repeats to form a hierarchical structure known as a risk tree.

Given the proposed structure, the following classification can be introduced [5, 17]:

1. Sources of risk:

– risk origin (the specific source generating the risk);

– controllability of risk reduction (the potential and effectiveness of measures aimed at reducing or eliminating risk);

– impact on the coastal eco-socio-economic system (the impact of risk on the environmental, social, and economic components of the coastal zone).

2. Risk factors:

– spatial coverage (the geographical area in which the risk occurs);

– time horizon of impact (duration of the period during which the risk has an impact);

– predictability (possibility of predicting the time and nature of the risk manifestation);

– probability of occurrence (frequency of risk occurrence in a given period).

3. Risk objects:

– the direct recipient of the risk (i. e. an element or system that is directly affected by the risk);

– the potential to induce a cascade of risks (the ability of a given risk to cause other, more complex risks);

– the position in the risk cascade (the position of the risk in the sequence of interrelated risk events);

– the scale of damage/consequences (the degree of negative consequences which may arise as a result of the risk occurence).

As a result, we made up a list of basic elements for each of the above risk components of the Arctic coastal eco-socio-economic system, as outlined in works [16–18]. This list generally contains:

– risk source (19 elements);

– risk factor (21 elements);

– risk object (18 elements).

Specialists assessed the relationships between the risk components using a scale from one to five [17]. Based on the obtained data, two matrices describing the components of the risk management process were developed:

– the first matrix is based on matching risk factors (in the rows) with sources of risk (in the columns). This $21 \times 19$ matrix is designed to numerically assess the intensity with which a certain risk factor is generated under the influence of each considered risk source;

– the second matrix is a structure in which the rows correspond to risk objects and the columns correspond to risk factors. This $18 \times 21$ matrix assesses the extent to which each risk factor may influence the correct and effective functioning of risk objects.

The key and minor risk elements for each matrix and structural component were determined based on summing up the values for the corresponding rows and columns.

*The model of risks to Arctic nature use in the coastal AZRF*

In accordance with the presented matrix approach for assessing the risk of nature use in Arctic coastal eco-socio-economic systems, the risk assessment methodology can be structured as an algorithm [5, 16].

1. The size of the risk matrices can be reduced by deleting the columns and rows corresponding to risk sources, risk factors and risk objects that are not available for a given local object.

2. The risk factors Ri are assessed using weight coefficients that are set according to the characteristics of the region under study [5]. Of note, the correction coefficients are actually matrices with a size coinciding with that of the matrices reflecting the ratio of risk elements.

The coefficients are calculated in accordance with criteria [16–18], based on analysis of the following data:

– information on past emergency situations of a natural or man-made origin. This analysis involves identifying the causes of these situations and assessing their consequences for the areas under consideration and adjacent territories;

– current and historical information on the situation of the study areas, obtained using satellite information. These analyses include the extent and types of development and infrastructure, coastline location, water's edge patterns and other spatial characteristics;

– information on the quantity and quality of infrastructure.

– plans for dealing with various emergency situations in the considered territories and adjacent areas;

– other information on the spatial and temporal features of the occurrence and dynamics of risk factors in the study territories.

3. The integral risk indicator $R_{Int}$ is determined by summing all the risk factors $R_i$, adjusted by the appropriate territorial coefficients. It is calculated according to the formula

$$R_{Int} = \sum(R_i).$$

The key conceptual principles of the model for Arctic coastal nature-use risk assessment cover the following [5]:

1) the Arctic coastal eco-socio-economic system is a clearly defined geographical area. The boundaries of this system can be defined as follows, for example:

firstly, it may be a district-wide coastal municipality embracing adjacent marine areas;

secondly, the boundary may coincide with a coastal municipality consisting of settlements and including inland water bodies;

thirdly, the boundary could be a key geographical feature, such as a settlement with adjacent inland waters or other units characterised by interrelated environmental, social and economic aspects;

2) A non-dimensional method based on matrices describing risk components is used to assess the AZRF territorial object's exposure to hazardous events and calculate a comprehensive risk indicator. The first matrix, which compares risk factors and risk sources, shows how strongly each risk source influences the formation of the corresponding risk factor. The second matrix establishes the relationship between risk objects and risk factors and determines the impact level of each risk factor on the stable and effective functioning of the risk object in question. This approach allows a comprehensive assessment of the territory vulnerability and reveals key factors determining the level of risk.

To illustrate the process of determining the level of risk associated with activities in the Arctic coastal zone, we analysed some coastal territories in the Murmansk Region:

– the urban settlement of Kandalaksha. It is located in the southern Murmansk Region. The settlement's territory is divided by the Kola Peninsula: the northern part is on the peninsula while the southern one is on the mainland. To the southeast, the area borders Kandalaksha Bay;

– the rural settlement of Teriberka. It is located in the northern Murmansk Region and is washed by the Barents Sea from the north;

– the rural settlement of Ura-Guba. It is located in the Kola District of the Murmansk Region. The Ura River flows into the gulf of the same name here, and the Kislaya Guba tidal power station is located nearby.

The study territories vary considerably in terms of key physical geographical and socio-economic indicators. This allows us to assess the versatility of the proposed methodology with respect to different types of Arctic coastal territory.

For the urban settlement of Kandalaksha's territory and the adjacent water area, the initial matrices were slightly reduced: the risk factor–risk source matrix was reduced to 19 × 16, and the risk object–risk factor matrix was reduced to 16 × 19. This is due to the exclusion of risk factors and objects that are not typical of this area; while the number of risk factors was reduced by only two: earthquake hazard and iceberg hazard.

Risk factor assessments according to risk component matrices, taking territorial correction coefficients into account, showed that the most significant risk factors are as follows:

– fire (score 20.2);

– high water in river mouths / flooding of the territory (score 14.8);

– man-made accidents (score 13.7).

The risk factors that have a significant impact on this territory (an assessment score ranging from 12.2 to 10.0) include solid waste pollution (in particular chemical and household waste); infectious and epidemiological hazards; abnormally high temperatures (melting of glaciers and permafrost, and rising sea levels); emissions of chemical pollutants into the atmosphere. The integral risk assessment score for this territorial unit is 552.6.

For the rural settlement of Teriberka and the adjacent water area, the initial matrices are reduced: risk factor–risk source to 16 × 11 and risk object–risk factor to 11 × 16, due to the reduction in risk sources and risk objects not available in the area in question. The following items were also removed from the list of risk factors: earthquakes; the emission of chemical pollutants / toxic substances into the atmosphere; the emission of chemical pollutants / toxic substances onto land / into the hydrosphere; oil spills on land; and radiation contamination.

According to the risk component matrices, which take into account territorial correction coefficients, the following risk factors were found to be the most significant:

– fire (score 22.9);

– man-made accidents (score 14.0);

– high water in river mouths / flooding of the territory (score 12.0).

Other significant risk factors for the above territory (an assessment score ranging from 9.7 to 8.3) include an abnormal high temperature regime (melting of the ice cover and permafrost, and rising sea levels); infectious and epidemiological contamination; wave and ice loads; and abnormal (intensive) precipitation. The integral risk assessment score for the territorial entity is 379.2.

When analysing the territory of the rural settlement of Ura-Guba and the adjacent water area, the risk matrices were also optimised. The size of the risk factor–risk source matrix was reduced to 15 × 13, and that of the risk object–risk factor matrix was reduced to 12 × 15. Six risk factors were removed: earthquake, iceberg hazard, emission of chemical pollutants / toxic substances into the atmosphere and on land / into the hydrosphere, oil spill on land, and radiation contamination.

Analysis of risk factor assessments using matrix models, taking into account the correction coefficients determined for this territorial unit, revealed the following most significant risk factors:

– fire (score 15.2);

– man-made accidents (score 12.0).

Other risk factors affecting the territory under consideration (an assessment score ranging from 10.7 to 9.7) include solid waste pollution, in particular chemical ones; municipal solid waste; infectious and epidemiological contamination; and an abnormal high temperature regime (melting of the ice cover and permafrost, and rising sea levels). The integral risk assessment score for the territorial unit was 274.9.

The presented model for the analysis of risks associated with the exploitation of natural resources in the coastal AZRF allows not only establishing the geographical distribution of risk levels and identifying key risk factors, but also modelling predictive assessments of risks and their components based on different scenarios. This functionality is realised through the potential addition or deletion of major infrastructure units or their aggregations.

**Results**

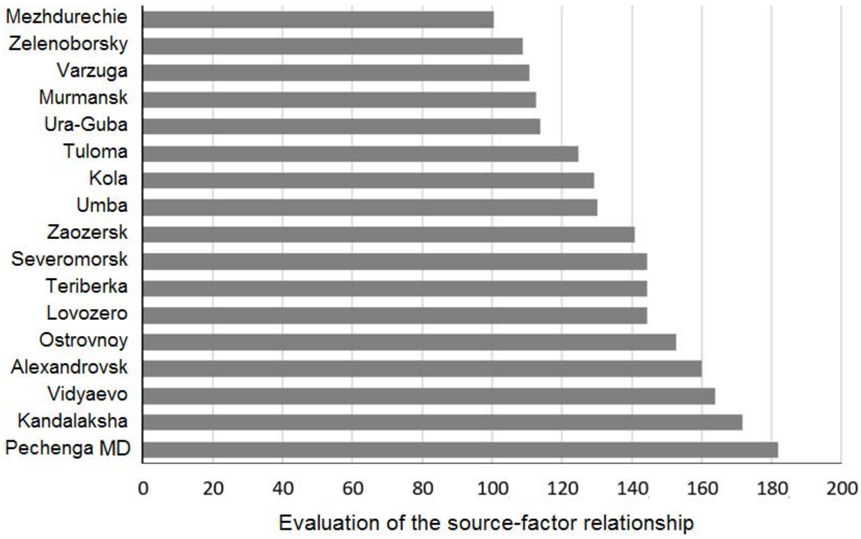
*Risk assessment of sustainable Arctic nature use for the coastal zone of the Murmansk Region*

The developed model for assessing the risks of Arctic nature use in the coastal AZRF was tested on 17 coastal territorial units of the local management level of the Murmansk Region. Calculations were carried out according to the described methodology using examples for local municipalities of the urban settlement of Kandalaksha, the rural settlement of Teriberka and the rural settlement of Ura-Guba. This allowed us to analyse the obtained results in the form of non-dimensional assessments of risk and its components without detailing the calculations.

The main risk factors were identified for each territorial unit, and their contribution to the impact assessment of the study territory was considered. The contributions of natural and anthropogenic factors (excluding fire and infectious diseases) were assessed separately. The selection of factors such as fire and infectious diseases is conditioned by their special nature; these risks can be caused by natural or anthropogenic factors or by a combination of these.

The analysis results showed that the identified risk sources produce the risk factor in the Pechenga Municipal District most intensively. For this territory, the non-dimensional assessment score of the source–factor relationship exceeds 180 (Fig. 1).

The main reason for the increased risk level in this municipality is the combination of a relatively high population density and diverse landscapes. Consequently, the Pechenga Municipal District shows a higher intensity of risk factor production than other coastal districts in the Murmansk Region. The urban settlement

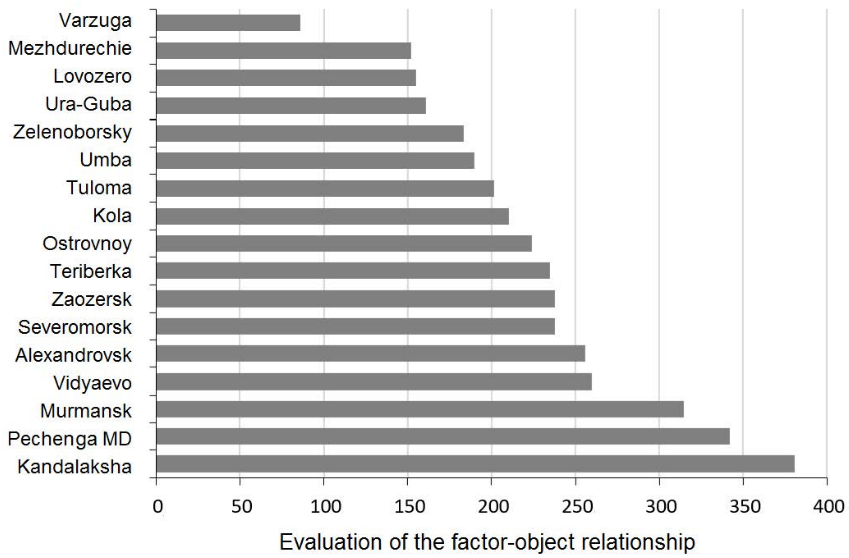



F i g . 1 . The degree of risk-factors production from exposure to risk-sources for the coastal local municipalities of the Murmansk region

of Kandalaksha is the second in terms of the degree of impact of identified risk sources with a source–factor relationship indicator of over 170. This high value is due to the reasons similar to those described for the Pechenga Municipal District. Kandalaksha is followed by the restricted administrative units of Vidyaevo and Aleksandrovsk with a source–factor correlation indicator of over 160 for each territory. The lowest indicator of risk factor production (slightly over 100) is registered for the rural settlement of Mezhdurechie.

When analysing the relationship between factors and objects in the coastal territories of the Murmansk Region, we assessed the potential impact of risk factors on the normal, effective functioning of risk objects. The objects of Kandalaksha were found to be the most vulnerable. The non-dimensional assessment score for this area exceeded 380, indicating a high risk (Fig. 2).

As for the Pechenga Municipal District, where the non-dimensional indicator was over 340, this result can be explained by a significant number of risk-prone objects concentrated in a densely populated coastal area of diverse topography. These factors together substantially influence the normal, effective functioning of the risk objects located in the region. The risk zone also encompasses objects in Murmansk, Teriberka and the restricted administrative units of Vidyaevo, Alexandrovsk, Severomorsk, Zaozersk and Ostrovny as well as in Kola and Tuloma. In these territories, the assessment scores range from over 310 to approximately 200.

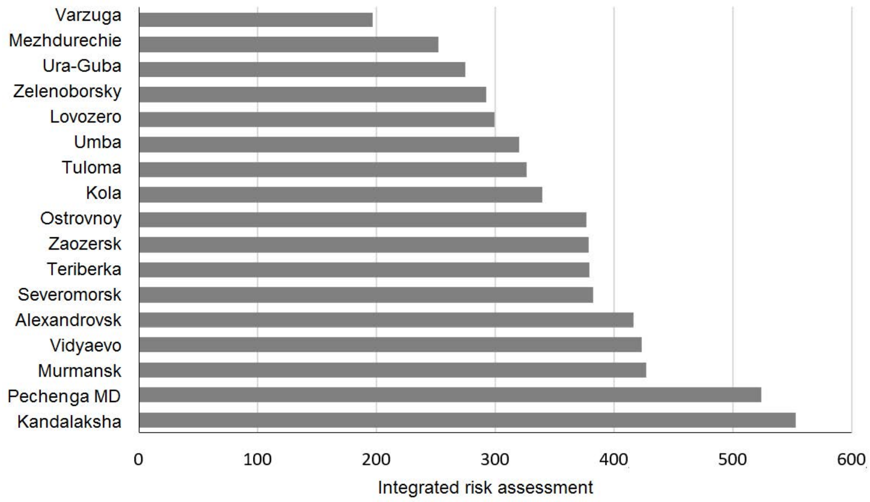



F i g . 2 . The degree of impact of the risk-factors on the normal effective functioning of risk objects for the coastal local municipalities of the Murmansk region

The lowest risk assessment score (over 85) was noted in the rural settlement of Varzuga. This is due to the small number of objects in the area with dispersed population with a homogeneous landscape. Taken together, these factors suggest that the potential risks have an insignificant impact on the normal and effective operation of risk objects in this region.

Analysis of the comprehensive risk assessment for the nature use in coastal areas of Murmansk Region municipalities revealed that Kandalaksha's coastal zone is at the highest risk. The integral risk assessment score for this area exceeds 550 (Fig. 3). This indicates that the occurrence probability for natural or man-made risks in this municipality is approximately 10%.

The coastal systems of the restricted administrative units of Aleksandrovsk and Vidyaevo as well as the Pechenga municipality and Murmansk are significantly influenced by risk factors, with integral assessment scores ranging from 410 to over 520. The lowest impact of risk factors is observed in the rural settlement of Varzuga, where the score is below 200 and the occurrence probability for adverse events (hazards) is 3%. Generally, the distribution of integral risk assessment values indicates a higher occurrence probability for various risks in relatively densely populated areas with a large number of functioning objects and a diverse landscape.




F i g . 3 . Integrated risk assessment for the coastal local municipalities of the Murmansk region

Having analysed the key risk factors differentiated by their impact on Arctic nature use objects in each seaside municipality, we can identify the following features:

– fires have the greatest impact on the objects of the Pechenga Municipal District (with a 9% probability of occurrence). The rural settlement of Varzuga is the least vulnerable to this factor;

– the risk of high water in river mouths / flooding of the territory is also minimal in Varzuga;

– nature-use objects of the urban settlement of Kandalaksha have the highest (9%) probability of man-made accident risk among all objects of the Murmansk Region;

– infectious and epidemiological contamination is the most probable (9%) in objects of the Arctic coastal eco-socio-economic system of the Pechenga Municipal District compared to other municipalities of the Murmansk Region. The lowest vulnerability to this factor is observed in Varzuga.

The analysis revealed differences in the degree to which natural and anthropogenic risk factors (excluding fires and infectious diseases) influence the seaside municipalities of the Murmansk Region. The Pechenga Municipal District demonstrated the highest contribution of natural factors (over 260, corresponding to a 9% occurrence probability of an adverse natural phenomenon). This is due to a large number of natural risk factors present in the district compared to other coastal municipalities. The urban settlement of Kandalaksha has the greatest contribution of anthropogenic factors (over 235, which corresponds to approximately 12% occurrence probability of an adverse event). This is due to the concentration of a large number of technogenic objects in a relatively densely populated area. The rural settlement of Varzuga shows minimum values of the complex contribution of both natural (approximately 4% probability) and anthropogenic (approximately 2% probability) factors. Thus, this settlement is the safest of the 17 coastal municipalities of the Murmansk Region.

## Conclusion

The model developed for assessing risks associated with natural resource use in the coastal AZRF is based on a matrix methodology for assessing sustainability risks in nature use. The model provides a spatial map of risk assessment scores and identifies key risk factors. It considers a database of criteria, types, sources and objects of risk, as well as their spatial scale and the nature of their impact. It also allows for the assessment of different combinations of individual risk factors, such as the impact of natural, anthropogenic and other factors.

It is possible to create cartographic materials and graphic models reflecting the eco-socio-economic systems of Arctic coastal territories. This approach has been successfully implemented using the Murmansk Region as an example.

Within the Russian Science Foundation project, the level of territorial risk associated with the nature use was assessed. This allowed developing recommendations for informed managerial decisions as to territorial planning and the rational use of available resources. The resulting cartographic and graphic materials can be used to optimise management and ensure the sustainable development of the Arctic region.

The proposed model is a valuable tool for analysing risk dynamics and determining the overall level of risk associated with the commissioning or dismantling of large infrastructure units or their complexes. The implementation of such a scenario implies the development of a forecast of changes in the risk components values and corrective factors, which, in turn, allows obtaining an integral risk assessment. Introducing the presented methodology and model will optimise territorial planning procedures and ensure the sustainability of Arctic coastal eco-socio-economic complexes. The improvement of this methodology and model is dependent on analysing the risks of nature use and adapting to changes in environmental and socio-economic spheres. This will provide flexibility when carrying out similar risk assessments within the set tasks.

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