geosciences

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Diagnostics and Mapping of Geoecological Situations in the Permafrost Zone of Russia

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Received: 27 June 2019; Accepted: 8 August 2019; Published: 11 August 2019

Abstract: The diagnosis of the geoecological state of natural landscapes during the economic development of the permafrost zone should be established by assessing destructive cryogenic processes. Furthermore, the geoecological state should be considered in terms of landscape resistance to an increase in cryogenic processes. In this paper, we examine and determine lithocryogenic stability parameters, including permafrost distribution over an area, annual mean temperature, ice content (humidity), and the protective properties of the vegetation. Activation of cryogenic processes in Western Siberia was estimated in terms of the area, development rate and attenuation, natural landscape damage, and hazards to engineering and mining facility operations. The evaluation procedure and the improvement in expert numerical scores are shown. A number of approved methods are proposed for creating assessment maps at various scales using landscape indication methods, decoded satellite images, expert assessments, statistical calculations, and analysis of spatial geographical information systems. Methodical techniques for digital geocryological mapping on the basis of the landscape are presented at scales from 1:3,000,000 to 1:20,000,000. All the maps were created by the authors and can be used for a wide range of applications, including design, survey organizations, and education.

Keywords: geoecological situations; permafrost zone; cryolithozone; cryogenic processes; landscapes stability; expert assessments; geoinformation mapping

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1. Introduction

The permafrost area of Russia shapes the geography of geoecological hazards that emerge during economic development. Permafrost-landscape studies are frequently used for environmental diagnostics and mapping. Since the 1930s, landscape permafrost conditions indication has been used as the basis for evaluation studies during permafrost surveys in different regions of the permafrost zone. The use of permafrost landscapes indication is only necessary if information about the study subject is limited and insufficient. The relief, vegetation, and land cover are the most indicative physiognomic landscape components. V.F Tumel [1] and V.A. Kudryavtsev [2] were the first scientists to point out the usefulness of this landscape-indication method in permafrost studies. In 1960, I. Yu. Baranov compiled the first landscape-based geocryological map of the USSR at a scale of 1:10,000,000 [3]. In the 1970s, the first surveys and mappings using the landscape-indicator method were carried out in Alaska [4], Canada [5], and in the north of Western Siberia [6,7]. According to these early studies of permafrost landscape indicators, in the first stage, the landscapes are identified by their appearance. Then, more detailed information—the relief, vegetation, and land cover—is acquired from specific landscapes.

The permafrost characteristics that are most commonly used to describe permafrost conditions include the distribution area of the permafrost, the permafrost temperature, the permafrost thickness, the ground ice content, the depth of seasonal thawing–freezing, and cryogenic processes. However, not all of these features are equally amenable to indication through the appearance of the landscape.

Taliks or islands of frozen rocks are most clearly recognized through the landscape, followed by the depth of seasonal thawing and, in some cases, the average annual temperature of permafrost. On the contrary, cryogenic processes and their consequences—cryogenic relief forms—are an integral part of the landscape indicator properties [8,9].

The landscape indication of permafrost is a critical research tool for fieldwork in the interpretation of remote sensing materials. It is frequently used in geocryological mapping to study the dynamics and evolution of permafrost, including the problems caused by the current climate warming [10–14]. This method is also very necessary for predicting and modeling changes in permafrost in northern and highly mountainous regions, which are strongly affected by climate warming [15–18].

The landscape-indication method is actively used in the Circumpolar Active Layer Monitoring (CALM) program—the world's primary source of information about the layer of seasonal freezing and thawing. The CALM observational network, established in the late 1990s, observes the long-term response of the active layer and near-surface permafrost to changes and variations in climate using more than 125 sites distributed in both hemispheres. Several groups of sites have been used to create regional maps of active-layer thickness [19–22].

In recent years, some new approaches have been proposed to map the distribution and dynamics of permafrost by integrating remote sensing data, field measurements, and process modeling. Remotely sensed data are more frequently used as the driving parameters in permafrost models and mapping schemes [23–30].

Geosystems stability is one of the fundamental concepts in physical geography and geoecology. The resistance of cryogenic landscapes to surface damage is the ability of the land to resist anthropogenic activation of cryogenic processes that may lead to irreversible deterioration of the environmental situation and unacceptable deformation of engineering structures [1]. Cryogenic processes are a key indicator of northern landscapes' reaction to external influences [2]. The mechanical damage arising during the operation of engineering facilities, such as mining, are widespread in the cryolithozone. The typical anthropogenic influences in northern areas include overgrazing of reindeer pastures, deforestation, and burning. All these activities intensify the development of thermokarst, solifluction, deflation, and foster the expansion of boggy areas.

The first works on cryoecological mapping in Russia appeared in the mid-1980s. It should be noted the author's classification and legends were compiled by L. Garagulya [31], E. Melnikov [32], A. Fedorov [33], D. Drozdov [34], L. Zotova [35,36], and others.

Geographic information system (GIS) technologies have simplified the permafrost landscape classification by overlaying methods and have also simplified map interpretation with approaches such as attributive tables [37–41]. If necessary, vector thematic layers are overlaid to change the content of the digital version of the map, depending on specific tasks and goals [42]. This enables GIS spatial analysis of the territory, the construction of tables and histograms, the identification of patterns, and, consequently, an increase in the information content of different maps [8,43]. Thus, the development of GIS, new spatial analysis methods, and computer modeling have provided great opportunities for a comprehensive and integrated analysis of permafrost areas.

In Russia, the most significant results of regional, local, and regime studies on landscape-based permafrost mapping were obtained by the Earth Cryosphere Institute, Tumen, Moscow (ECI SB RAS) [32,34,44–49]; the Melnikov Permafrost Institute SB RAS, Yakutsk [33,38,43,49–53]; and Lomonosov Moscow State University, Faculty of Geography [8,36,45,54–62]. These are well-known scientific schools with many years of research and mapping experience.

Modern expert evaluation methods of landscapes consist of a number of procedures, including the selection of factors that influence landscape resistance, the establishment of interrelations between factors, and assessment of the influence of these factors using weights. The most popular method is multi-criteria decision analysis (MCDA), which applies ranking criteria (factors) for an objective assessment of different solutions [63,64]. In Russia, MCDA methods in geoecological studies have been successfully applied in the Northern (Arctic) Federal University named after M.V. Lomonosov

(Arkhangelsk). For example, MCDA was applied in an expert assessment of oil and gas fields in the Bolshezemelskaya tundra [65–67]. An overview of the foreign literature suggests that there are no published papers on the use of MCDA methods for the GIS mapping of permafrost regions.

The object of this study is the whole territory of the Russia permafrost zone, which occupies 10.7 million km^2. The main objective of this work was to identify the leading factors that determine the landscape's resistance to cryogenic processes during surface disturbances on different scales. We used these factors to rank the cryolithozone landscapes by resistance groups to cryogenic processes activation during economic development. As an overview, analysis of aspects the main permafrost characteristics is necessary, such as the distribution area, the annual mean temperature, and ice content degree. The permafrost area shapes the geography of geoecological hazard emergence. The annual mean temperature influences permafrost and cryogenic landscapes stability. Generally, the lower the temperature, the lower the geoecological hazard. For geoecological purposes, information on a cryogenic structure is also the most important [8], since the development hazard is directly proportional to the degree of ice content of the permafrost. At the local scale, the range of factors influencing permafrost is larger, including ice content and temperature of the permafrost, the depth of seasonal thawing or freezing, relief, heat-insulating properties of the vegetation, the rate of permafrost self-recovery, and bioclimatic indicators.

At all scales, the focus is on the layer of seasonal freezing and/or thawing, called the "active layer". It is the first permafrost horizon from the surface in which ecologically hazardous cryogenic processes occur [19,56,57]. The change in its thickness is integrated with these cryogenic processes and indicates their activation. During engineering research and calculations, this parameter is of paramount importance and, along with ground temperature, ice content (or humidity) is used for ensuring stability and reliably of buildings, facilities, and communications operation and maintenance specific engineering-geological operations.

We used all these leading evaluation factors to rank cryolithozone landscapes by their resistance to the human-induced activation of exogenous geological processes. The evaluation and mapping of geoecological situations were demonstrated in a key area on a large scale and displayed as small-scale overview maps. Here, a detailed review of methods for assessing and mapping permafrost hazardous processes is presented for the first time. This article also presents a number of regional-scale overview evaluation maps, which were created by the authors, for the entire Russian permafrost zone. Most of the maps have already been published in atlases. However, the last three maps in this article are presented here for the first time.

The methods presented in this study are quite flexible and can be adapted to other geographic permafrost areas in different countries.

2. Materials and Methods

2.1. Estimating and Mapping the Landscape Sustainability

Geoecological research is based on identifying factors that influence the lithocryogenic state of the landscape, decrease landscape stability, and, as a result, activate cryogenic processes [8,55].

The characteristics for determining landscape sustainability in the permafrost zone can be combined into two groups: (a) "Non-permafrost" factors (climate, relief, composition, rock properties and genesis, and protection by ground vegetation cover); (b) "permafrost" factors (annual mean temperature, thickness, cryogenic structure of rocks, cryogenic processes, the depth of seasonal freezing–thawing, and distribution of permafrost areas). Various methods for determining cryogenic landscape stability use different combinations of these factors depending on the level, scale, and objectives of the research. Most of the assessments are expert-based and rely on theoretical qualifications and the regional experience of researchers [8,36,68–71].

The evaluation procedure of our method includes the following steps:

Step 1. Selecting the main factors that influence landscape resistance to loadings (activation of cryogenic processes);
Step 2. Creating a matrix table of influence factors, each of which is assigned a specific weight (qualimetric) coefficient (usually ranging from 0 to 1) depending on the contribution of the factor to the final grade;
Step 3. Calculating the integral index of resistance to the activation of cryogenic processes in all landscapes;
Step 4. Ranking all landscapes from the third to fifth stability gradation on the basis of their vulnerability to the mechanical impacts according to the calculated indexes;
Step 5. Performing evaluative GIS mapping and spatial analysis of the territory according to the degree of sustainability.

Two additional operations are conducted before ranking if the statistical program is used for the integral index calculation:

(3a) Expert assignment of integral index values (0–1) to each landscape on the basis of the evaluation of the actual intensity and the occurrence spectrum of the processes, as well as to the bioresource value;
(3b) Analysis of the correlation with the purpose of sorting out secondary criteria and the production of a multiple regression equation for calculating the "total hazard score" (for example, the permafrost stability coefficient, *PSC*) for each landscape.

Multiple correlation enables the assessment of the relationship between a selected factor and all other factors in the system. Our research experience with numerous test objects [8,68] confirmed the usefulness of the multivariate correlation analysis and the output of multiple regression equations using a simple statistical program.

The proposed technique of expert evaluation is partially based on MCDA, which includes the development of a criteria (factors) matrix, which should be ranked and combined to assess a solution [65,66]. Methods of multi-criteria evaluation also have similar steps:

1. Set the goal/define the problem;
2. Determine the criteria (factors);
3. Standardize the scores of the factors/criteria;
4. Determine the weight of each factor;
5. Aggregate the criteria;
6. Validate/verify the result.

According to this algorithm, we assessed all landscapes or areas on the basis of our goal—to evaluate their potential resistance to the appearance of dangerous relief-forming processes.

If we derive an integral index (for example, for the dangers of exogenous geological processes) for each landscape of the test site in points or cents, then, using the area values of each of site, we can calculate the index D_y, which denotes the weighted average hazard index of the processes throughout the whole area:

$$D_y = (\sum_{i=1}^{n} D_i \times S_i) / \sum_{i=1}^{n} S_i$$

where D_y is the hazard index for the test site as a whole, D_i is the hazard value of the ith landscape, S_i is the area of the ith landscape, and n is the number of test site landscapes.

By calculating the weighted average hazard indices for several sites and accounting for the maximum and minimum values of the indices, we can compare them and conclude which site is more susceptible to the manifestation of dangerous exogenous processes and determine their variation among the test sites [8]. Next, we can compare several geosystems or site areas to establish environmental protection measures.

With this technique, engineering permafrost (lithocryogenic) stability maps are created on the basis of landscapes. Depending on regional specifics and the scale of the research, the number and range of the factors might vary. For example, in Central Yakutia, it is necessary to consider a number of bioclimatic factors [72], including the crown density of a forest stand [8]. In a previous work, a landscape stability map of the Western Siberia cryolithozone (scale 1:4,000,000) [36] was created by selecting six factors that directly influence the activation of cryogenic processes and are connected with the phase transitions of water: Dissected relief, ground composition, permafrost temperature, the ice content (humidity) of the ground, the degree of vegetation recoverability, and the relative change in the active layer. In research by Author et al. [8,36,55,73], their choice of factors was explained in detail. The main criterion is that the factors should be independent and not correlated with each other.

In traditional geoecological estimations, expert scores are frequently used to compare objects. The sum of the scores or the arithmetic mean values (and rarely the geometric mean values) are calculated. The statistical method can also be used for the correlation analysis of multifactorial landscape biotic and lithocryogenic properties. The advantage of using scores is the possibility of numerically comparing quantitative and qualitative characteristics. The disadvantage is the subjectivity of the parameter selection and the ranking scale development. The summation of points is valid (especially for research at overview scales), although it has serious limitations, including the lack of dimensionality [74]. For a more accurate evaluation, we suggest defining the score dimensionality using so-called "quality cents" accompanied by building the interval 100% cent scale [8,75]. Each chosen factor has a weight expressed in cents.

There are several methods to determine the weight of each factor [65,76].

- Direct placement. The sum of all weights = 1. Apply with a small number of factors.
- Ranking factors in ascending/descending order of their properties.
- Assignment the significance coefficients to factors according to the regression equation.
- Hierarchy analysis method. Pairwise comparison Analytical Hierarchy Process (AHP) by Thomas Saati [77,78]. Difficult, but unconditionally recognized method.
- In the following example, we calculated the percentage values of the six chosen indicators using the geometric mean (not the sum), which is called the hazard coefficient *Ch* that corresponds to each landscape. The smaller the value of *Ch*, the more stable the landscape. Thus, two techniques for splitting all landscapes into clusters by their stability were tested: A simple point-summing method and calculation of the percentage geometric mean value.
- Figure 1 shows that the greatest risks to economic development in this region (in terms of destructive exogenous processes) are the landscapes classified in the righthand part of the figure. These risks include slightly dissected landscapes with an annual mean ground temperature between 0 and −1 °C, landscapes made of peat, landscapes with more than 50% ice content, and landscapes with vegetation that has low recoverability (covering less than 20%), which can increase the thickness of the seasonal freeze–thaw layer by more than double if their surface suffers mechanical damage.

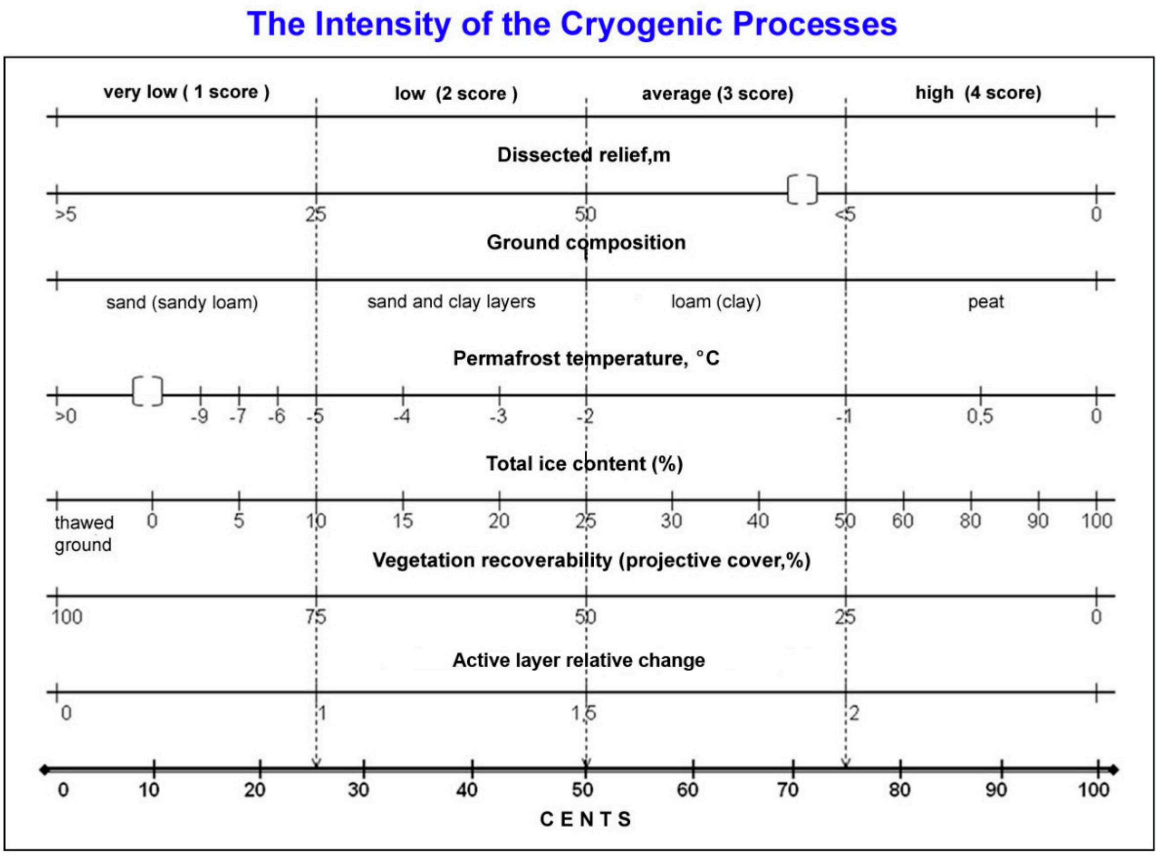

Figure 1. The ratio of the estimated factor scales affecting the intensity of cryogenic processes in Western Siberia.

The landscape type and classification values were combined to display each factor as a separate thematic layer (ice content degree, ground temperature, etc.) for further use in overlaying in a map. This process, however, is rather complicated and not always justified. To simplify mapping, we assessed a range of factors with calculated integrated indexes: The permafrost stability coefficient (*PSC*), ecological hazard coefficient (*EHC*), the hazard coefficient (*Ch*), and others [8,55,68]. In large-scale research, it is expedient to perform a multiple-factor correlation analysis of the estimated factors because, first, it enables us to estimate the importance of a particular factor and, second, improves the quality of the quantitative score.

The described assessment procedure is easily incorporated into GIS for geospatial analysis by comparison with the following works [79–81]. The book by Jacek Malczewski and Claus Rinner [82] provides a comprehensive account of the theories, methods, technologies, and tools that can be used to effectively integrate MCDA with Geographic Information Science (GIScience).

2.2. Method of Estimating & Mapping Cryogenic Processes Activation

The ecologically hazardous cryogenic processes can be divided into two periods: Summer and winter [56]. The seasons affect the diagnosis of geoecological situations as, in summertime, the vegetation ground cover is mainly investigated, and in winter, the snow cover is considered. The first group of the processes occur in the summer as a result of permafrost thawing, including: Thermokarst, thermoerosion, thermoabrasion, and solifluction, which, under the increase in soil humidity, can cause mass dislodging. The second group of the processes occur in the autumn and winter period when water turns into ice and further cooling of soil occurs, so frost heave and frost cracking are observed. These processes combinations allow us to diagnose the geoecological situation and to estimate the degree of their hazard for both the environment and for human facilities. All the names of exogenous relief-forming processes discussed in this article are in accordance with The Multi-Language Glossary of Permafrost Terms [83].

The assessment of the degree of process activation is based on the analysis of the following factors (Table 1): Cryogenic structure (or ice content) and the temperature regime of the ground in the upper part of the soil, which corresponds to the layer of annual heat transfer. Of the non-permafrost natural components, the leading factors that affect permafrost are vegetation and geological/geomorphological conditions [8,56].

Table 1. The main factors intensifying cryogenic processes.

Permafrost			Vegetation		Factors Influence on Cryogenic Processes
Ice Content (Rock Volume Fraction) & Types of Ground Ice	**The Average Annual Temperature °C**	**Distribution**	**Protective Properties**	**Self-Healing Vegetation**	
less 0.1	below −10	rare island	the arctic tundra - weak	the arctic tundra - bad	weak
0.1–0.2	−5 … −10	island	typical tundra - moderate	forest-tundra - moderate	moderate
0.2–0.4 Epigenetic massive ice	−3 … −5 0 … +2	massive island	south tundra - good	taiga - good	average
0.4–0.6 polygonal ice wedge, frost heave mound	−3 … −1	discontinuous	forest-tundra and taiga - significant	tundra - significant	strong
more 0.6 polygonal wedge & massive ice sheet, frost heave mound	0 … −1	continuous	marsh landscapes - the greatest	marsh landscapes - the greatest	very strong

Vegetation damage is a universal type of change in heat exchange on the surface, so it often triggers cryogenic processes. Vegetation has a dual role: Under natural conditions, it is one of the main stabilizers of permafrost conditions, performing heat insulation and fixing functions (a protective role of vegetation). After anthropogenic damage, the rate of vegetation cover restoration mitigates permafrost processes attenuation [8,56].

The predictive evaluations of areas of damaged vegetation, the rate of damage development and reduction, along with remediative, environmental, and engineering activities are used to stop these processes. The gradation of particular characteristics of the processes is based on quantitative or qualitative (points) indicators to enable their numerical comparison. A total score for these indicators denotes the extent of their activation in the territories under development. According to the Set Of Rules "Geophysics of hazardous natural processes" for engineering surveys and urban planning [84], all indicators used to evaluate the hazard categories of natural influences should be listed in the tables. Some of them are given below (Tables 2–5). Information about process speed and recurrence was obtained from previous publications [8,56,68].

The most important indicator is the area of cryogenic damage, which is classified from less than 5% to more than 75% of the territory under development. The second most important indicator is the processes development rate (Table 2). The lower the rate, the less the geoecological danger of economic development.

Permafrost processes, except for area distribution and the speed of development, influence the shape of a landscape in general, and can only be estimated qualitatively (Table 3). The first step in the transformation of natural landscapes into the unsuitable areas of land is thermoerosion due to deep surface fragmentation. Then, solifluction occurs, turning areas into the impassable sites because of the quicksand.

Table 2. Development rate and recurrence of cryogenic processes.

Processes	Speed				Recurrence		
	Slow (1 Point)	**Average (2 Points)**	**Quickly (3 Points)**	**Catastrophic (4 Points)**	**Rarely (1 Point)**	**Periodically (2 Points)**	**Annually (3 Points)**
Thermoerosion, m/year		less 5	5–30	30–100			
Thermoabrasion, m/year	less 0.5 (small lakes)	0.5–2 (large lakes)	2–5 (sea shores)	less 10 (reservoirs)			
Thermokarst, m/year	less 0.05	0.05–0.1	0.1–0.15	0.15–1.0			
Solifluction, m/year	less 0.2	0.2–10	more 10	m/day			
Frost heave, m/year	less 0.05	0.05–0.1	0.1–0.5	>0.5			
Icing formation					every 5 years	every 2–5 years	every year
Frost cracking					every 5–10 years	every 3–5 years	every year
Kurums, m/year	less 0.01	1–3	4–10	more 10			

Table 3. The impact of cryogenic processes on landscapes.

Processes	The Impact of Cryogenic Processes on Landscapes			
	Not (0 Points)	**Poor (1 Points)**	**Moderate (2 Points)**	**Strong (3 Points)**
Thermoerosion			+	+
Thermoabrasion		+	+	
Thermokarst		+	+	+
Solifluction		+	+	+
Frost heave		+		
Icing formation	+	+	+	
Frost cracking	+	+		
Kurums		+	+	

The assessment of the degree of work safety at engineering facilities (including accident rate) is shown in Table 4.

Table 4. The assessment of the degree of work safety at engineering facilities.

Processes	The Accidents Emergence Danger			
	Not (0 Points)	**Poor (1 Points)**	**Moderate (2 Points)**	**Dangerous (3 Points)**
Thermoerosion			+	+
Thermoabrasion			+	+
Thermokarst		+	+	+
Solifluction			+	+
Frost heave			+	+
Icing formation		+	+	+
Frost cracking	+	+		
Kurums		+	+	

Almost all processes that are listed in this table, except frost cracking and kurum (rock stream) formation, forecast high accident rates at engineering facilities that produce considerable anthropogenic impacts [56,58].

The integrated assessment of geoecological situations must include the reduction rate of hazardous processes, along with the efficiency of environmental protection activities, to provide information for engineering and remediation decision-making (Table 5). The natural attenuation of cryogenic processes can be connected with the consumption of ice, along with low temperatures, rapid vegetation restoration, and relief alignments [56].

Table 5. Cryogenic processes attenuation rate and availability of engineering protection.

Processes	Attenuation Rate				Engineering Protection			
	Not (0 Points)	Slow (1 Points)	Moderate (2 Points)	Fast (3 Points)	Not (0 Points)	Bad (1 Points)	Available (2 Points)	Good (3 Points)
Thermoerosion		+	+		+	+	+	
Thermoabrasion	+	+	+		+			
Thermokarst		+	+	+	+	+		
Solifluction	+	+		+	+	+		
Frost heave	+				+	+		
Icing formation	+	+					+	+
Frost cracking	+			+	+		+	
Kurums		+	+		+			

According to the above tables, the whole range of environmentally hazardous processes and the degree of infestation of each landscape were determined; the rates of their development and attenuation were estimated; the processes were ranked according to the degree of the threat to the existence of engineering structures; and measures to combat and protect the landscape from these processes were considered.

Evaluation studies were carried out on a landscape basis with the help of expert scores. The assessment and mapping of process activation at the overview-regional scale were based on five main factors (Table 1): The permafrost distribution area, the annual mean temperature, the ice content degree, vegetation (protective properties and self-recovery), and geological/geomorphological conditions [8,56]. An expert assessment was performed for all landscapes of the estimated territory for each of these factors, which were compared in various ways (see Section 2.1) for a final assessment. Further, landscape units were ranked into five categories of potential process activation.

In each landscape province, the intensity of the manifestation of the leading cryogenic processes and their combinations were expertly evaluated. The areas affected by the processes, the development rate and recurrence of the processes, the range of processes within one territory, the degree of their negative impact on natural landscapes and the functioning of engineering facilities, and their attenuation rate during the corresponding environmental measures were taken into account. Tables 2–5 show some indicators to enable their numerical comparison. The number of expert points, which range from 1 to 5, indicates their weight, which represents their contribution to the overall assessment of hazardous process manifestation. The overall assessment of these particular indicators results in the degree of their activation in developed areas. A total score of the individual indicator values reveals the degree of their activation in the mapped area.

Digital small-scale global and regional maps (1:2,500,000 ... 1:10,000,000) of cryogenic process activation were created from local databases of medium-scale maps (1:100,000 ... 1:200,000). The layers of the following thematic maps can be used: permafrost thickness, ground temperature, ice content, lithology, vegetation cover, territorial types of the active-layer thickness, and landscapes units.

These are maps of the well-investigated areas throughout the Russian cryolithozone. These areas can be considered environmental «key sites» [40], the details of which can be extrapolated and interpolated using the geosystem approach. Most of them are from the CALM network and have a long history of permafrost monitoring [19,21,22]. The CALM information includes air temperature, soil moisture, soil temperature at different depths, snow cover, lithological composition, and landscape characterization. Metadata include detailed test site descriptions and photographs. In our work, we used the layer of reference test sites and the layer of meteorological stations. Figure 2 shows the location of the reference test sites, which were used to map cryogenic processes activation.

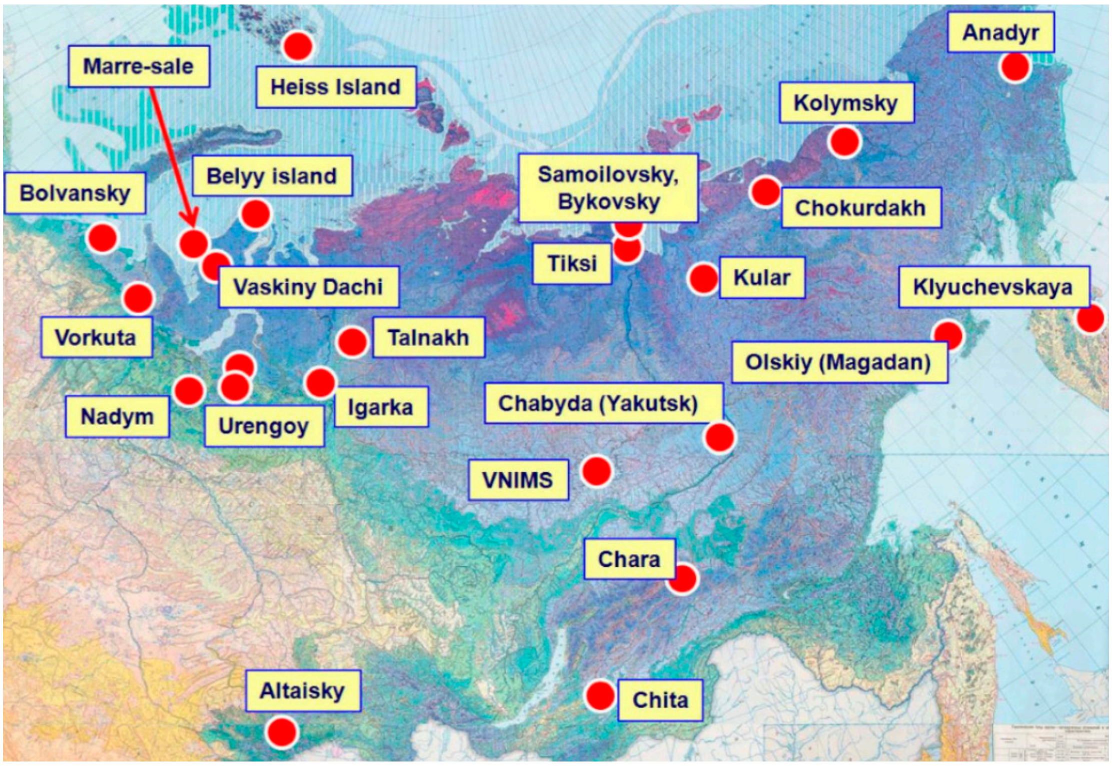

Figure 2. The location of the reference test sites within the permafrost zone.

The information on the thermophysical properties of snow, ground cover, and soils was used to create regional maps of the active-layer thickness at different scales. The territorial types of seasonal freezing–thawing were determined by calculating the active-layer thickness for each landscape using the approved rapid method [85] according to Stefan–Feldman formulas [86] and permafrost engineering normative documents.

The geosystem approach and the methods of summarizing the available data allow us to characterize the age, composition and basic properties of permafrost, its temperature and the cryogenic structure and also to associate these parameters with hydrometeorological data for possible forecast and geoecological situations estimates. The main technological steps of permafrost arears digital mapping are as follows [37,40]:

Step 1. Linking raster images of remote sensing data and source maps to a working cartographic projection.

Step 2. Digitization of source maps to obtain thematic electronic layers of various contents–landscapes, geological complexes, vegetation types, geomorphological objects of processes, etc.

Step 3. Combining the thematic layers of the same content which were obtained from different sources in a single electronic coverage.

Step 4. Editing of thematic layers–electronic maps of various content–in accordance with remote sensing data.

Step 5. Linking electronic maps with databases of landscape, geological, geocryological, and other information and generating corresponding legends to maps.

Step 6. Compilation of electronic and "paper" versions of thematic maps using the information and graphics capabilities of GIS programs (ArcInfo, MapInfo, etc.).

The creation of such maps requires operating and generalizing a large amount of information on natural and technogenic geosystems and the structure, properties, and temperature of permafrost, as well as exogenic geological processes and hydro- and meteorological parameters. The digital landscape map is a basis for the creation of several maps: the map of permafrost extent, the map of cryogenic geological processes, and prognosis maps of landscape stability to cryogenic processes.

2.3. Basic Mapping Materials

As sources for creating small-scale maps for environmental purposes, four permafrost maps were used: The 1997 Geocryological Map of the USSR (scale 1:2,500,000 [87], the 1970 Geocryological Map of the USSR (scale 1:5,000,000) [88], the 1997 Circum Arctic Map of Permafrost and Ground Ice conditions (scale 1:10,000,000) [89], and the 1985 Cryolithological Map of the USSR (scale 1:4,000,000) [90].

The most comprehensive source of detailed characteristics of permafrost conditions in Russia is the Geocryological Map of the USSR (scale of 1:2,500,000) on Figure 3. From this map, we used the data on the permafrost temperature, thickness, lithological composition, genesis, cryogenic structure, and ice content that were coordinated with a landscape map.

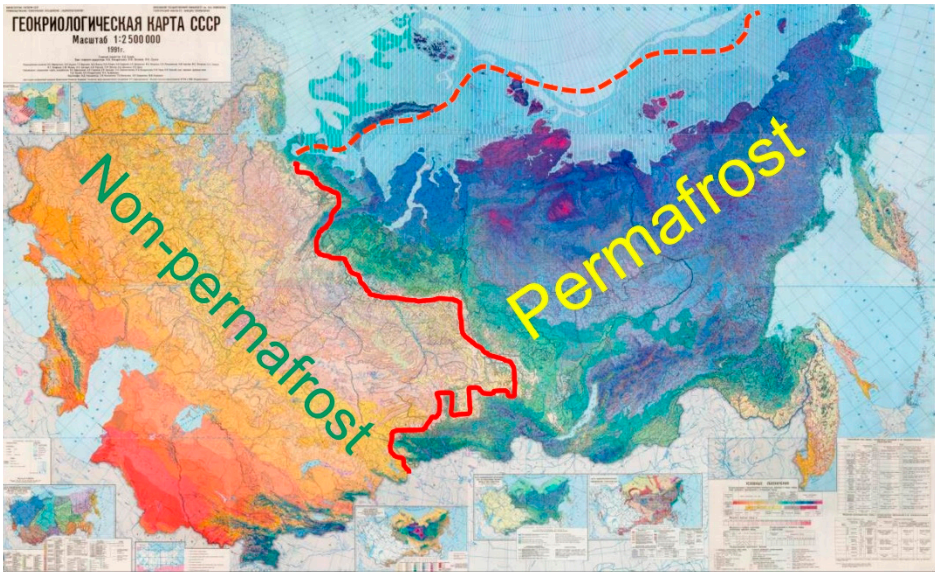

Figure 3. The Geocryological Map of the USSR, scale 1:2,500,000.

The well-known map to foreign scientists is "Circum-Arctic map of permafrost and ground-ice conditions" (Figure 4). It shows the distribution and properties of permafrost and ground ice in the Northern Hemisphere (20°N to 90°N), using a physiographic or landscape approach for the delineation of the map units which includes three major national permafrost regions (Russia, Alaska, and Canada). The original paper map includes information on the relative abundance of ice wedges, massive ice bodies and pingos, ranges of permafrost temperature, and thickness. For Russia, the average annual temperatures are given in more detail, taking into account the landscape structure, composition, and ice content of the rocks. The map is supplemented with tables in which complexes of cryogenic processes are listed by region. The distribution and ice content permafrost are shown differentially for loose and indigenous sediments, which makes it possible to coordinate them with the landscape basis of permafrost-ecological maps. Reflection of landscape features is complemented by showing the northern boundary of the forest. The disadvantages of this map include features of the projection, which are difficult to compare with regional maps, and poor readability of the content.

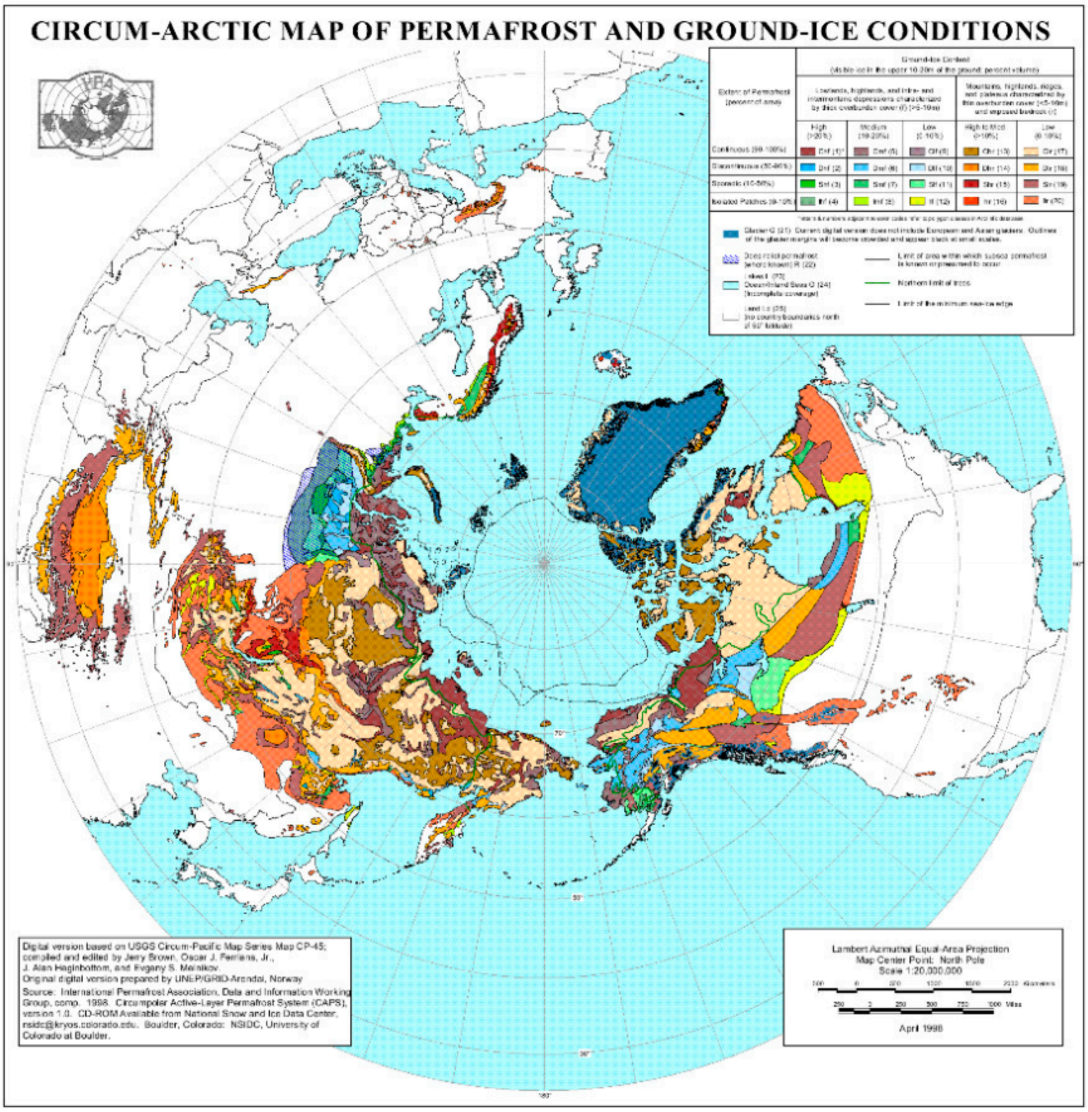

Figure 4. The Circum-Arctic Map of Permafrost and Ground-Ice Conditions.

In 2002, the map was updated and digitized. It is often called the Global Permafrost Zonation Index Map. This data set contains a global (excluding Antarctica) 1-km map of permafrost zonation. The digital data set of this map [85] shows discontinuous, sporadic, or isolated permafrost boundaries. Permafrost extent is estimated in percent area (90–100%, 50–90%, 10–50%, <10%, and no permafrost). Relative abundance of ground ice in the upper 20 m is estimated in percent volume (>20%, 10–20%, <10%, and 0%). The data set also contains the location of subsea and relict permafrost. Also included are the glaciers and ice sheets for North America (including Greenland) and the arctic islands that were available from digital databases.

On the basis of this map, many regional works about permafrost and climate change have been performed. Such studies include investigating permafrost zonation in the Himalaya region [91], mapping land cover in northern high-latitude permafrost regions [25], and modeling and mapping permafrost in northern Ontario, Canada [24], among other research efforts. All CALM investigations, particularly those from the University of Alaska Fairbanks, have used the shapefiles of this map (for example, [92–96]).

Well-known maps such as Northern Circumpolar Soils Map [97], Circumpolar Arctic Vegetation Map [98], and Landscape Map of the Russian Arctic Coastal Zone [99] have also been based on a digital circumpolar Lambert projection map. A circumpolar map series was compiled by a large team of authors from Greenland, Iceland, Canada, Norway, Russia, and the USA [100] under the leadership of Donald A. Walker. The Russian sector of the geosystem map was compiled under the direction of D. Drozdov.

For displaying the natural background on which various geoecological situations are formed, it was necessary to analyze a number of small-scale permafrost maps on a uniform landscape basis on a geosystem grid of various scales. We used our own maps, which were compiled for geographical atlases [58–62], as well as the generalized Landscape Map (scale 1:4,000,000) for the territory of Russia edited by Isachenko [101], to create a landscape map at a scale of 1:15,000,000 (Figure 5). In the legend of this map (Figure 6), landscape zone types are shown in horizontal ranks. The vertical columns correspond to the landscape type: The relief and lithological differences of rocks. The legend facilitates the selection of separate components of landscape characteristics according to lithogenic features, relief, vegetation in the zone, and sector aspects that are necessary to understand the permafrost situation.

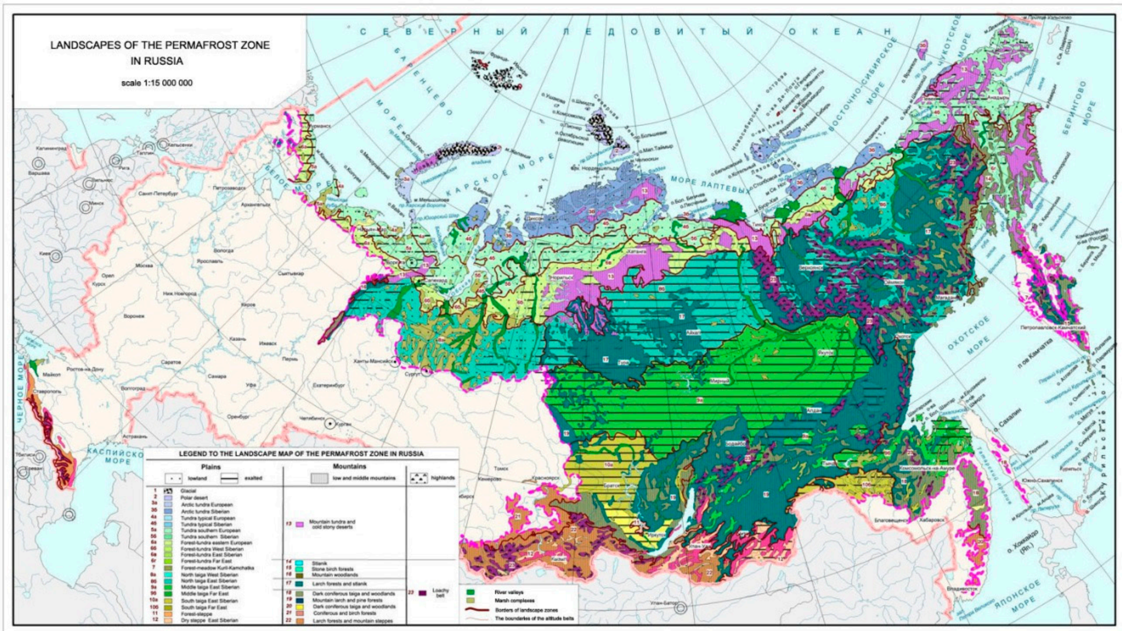

Figure 5. Landscape map of the permafrost zone in Russia.

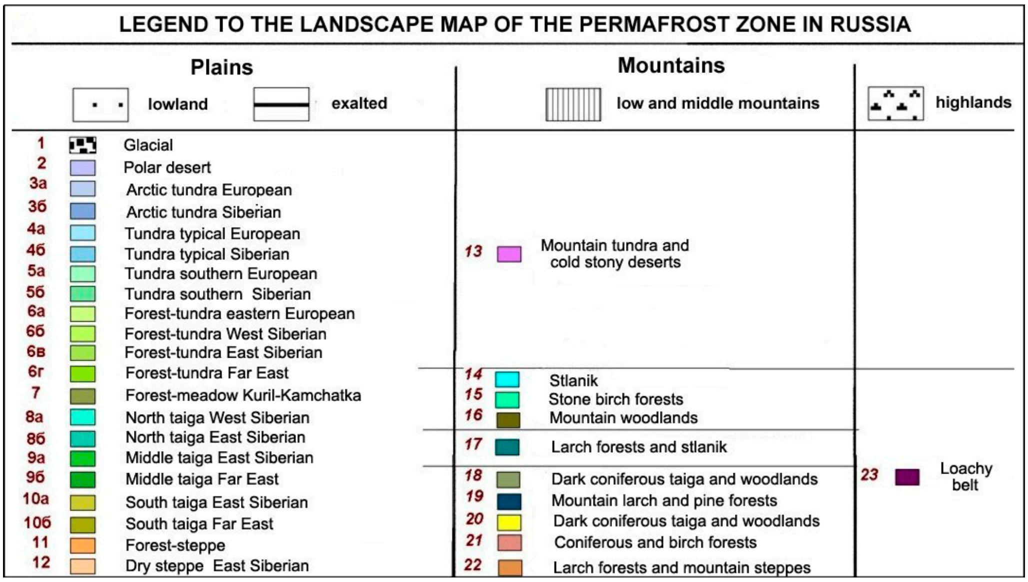

Figure 6. Legend to the landscape map of the permafrost zone in Russia.

Let us consider two basic permafrost maps (scale 1:20,000,000) compiled by the authors and published in the Ecological Atlas of Russia [58,60]: Permafrost of Russia [58] and Seasonal Freezing and Thawing [60]. The permafrost map of Russia (Figure 7) shows four main types of permafrost distribution: Continuous, discontinuous, massive-island, and island.

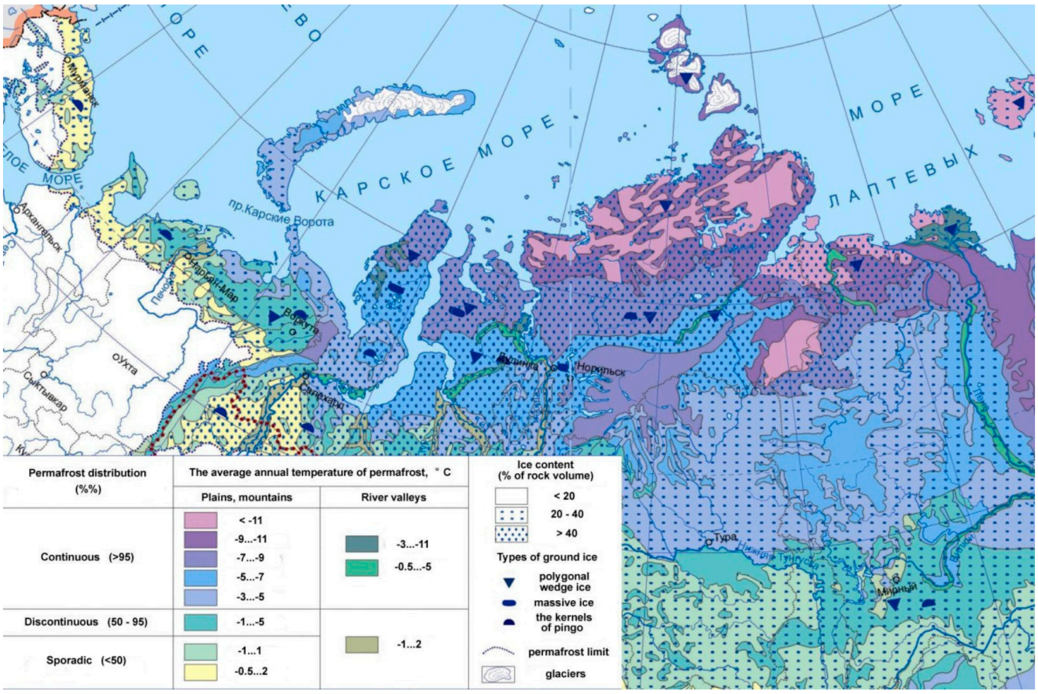

Figure 7. Map fragment the permafrost of Russia, scale 1:20,000,000.

Within each type, the territories with different annual mean permafrost temperature are defined within the distribution area. The temperature on plains and plateaus increases from north to south. In mountainous landscapes, the temperatures are lower than on the adjacent plains. The greatest variety in temperature is in the continuous permafrost zone, ranging from –11 °C to –3 °C.

In the discontinuous permafrost zone, it is difficult to differentiate the permafrost temperature within the map scale. This type of permafrost is most widespread in mountains and the uplands in the south and east of the Russian cryolithozone. Massive-island and island permafrost types are characterized by temperatures above –1 °C, and the thawed areas here are 1–2 °C. The map (Figure 7) shows three main permafrost types due to the ice content degree. Thus, the low-ice permafrost (<20%) is mainly observed in the cryogenic eluvium of the highlands and plateaus, in the upper part of the fractured rocks and sands. The mid-ice permafrost (20–40%) is represented by sandy and loamy areas within denudation plains. The high-ice permafrost (>40%) is most often observed within low accumulative plains with loamy and sandy ground. The dark blue signs on the map show the areas of monomineral ice massifs distribution, such as polygonal-vein ice massifs, the kernels of frost heave mounds, and ice beds [8,56,69,102,103].

The second important map that is necessary for geoecological research is the Seasonal Freezing and Thawing Map (Figure 8). To create this map, we used the landscape map by Isachenko [101] and the Geocryologic Map of the USSR, scale 1:2,500,000 [86], along with the results of regional research on seasonal freezing and thawing from publications [6,19,21,33,36,44–48,54–56,69,84–87,102,103], funds data, and the authors' personal archive.

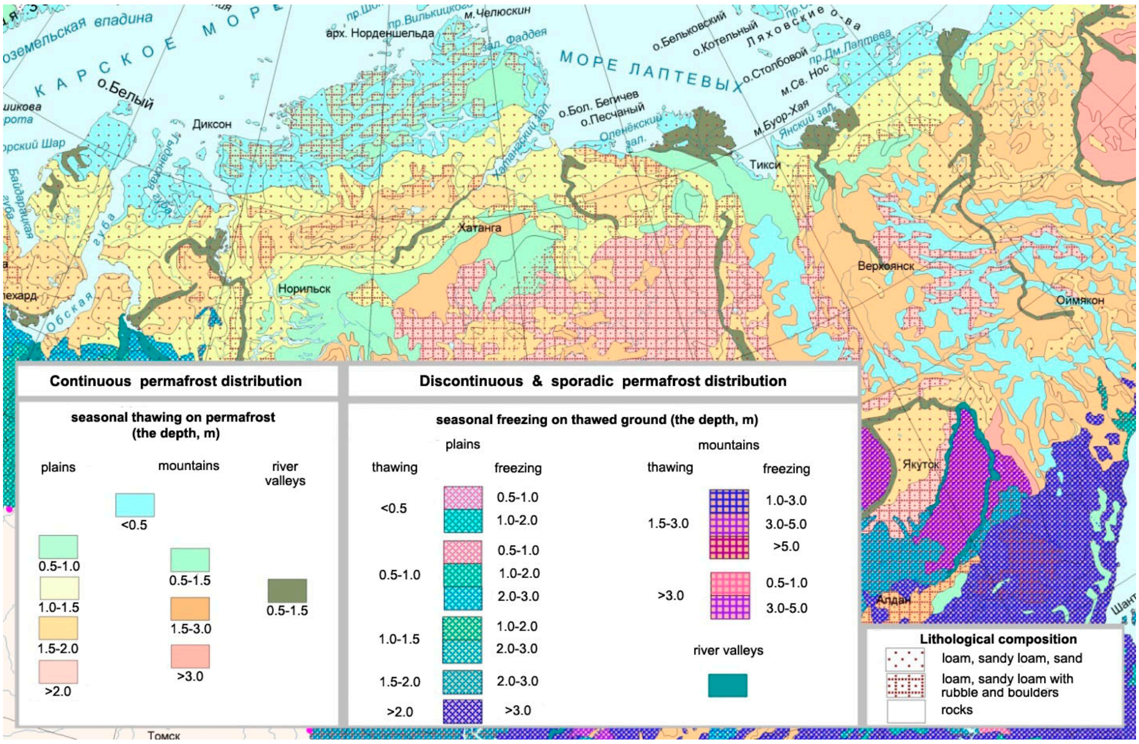

Figure 8. Legend and map fragment of Seasonal Freezing and Thawing map.

In the Seasonal Freezing and Thawing map, within the borders of the Russia cryolithozone, not only is seasonal permafrost thawing evaluated, but also seasonal freezing in taliks. The area of the latter increases approaching the southern permafrost limit. Taliks are almost absent in continuous permafrost, and in the south of the cryolithozone permafrost, they occupy no more than 5–10% of the area. Therefore, in the discontinuous permafrost within the same area, small-scale maps display both the depths of seasonal thawing and seasonal freezing.

The influence of a relief is shown by creating separate scales for their different constituents: Plains, mountains, and river valleys. The depth range of seasonal freezing and thawing is subdivided into three types: Shallow (up to 0.5 m), in which the majority of factors interfere with the processes of seasonal freezing and thawing; average (1.0–1.5 m), with some factors affecting and interfering with the process; and deep (greater than 1.5 m), in which most factors affect the process. The degree of the geoecological hazard increases from the deep to the shallow active layer. In this direction, there is an increasing risk of damage to the natural environment due to increased anthropogenic activities [8,56].

The diagnostics of geoecological situations are based on geographical features of active layer depth distribution. In the continuous permafrost zone, only the depth of seasonal thawing was mapped, which, in general, is subject to latitudinal and altitudinal zonation. The thawing at depths less than 0.5 m is shaped by the severe climatic conditions in the Arctic and is observed in the polar deserts of the Arctic Ocean islands and on the loaches of ridges of Northeast Russia. The thawing from 0.5 to 1.0 m is characteristic of peats and peaty soils of the lake and marsh landscapes. The average thawing due to depth (intervals of 1.0–1.5 m and 1.5–2.0 m) is found in the associated soils of tundra and forest-tundra landscapes within Northern Europe, the Western Siberia peninsulas, in the north of the Taimyr Lowland, and the seaside lowlands of the Northeast of Russia. At depths greater than 2 m, thawing is localized in the sandy landscapes created by ancient sea and alluvial and lake-glacial sediments. In the mountains, according to the landscape zonation and reduction of absolute heights, the depth of thawing increases.

All maps presented in this article were created on a single cartographic basis at the Geography Faculty of Moscow State University using the latest satellite materials.

To determine the types of geoecological situations on a large and medium scale, anthropogenic load maps must be used. These maps should display all kinds of mechanical damage to the topsoil cover as a result of the impact of engineering structures as well as overexploitation during deer pasturing [68,104]. Mechanical surface damage leads to the increase in the annual mean ground temperature, the growth in seasonal thawing depth, and, as a result, the reduction in the ground strength properties and increase in exogenous geological processes, which are most hazardous in the north.

3. Results

3.1. Evaluation of Geoecological Situation at Local Level

The legend for the Geoecological Situations Map was prepared in the form of a matrix table (Figure 9). Permafrost ecological state groups are provided in accordance with three *CPS* gradations on the horizontal axis. Four categories of loads of a specific spectrum and intensity are provided on the vertical axis [8,68].

Groups of permafrost state of *CPS* / Degree of impact		Stability less 0.45	Weakly stability 0.45-0.75	Unstability more 0.75
	scores	1	2	3
	score sum	score sum		
None	1	2*	3	4
Weak	2	3	4	5
Moderate	3	4	5	6
Strong	4	5	6	7

* Geoecological situations (score sum):
critical (6-7); emergency (5);
tense (4); satisfactory (2-3).

Figure 9. Matrix table of Geoecological Situations map.

The types of possible situations are defined based on the score in each matrix cell, in accordance with the expert evaluation of the occurrence of exogenous processes (based on the speed of hazardous cryogenic processes development and the area damaged by them). As a result, all cells were united into four groups on the basis of the score sum and were classified into the following geoecological situations: Satisfactory, tense (stressed), emergency, and critical. Each situation is characterized by a specific set of exogenous processes with different intensities [8,68,104]. Therefore, all the landscapes in the geoecological situations map (Figure 10) were classified into these four groups on the basis of their ability to manage different anthropogenic loads.

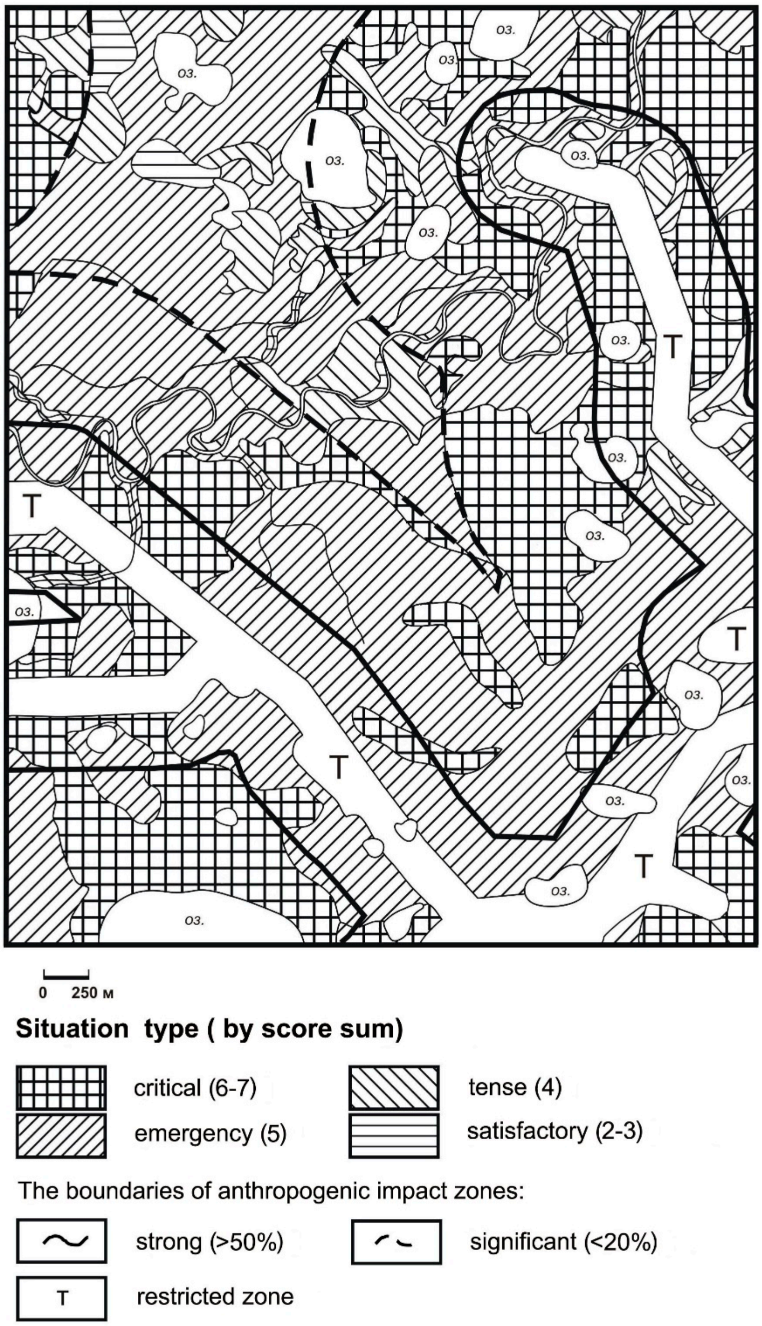

Figure 10. Fragment of the geoecological situations map for the Yamburg field.

Critical ecological situations occur when significant and poorly compensated changes occur in landscapes. This situation is formed in two cases: in the landscapes, which have unstable permafrost (gibbous hillocky and hillocky peatlands with patterned vein ice) due to significant and strong anthropogenic impacts, and in relatively unstable landscapes (tundra on dusty sands and low peatlands) within zones of strong mechanical damage. Each situation is characterized by a set of exogenous processes of different intensities. Thus, typical processes of the crisis stage in the forest-tundra of Western Siberia are: In peatlands, vein ice thawing out, deep thermokarst in patterned vein ice, peat block subsidence, intensive thermal erosion in cracks, ice thawing out in frost mounds and their turning into lakes, in bogs with low-center polygons, progressive swamping, thermokarst, seasonal, and long-term frost heave. Frost cracking (thermal erosion) is activated in cracks and intensive deflation develops with the formation of deflation basins in tundra on ice and ice-rich dusty sands with topsoil cover removed [71,104].

The duration of geoecological situations and, therefore, the degree of cryogenic processes, depends on the stages of territory development. Figure 11 depicts the growth and decline of the severity of each geoecological situation at different stages of environmental management according to information in newspapers, television, in the scientific literature [8,54,56,69,70,102–105], and the authors' own experience. It shows that rather satisfactory and intense situations last from 3–5 and up to 10 years in accordance with the time when the survey and construction occurred. Critical and crisis situations arise during the mining operation. Further destruction of the natural complex and activation of the processes occur within the first 5–10 years of commercial production of hydrocarbons. Then, cryogenic processes gradually subside, both for natural reasons and because as a result of implemented engineering and remediation measures [105].

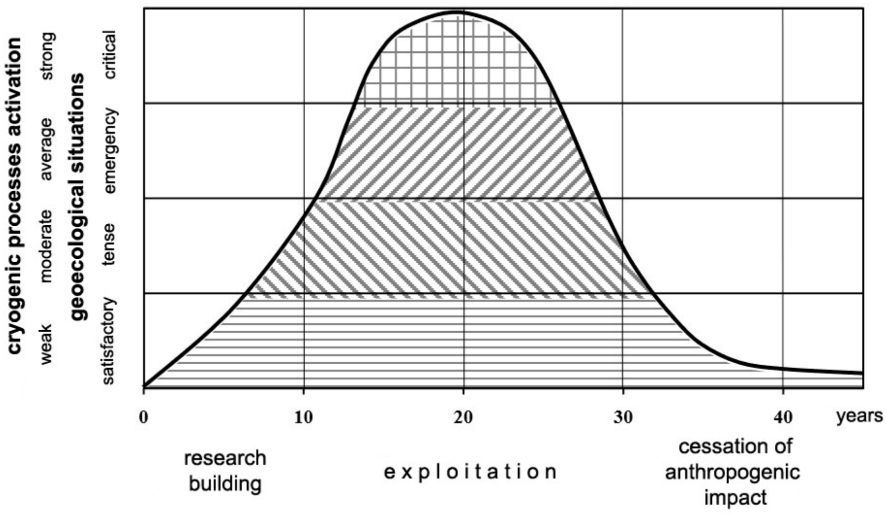

Figure 11. Types of geoecological situations depending on the stages of development and intensity of cryogenic processes manifestation.

3.2. Assessment and Mapping of Geoecological Situations at the Regional Level

On the overview-regional scale, the evaluation and mapping of ecological situations are based on the identification of territories based on permafrost, climatic, and landscape conditions and anthropogenic loading degree. The potential hazard of cryogenic processes manifestation in Russia' cryolithozone is defined by the extent of their activation and the combination of the most typical processes within various natural complexes [8,56]. The colored small-scale map of the Russia permafrost zone (Figure 12) includes five groups of potential process activation from weak to very strong. The assessment of the extent of permafrost process activation varies for plain and mountainous territories. On the plains, the estimation was applied to the whole area of a landscape. For highlands, the process activation is separated for mountainous terrain and valleys [8,58–60].

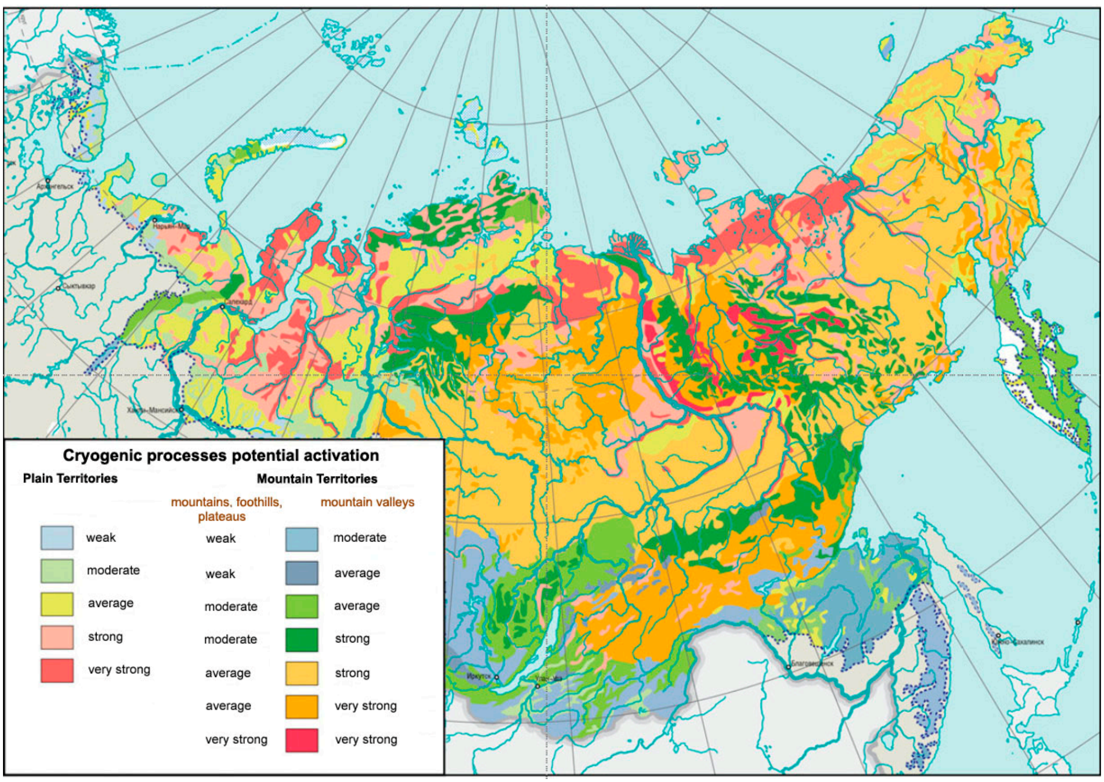

Figure 12. The map of the potential for cryogenic process occurrence.

The distribution of various combinations of the main cryogenic processes is presented in Figure 13. These combination groups are united in 11 groups according to the zone and regional varieties in the permafrost, landscape, and climatic conditions. They are characterized by different variations of the eight most ecologically and technologically hazardous and typical cryogenic processes. In the legend of this map, the first 6 groups characterize processes specific to plain landscapes, and the groups from the 7 to 11 are for mountains and foothills, including the river valleys dividing these territories [8,57]. We calculated the areas of each of the 11 process combinations. They vary within a wide range: From 25% to 4% of the Russia permafrost area. This is an important practical indicator to assess the hazard to engineering constructions due to cryogenic process activation. We divided the whole range of areas into three groups, namely, areas in which these processes accounted for more than 25%, 10–15%, and less than 10% of the area. Each group includes a significantly different combination of processes.

The diagram (Figure 14) shows the percentage of the three combination groups of cryogenic processes. The hatching shows combinations of processes in accordance with the table legend inside the map in Figure 13. Three colors (red, yellow, green) indicate three territory types of the Russian permafrost zone, grouped by combinations of hazardous cryogenic processes.

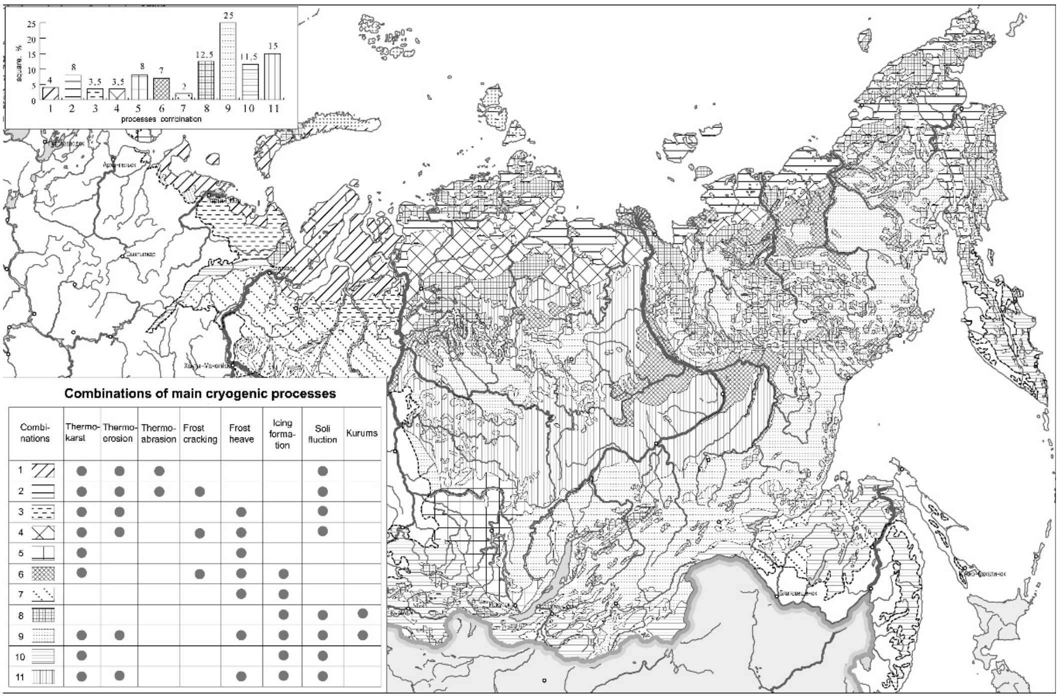

Figure 13. The map of combinations of the main cryogenic processes.

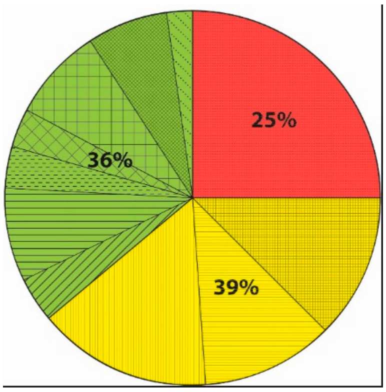

Figure 14. The combinations groups of the cryogenic processes.

Cryogenic process groups were combined according to the geomorphology of the typical conditions in their typical distribution areas (midlands, lowlands, plains, mountains). This is indicated in the subtitles of three maps (Figures 15–17).

The first group (red) occupies a quarter of the permafrost zone (Figure 17), where mountain and valley processes combine, i.e., thermokarst, thermoerosion, frost heave, icing formation, solifluction, and kurums, which are spread in a mountainous-highland belt of Central Siberia, the Far East, Baikal, and the Transbaikal ridges [56,57,69,102,103]. Highlands occupy the most part of the permafrost zone. The development of these territories is highly localized, though there are many problems with engineering constructions, but they rather rarely occur. The territories of the first group are exposed to minimal environmental hazard.

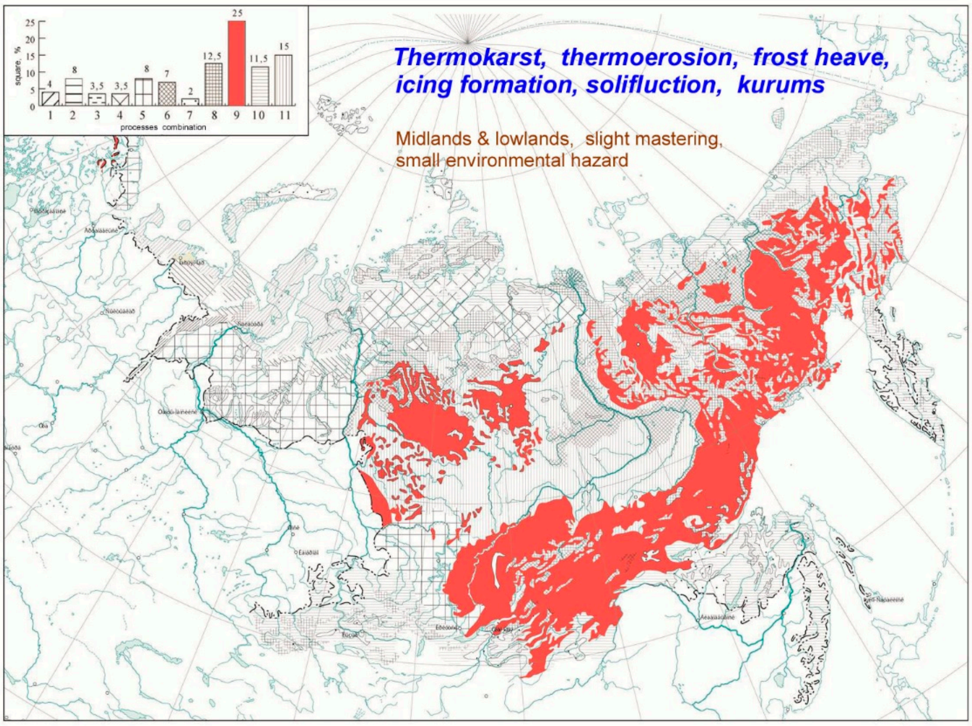

Figure 15. The first group of processes combinations (red color).

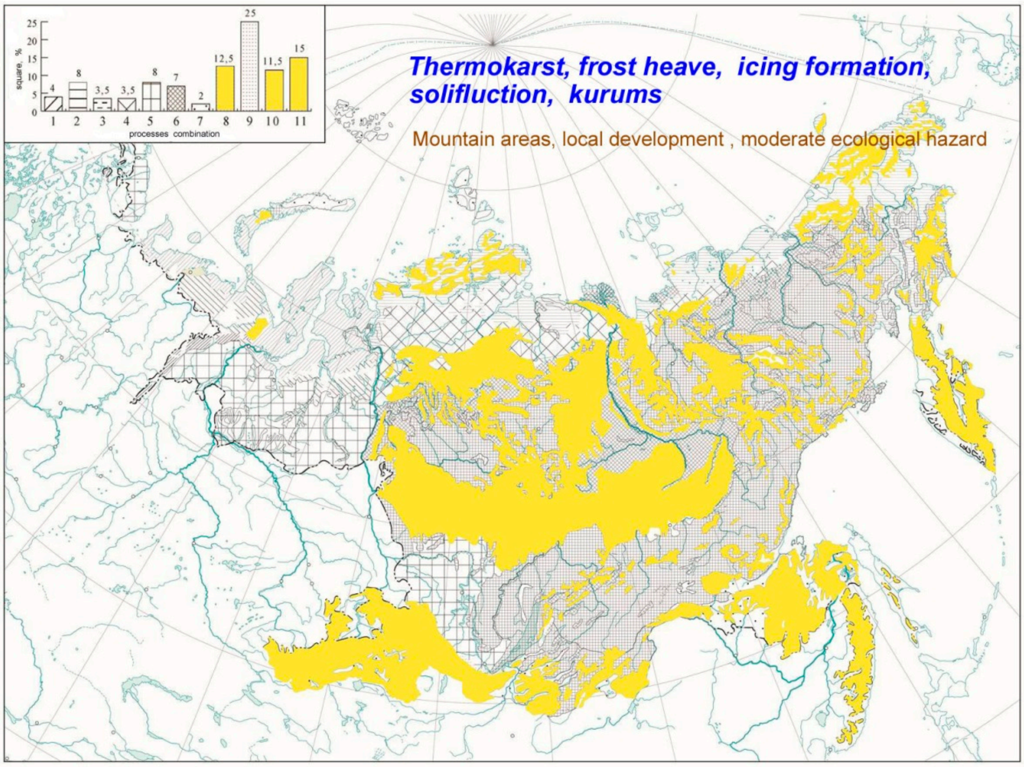

Figure 16. The second group of process combinations (yellow color).

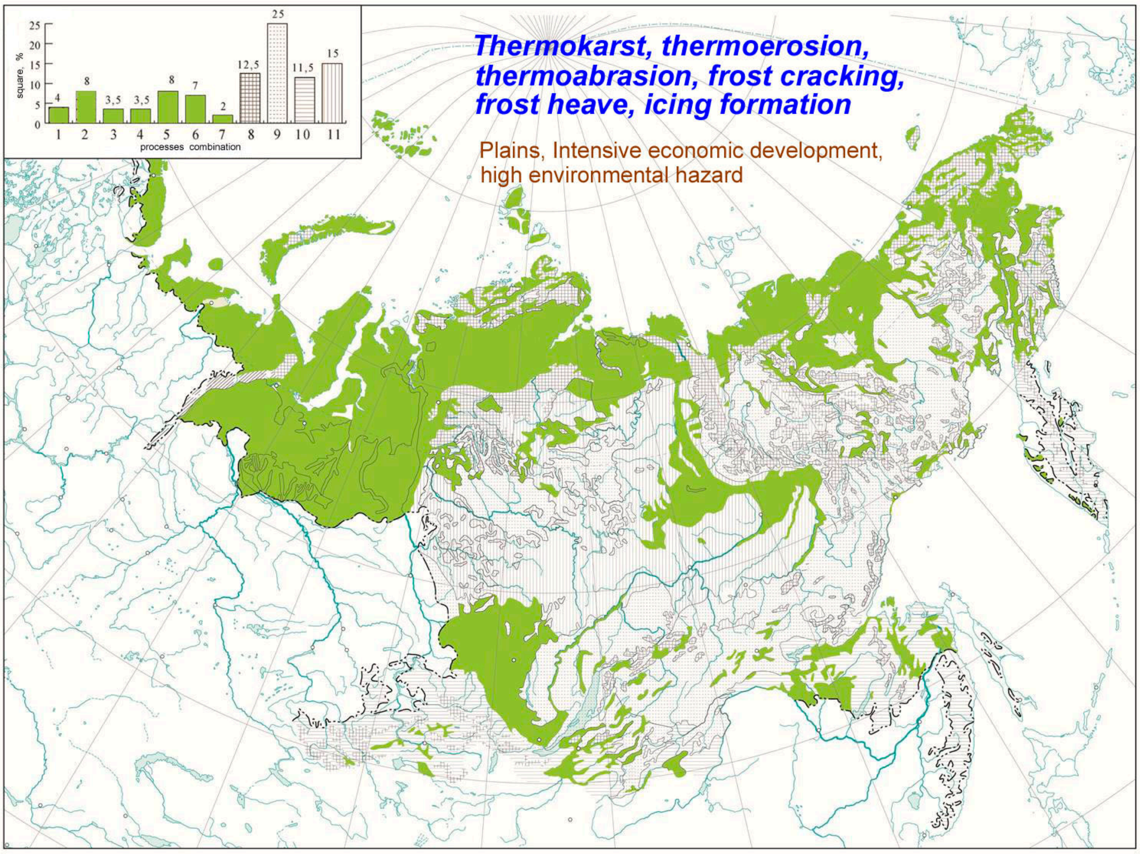

Figure 17. The third group of processes combinations (green color).

The second group (yellow) in Figure 16 includes three groups of processes combinations that occupy the greatest part of the permafrost zone at 39% (Figure 14). These are also highlands, but are different in morphology. There are highlands and loaches of the northern low mountains where slope processes and icing in the valleys are typical. Human settlements are insignificant here, so the problems caused by construction are very rare. The territories of the second group of processes are subject to moderate environmental hazard [56,57,69,102].

The third group (green) in Figure 17 comprises processes that each occupy less than 10% of the total area, but the total area of this group of processes is 36% of the Russian cryolithozone (Figure 16). The diagnostics are the most difficult for this group because it has the highest number of combinations (numbers from 1 to 7). The geomorphology of the area includes plains and mountain hollows. It is here that there is an active alteration of the territory due to mineral wealth and convenient development conditions. As a result, the area has the most active cryogenic processes. They occupy the largest areas, their speed is high, and they have multiple combinations, thus threatening engineering facilities in various ways [56,57,69,102].

Monographs on the regional analysis of different geoecological situations have been published [69, 102,103,105]. We limited our use to those with regional examples of environmental problems, which mainly occur in Western Siberia, linear objects in Yakutia, and the vicinity of Lake Baikal.

4. Discussion

Cryogenic processes are a key indicator of northern landscapes' reaction to anthropogenic disturbances. This article discusses the eight most typical relief-forming cryogenic processes that are most ecologically hazardous to infrastructure facilities. The processes that occur in summer are thermokarst processes (soil subsidence when thawing), thermoerosion (thermal and mechanical destruction of frozen rocks by water flows), thermoabrasion (hydromechanical and thermal destruction of the frozen shores of seas, lakes, and reservoirs), and solifluction (movement of seasonally thawed soils on slopes). The cryogenic processes that occur in the autumn and winter periods are frost heaves (increase in soil volume during the transition from thawed to a frozen state), icing formation (freezing with repeated outpouring of natural and technogenic waters), frost cracking (the formation of cracks in frozen soils due to compression during cooling), and kurums (accumulation of coarse material with ice on mountain slopes and rock streams) [8,82].

Each process has a different hazard degree depending on the zone and regional variation in the permafrost, landscape, and climatic conditions. The main factors that intensify cryogenic processes are listed in Tables 1–5, which clearly show that thermoerosion has the greatest influence on landscape transformation because deep surface fragmentation occurs. Solifluction, including cryogenic landslides, has the second greatest influence [106]. The most hazardous processes for engineering objects are cryogenic slip landslides and cryogenic landslides of currents and the advancement of ground masses (calculated in meters per second), while creep and closed solifluction are practically nonhazardous to economic infrastructure [107]. Of interest are some works on phytoindication mapping of landslide geosystems in the West Siberian tundra [108,109].

We found that hazardous geoecological situations in the cryolithozone are defined by an abrupt of cryogenic processes activation and radical biota change, leading to a negative change in the natural landscape and threatening the functioning of engineering structures as well as mining operations [8,30,54,68,106]. Their diagnostics are based on the consideration of (1) the degree of mechanical damage to the topsoil cover as a result of the impact of engineering structures as well as overexploitation during deer pasturing and (2) the landscape resistance to these types of damage, which includes their ability to resist the activation of cryogenic and deflation processes.

All types of evaluation studies are carried out by us on the landscape basis with the help of expert scores. The mechanical load intensity is compared with natural landscape stability gradations using the matrix method. The various intensities of anthropogenic load are ranked with regard to the development type based on type of mechanical damage, residual deer capacity, the vegetation recovery rate, and the share of disturbed land.

We chose leading factors typified by three or four development risk gradations and then compared different methods with the aim of landscape sustainability assessment. Different mathematical methods were used to detect the interrelation of the factors: Correlation, regression, cluster analysis. The number and the spectrum of these factors vary depending on the regional characteristics and the research scope.

The following parameters are important in the northern regions: permafrost distribution area and profile, annual mean temperature and permafrost thickness, the cryogenic structure of the upper part of the permafrost, cryogenic forms of the relief, and layer of seasonal thawing and freezing. The limits of permafrost are important, because as the boundaries of permafrost quality change, so does its stability.

The most significant permafrost factors at the overview-regional scale are listed below.

1. In geocryology, permafrost typization depends on the area it occupies. The permafrost distribution area is estimated as a percentage of the total landscape area: Continuous permafrost covers more than 90—95%, interrupted permafrost covers 50—95%, massive-island permafrost covers between 5% and 10—15%, and sporadic permafrost covers less than 5%.
2. The annual mean temperature of the permafrost from less than −11 to 0 °C has separate scales for plains and mountains. The most frequently used temperature scale is divided into the ranges 0–1 °C, −1 to −2 (3) °C, −2 (3) to −5 °C, −5 to −10 °C, and below −10 °C (3).
3. Ice content permafrost is estimated in parts or as a percentage. The most common ranges are less than 20%, 20—50%, and more than 50%.

A situation's hazard severity due to cryogenic process activation increases as the area and ice content of the permafrost increase and as the permafrost temperature approaches 0 °C.

The basis for the diagnostics and mapping of geoecological situations is landscapes, and the diagnostics instrument is the thawing depth. We chose the latter as the most sensitive indicator of a situation's change in space and time. However, the active layer is not the starting point for assessing the degradation of permafrost. Before the layer of seasonal thawing increases in width, the average annual temperature of the rocks increases. These increases occur not only in summer, but also in winter.

Thus, the diagnosis of geoecological situations at a review level is based on the assessment of the activation of anthropogenic cryogenic processes by taking into account the speed of their development, damage to natural landscapes, and threats to the functioning of engineering structures.

For the first time, we simultaneously considered the geographical aspects of various combinations of hazardous cryogenic processes for the entire Russian permafrost zone, which occupies more than 10 million km^2. Previous studies have performed either the large-scale mapping of individual regions or the mapping of a single cryogenic process. Contrary to these methods, we used a broad range of data on the thermal insulating properties of ground vegetation. The possibility of determining the system connection between permafrost and landscapes for small-scale mapping is also demonstrated in this article for the first time.

At the local level, the range in estimative factors is wider. The ice content degree and temperature of the permafrost, the depth of seasonal thawing or freezing, the relief, the heat-insulating properties of the vegetation and the rate of its self-recovery, and the bioclimatic indicators are all influential factors. During the process of evaluative mapping of the permafrost contents, various techniques were used: Methods of statistical calculations, indicative signs, maps-indicators, scientific hypotheses, and extrapolations. The ecological indicators are generally defined based on expert estimates and rely on the long-term experience of regional research. Based on our analysis of the chosen factors, we calculated the integrated indicator of their cumulative influence. This value can be either the simple sum of factor points, their geometric mean, or the calculated coefficient developed in the multiple regression equation. For determining point dimension, we proposed the use of a percentage-based scale. The graphic-analytical method of assigning scores out of 100 allowed us to provide numerical scores on difficultly comparable scales, as well as to supplement traditional points with an estimate of their own weight.

For large-scale mapping, this article presents an original method for comparing natural factors that affect the activation of hazardous processes, as well as a matrix evaluation of geoecological situations, by considering the calculated indices of the danger and intensity of anthropogenic loads.

This article presents a number of evaluation maps, which were compiled by the authors, of an overview-regional scale for the entire Russian permafrost zone (Figures 12, 13 and 15–17). Geoecological situation zoning was performed by synthesizing two factors—geocryological and landscape factors. Small-scale mapping has been successfully carried out in separate regions, including the territory of Yakutia [33,39,51], Alaska [14,95], and the Arctic zone of Russia [40,41,99]. However, only the Faculty of Geography, Lomonosov Moscow State University, has carried this out for the whole cryolithozone of Russia [58–63].

The creation of the submitted overview-regional scale zoning maps of cryogenic process activation of Russia's vast territory requires a large amount of data. Besides cryogenic characteristics (ice content, ground average annual temperature, the active-layer thickness), the data applied in this study include the climate data of hydrometeorological networks; different scales of geological, geobotanical, soil, and landscape maps, among other map types; and remote sensing materials. The mapping work used the output of permafrost monitoring studies at key sites, including the materials obtained by drilling and geophysical methods. We also used modeling and calculation methods.

The comparison and synthesis of a large amount of information are advised to be carried out with the help of landscape classifications and geoinformation mapping. The most well-known geocryological maps, such as "The Geocryological Map of the USSR" [86] and "The Circum-Arctic map of permafrost and ground-ice conditions" [88], indirectly used the landscape method. The only conditional permafrost map that fully utilizes regional landscape differentiation is the updated "Permafrost-Landscape Map of the Republic of Sakha (Yakutia) on a Scale 1:1,500,000" [43], part of the maps of Tibet [13,26], and a number of maps created by the Institute of Earth's Cryosphere [47,49].

5. Conclusions

The ecological component of the majority of geocryological research consists of the assessment of the manifestation of cryogenic processes that are observed in nature. We mapped the cryoecological state by identifying areas of anthropogenically provoked cryogenic processes. Scientific and methodological approaches of this evaluation can be applied to engineering geocryology, the predesign stages of research, and strategic decision-making by environmental organizations for cryolithozone development.

Human activity in the Arctic regions, if not adjusted, can quickly turn the highly inhabited circumpolar belt into a monotonous "gray-brown artificial desert". Such transitions have been observed in the Norilsk and Monchegorsk regions, among others. Therefore, it is necessary to create a larger number of bioresource reserves with strict protection regimes for biodiversity conservation in the Russian permafrost zone [110,111].

It should be noted that research on the local level (primarily in the oil and gas fields for infrastructure and ecosystem planning) has extensively mapped predictive cryogenic process activation on a landscape basis [31,35,37–39,48,50,68]. Such maps at the global and regional level have been compiled and published significantly less often [36,42,43,47,58–63,88].

The main topic of this paper focuses on digital evaluation maps, the detail and scale of which correspond to geographical atlas mapping using «Illustrator» and ArgGIS software. Landscapes and permafrost characteristics were corrected by using information from key sites (Figure 2) and satellite images. Overlay layers of different types of development (transport routes, mining complexes, etc.) will make it possible to more specifically predict the occurrence of hazardous geoecological situations. It is also possible to forecast permafrost-ecological situations by studying evolutionary climate trends.

The atlas maps, designed on a common landscape basis, have universal value, allowing us to arrange, analyze, and generalize information about permafrost zone landscapes for environmental management. Their content, the chosen indicators, classifications, and gradation of values were developed considering the possibility of their further application in geoecological estimates and for administrative decision-making. They are actively used in the educational process as visual aids.

Author Contributions: N.T. developed the ideas of atlas mapping and the content of small-scale legends and maps. Writing—Original Draft Preparation. L.Z. developed the technique of large-scale evaluation and mapping along with the methods of expert numerical scores development, as well as Writing—review and editing.

Acknowledgments: This research was supported by Russian Science Foundation grant No. 18-05-60080. The authors express deep gratitude to Natalia Koroleva for her professional cartographical work and gratitude to anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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