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Temporal and Spatial Geophysical Data Analysis in the Issues of Natural Hazards and Risk Assessment (in Example of North Ossetia, Russia)

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Abstract: The paper considers the aspects of hazard assessment within the framework of a generalized approach. The aim of the study is to improve the methodology for more accurate and detailed probabilistic assessments of risks of various nature. A complex hazard map is constructed in an example of the territory of the Republic of North Ossetia-Alania and the construction site of the Mamison resort. Based on the analysis of data on Quaternary formations and quantitative estimates, it was concluded that the natural average static environmental evolution proceeds in the mode of the dynamic balance of two factors: mountain building and the equivalent increase in denudation, of which about 90% is transported and deposited by river waters and winds outside the territory. The remaining 10% is deposited in intermountain depressions and river valleys in situ. Geodynamic and climatic factors of influence on the geoenvironment create the danger of excessive environmental impact and disruption of its equilibrium development under anthropogenic impacts, which must be taken into account in designing.

Keywords: natural hazards; landslides; mudflows; avalanches; zonation; geophysical data; geomorphological conditions

Citation: Melkov, D.; Zaalishvili, V.; Burdzieva, O.; Kanukov, A. Temporal and Spatial Geophysical Data Analysis in the Issues of Natural Hazards and Risk Assessment (in Example of North Ossetia, Russia). *Appl. Sci.* **2022**, *12*, 2790. https://doi.org/10.3390/app12062790

Academic Editors: Alexei Gvishiani and Boris Dzeboev

Received: 1 February 2022
Accepted: 4 March 2022
Published: 9 March 2022

1. Introduction

The analysis of approaches to the assessment of natural hazards of various nature, used in the world, showed the following. There are no generally multi-hazard approaches: the spatial representation of natural disasters must consider all types of hazards with the help of a multi-risk approach at all spatial levels (regional and local). With few exceptions (France, Italy), the multi-risk approach is not used due to the differences in the responsibilities of sectoral planning departments for different disasters.

The intensity of the attention given to natural disasters usually depends on the experience of recent catastrophic events rather than the occurrence of catastrophic events in the more distant past (the Kolka glacier collapse in 2002, which repeated the 1902 collapse scenario). As a result, risk assessment and management are focused on more frequent hazards (river floods, avalanches, forest fires) than on less frequent events. This leads to a tendency to underestimate the hazard and risk posed by extreme events.

At present, spatial planning plays only a minor role in risk management: at the regional level, various sectoral planning departments are responsible for natural risk management. Regional planning is often just one of the subsidiary entities charged with the duty of ensuring the implementation of measures that are carried out by sectoral planning units.

Geohazards can be formed through continuous natural processes, such as weathering or erosion [1], though they are predominately created and accelerated by anthropogenic activity [2]. Geohazards that have occurred, and been thoroughly investigated to determine their source, can be used to predict vulnerability in similar formations and situations elsewhere [3] and to extend this knowledge to areas not yet developed. There are a number of works where geohazard mapping has been developed using multi-form, digital image data, permitting a regional assessment of risk concerning slope instability. Slope angle and slope aspect data were derived from a digital elevation model (DEM), produced from stereo air photographs. The geohazard map was then compiled by merging digital slope data with geotechnical characteristics, using map algebra within a geographic information system (GIS) [4–7]. An important aspect of the geohazard study is identifying the temporal and spatial distribution of zones liable (prone) to movement, including the location of potential slip surfaces.

The methodology adopted for the landslide hazard zonation of the study area includes the various geoinformatical tools comprising geographical information system (GIS) technology and the satellite remote sensing (RS) techniques [8]. Geomorphological parameters (elevation, slope, aspect, curvature) and drainage are widely extracted from a DEM based on the Shuttle Radar Topography Mission (SRTM) [5]. Furthermore, the use of GIS facilitated the extraction of geomorphic and hydrological parameters required for susceptibility assessment. More detailed DEM may be obtained using low altitude UAV photogrammetry [9]. All of the mentioned techniques are itself of data collection and should be supplemented by geophysical data, expressed in the manifestation of processes in physical fields, and on the other hand, the results of their interpretation in the form of tectonic schemes, fault schemes, geological structures, and geotechnical parameters.

A methodology for the comprehensive assessment of geological hazards of various nature on the basis of the method of expert assessments is proposed in the present paper. The relevance of the topic is caused by the fact that the territory of North Ossetia is prone to the destructive effects of almost all known types of hazardous geological processes that can lead to the death of people and enormous material losses, having a significant impact on the socio-economic situation and safety of the territory of the republic. This is due to the great variety of geological, morphological, climatic, and overall landscape conditions of the mainly mountainous territory of North Ossetia. Vivid examples are the collapse of the Kolka glacier in 2002, the collapse in the area of the Devdorak glacier in 2014, and the activation of the Matsuta landslide in 2019.

Various natural hazards and the risks of loss caused by them in different spheres are divided according to the occurrence area into geological, hydrological, meteorological, biological, and mixed. Many of them are closely interrelated, being either the main condition or the cause (impetus) of the origin and development of secondary natural hazards, often leading to greater losses than the primary hazardous natural and man-made processes that caused them. Despite significant genetic differences, all these hazards have a number of important common features (from the standpoint of forecasting and subsequent risk assessment), which consist in the uniformity of their sources in terms of the occurrence area and the nature of impacts in time and space (autochthonous or allochthonous, simultaneous or permanent).

The object of study is dangerous natural processes in the North Ossetia-Alania and adjacent regions of the North Caucasus. The aim of the study is to improve the methodology and obtain on this basis more accurate and detailed probabilistic assessments of risks of various nature.

Scientifically substantiated forecast of environmental state, based on the current endogenous geodynamic activity and the development of various genetic types of hazardous exogenous geological processes determines the relevance of ensuring the safety of the functioning and development of the tourist and recreational complex “Mamison”. The territory was well investigated and provided detailed data for analysis. So different levels of complex natural hazard had been considered, from the Republic of the North Ossetia-Alania with major natural factors to Mamison resort construction region with the number of factors increased up to 27.

2. Geographical and Geological Setting

The Republic of North Ossetia-Alania is located in the south of the Russian Federation, on the northern slope of the Greater Caucasus (the eastern part of the Central Caucasus) and on the sloping plains adjacent to it between 43°50′–42°50′ north latitude and 43°25′–44°57′ east longitude (Figure 1).

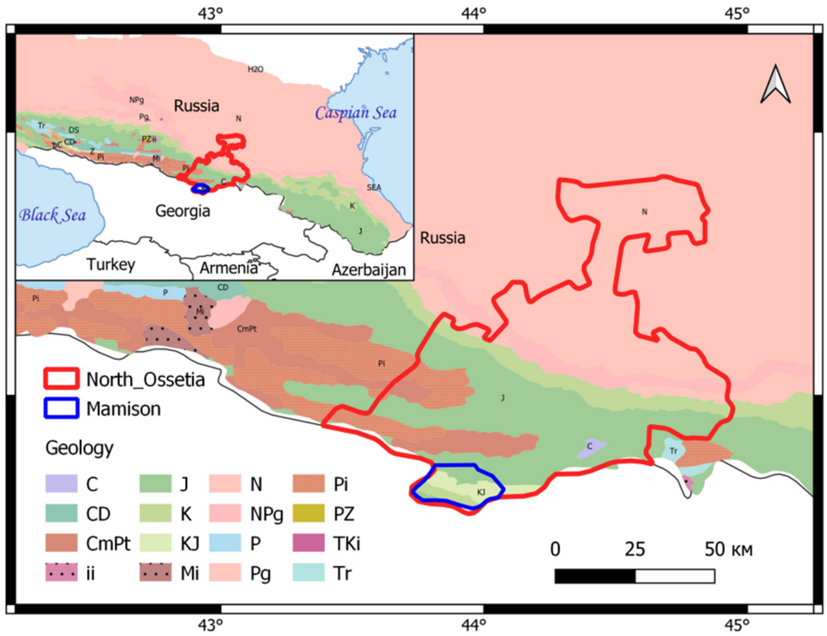


Figure 1. Geographical and geological setting of the study area: geologic scheme of the North Caucasus (modified from the work of [10]) and location of the Republic of the North Ossetia-Alania.

The Republic of North Ossetia-Alania occupies a special geopolitical and transport-geographical position in the south of Russia. It is due to the border position and the central place in the system of ciscaucasian and transcaucasian transport corridors [11]. A variety of sedimentary, igneous, and metamorphic rocks, from Precambrian to modern, take part in the geological structure of the territory of North Ossetia. There are three structural and formational levels: Caledonian-Hercynian, which includes geological formations from Precambrian to Lower Jurassic, Lower Alpine (Lower Middle Jurassic), and Upper Alpine from Upper Jurassic to modern rocks.

The Precambrian within the republic is unknown. Crystalline schists and gneisses of the river basin. The Ardon (Buron Formation) is defined as Precambrian only on the basis of analogy with the crystalline formations of the Western Caucasus. The Middle Paleozoic includes the Kasar Formation of the outcrop of metamorphic shales, which form a strip 2–3 km wide in the upper reaches of the Tsei, Ardon, and Bad rivers.

A very large and increasing in time and space for the socio-economic development of the republic, in contrast to world and Russian features, are natural emergencies, such as hazardous atmospheric phenomena, floods and avalanches, and some other hazardous natural and man-made natural processes. This is due to the great variety of geological, morphological, climatic, and overall landscape conditions of the predominantly mountainous territory of North Ossetia. The situation is aggravated by powerful anthropogenic pressure, which provokes the emergence, qualitative and quantitative growth of natural and natural-technogenic emergencies.

The territory of the proposed construction of a recreational complex "Mamison" is part of the Alagir district of North Ossetia-Alania, unites 13 settlements with a total population of 110 people for 2020 as part of the local government of the Zaramagsky rural settlement (village N. Zaramag), located in the upper reaches of the river. Ardon on the northern slope of the main range of the Greater Caucasus (Figure 1). The area is sparsely populated. There are no resources for industrial and agricultural development, and the mining industry is unprofitable. At the same time, the region has prospects for economic development due to the maximum use of the natural and climatic resources of the territory in an environmentally safe mode. This resource consists of: unique natural and climatic conditions for the organization of an all-season ski complex and tourist routes of various categories of difficulty along the objects of the geopark; numerous mineral springs (waters carbonic hydrocarbonate, sodium-calcium), the largest of which are: Kartysuar, Kalak, Kamskho, Dvugolovy, Lisri and Tib-1, Tib-2.

3. Materials and Methods

The methodological substantiation of the research is based on modern theoretical and empirical ideas about geodynamic processes, structural-tectonic and lithological features of the geological environment, a complex of physical-mechanical, geophysical, and geochemical characteristics of rocks and their physical fields [12]. The determining factor of the methodological basis of the research is also geomorphology, the influence of which on the intensity of exogenous processes formation depends on the ability of relief elements to collapse and on the conditions for the accumulation of erosive material by landforms [6].

Multi-criteria evaluation (MCE) involves the assessment, weighting, and aggregation of the attributes in a collective rather than sequential way. Certain factors (or attributes) are suspected as having a greater effect on slope stability or other exogenous processes than others. The assessment of their relative importance involves the derivation of a series of weighting coefficients. These factor weights control the effect that each factor has on the outcome. The relative significance of each factor and its influence on the system concerning the other factors need to be evaluated. The factors are ordered into a hierarchy of significance with respect to their relative influence on each process. This has been done using a comparison matrix whereby each factor is rated according to its significance relative to every other factor in the matrix [4].

Many factors (geological type, topography, presence of hazardous processes) were taken into account to form the rating of the identified taxa. According to the developed approach, the set of conditions is divided into several levels of vulnerability. Each level corresponds to the values of hazards that form vulnerability. In other words, we used the expert assessment. Further, each factor value was assigned its weight rating, also established from past experience. The following ratio was used to calculate the vulnerability rating [13]:

$$W = W_i \times D_i / S, \quad (1)$$

where W_i is the weight of i-th factor, Di represents subclass weight of ith factor, and S is the spatial unit of the final map.

The weighted overlay method (WOM) is a simple and direct tool of Arc GIS to produce susceptibility maps [5,13,14]. Many researchers used WOM to produce a landslide susceptibility map [15–17]. All layers were combined by using the weighted overlay tool based on Equation (1). In this paper, the number of the considered factors, based on the relevant databases was 27 different parameters (of 4 classes: endogenous, lithological, geomorphological factors, and factors of exogenous and natural-climatic nature). The algorithms used to recognize hazardous geodynamic and atmospheric-climatic processes affecting the environmental state of high mountain landscapes are shown in Figure 2 [17]. In the work of [18], performed for the territory of the Krasnodar Territory, the number of the considered factors was 9 indicators, for landslide hazard assessment number of parameters varies from 5 for Mussoorie Township case study [19] to8 factors in the work of [20] for Indian Himalaya.

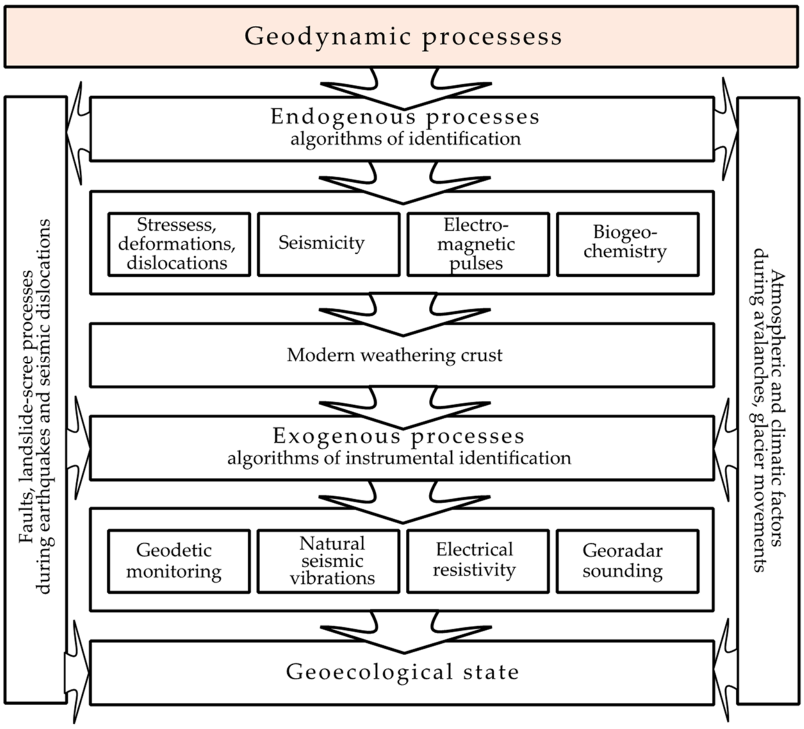


Figure 2. Algorithms for recognizing hazardous geodynamic processes affecting the environmental state of high mountain landscapes.

The weight of each factor is set based on the expert rule approach [21–29]. Or weights may be calculated on the basis of cases study (In [30], statistical procedure consisted in calculating a landslide frequency per class area expressed in percentage, i.e., number of landslide pixels.km^{-2} $\times$ 100). Logistic function may be used to weight factors is a suitable example of weights calculations based on landslides distribution data [31].

The geological environment is heterogeneous, consisting of voids, fluids, layers, blocks with a different stress state, so rhythms and catastrophes are propagated in the environment in different ways. To study all these processes, geophysical monitoring is required, and as a special case, seismic monitoring [17,32–37], gravity monitoring [38], combined geoelectric and geoelectromagnetic monitoring [39].

Promising directions of methodological solution of spatial-temporal intervals of endogenous events, their dynamic and kinematic characteristics, scales, and features of their course are considered as the basis for creating a verified database of geological, hydrogeological, seismotectonic, and technogenic processes for a comprehensive generalization of the degree of their impact on construction objects and infrastructure elements. The methodology for providing geological information stipulates the collection and processing of engineering survey materials of past years. At the same time, an important role is given to the interpretation of remote materials, including materials from traditional surveys [40].

The formation and interrelationship of erosion hazardous geological processes and their impact on the environment of high mountain areas are shown in Figure 3. The location of the investigated area in the zone of alpine tectonomagmatic activation of the Greater Caucasus determines the complex engineering and geological conditions inherent in the areas of alpine folding, caused by the diversity of the lithological composition of rocks, their intense tectonic disturbance, active neotectonics and seismicity, and the wide development of modern exogenous geological processes (Figure 3) [41,42].

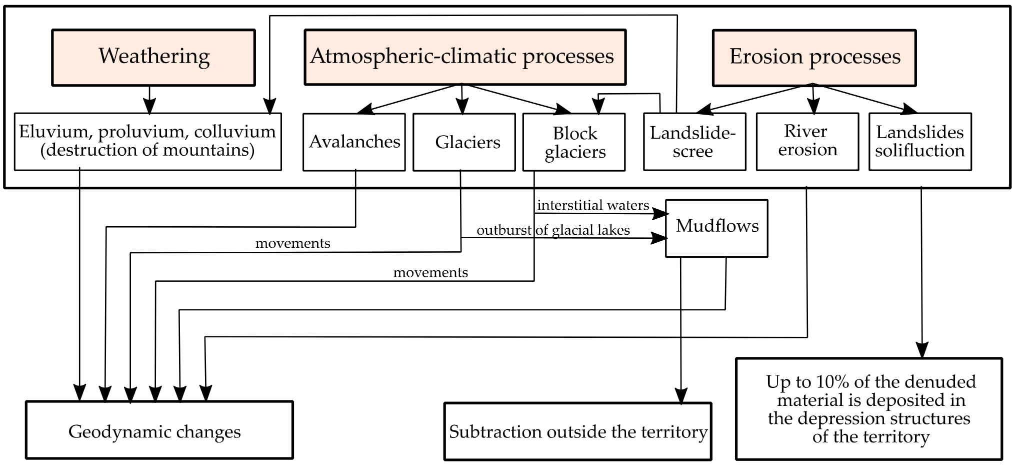


Figure 3. Typical hazardous natural exogenous geological processes of impact on the environmenta lstate of high mountain areas.

Information about genetic types, spatial and quantitative characteristics, the state of objects of hazardous exogenous geological processes are the main initial data for the pre-project solution of engineering surveys [43–45] and can be used to develop security measures and planning by security management structures [46–49]. The following exogenous geological processes are common for the territory: weathering, erosion, mudflow and gravitational (landslide, landfall), avalanche, solifluction, suffusion [43].

Weathering is the most common geological process. Liasshales and flysch rocks are especially intensively weathered. Sandstones, siltstones, and limestones break up into separate blocks and pieces. The process is widely developed over the entire area, both on its ridge sections and the slopes; it is especially manifested along rupture tectonic faults and zones of their influence. This is the main source of clastic material for the formation of mudflows, landslides, and the formation of slope deposits of various genetic types and eluvial on the ridge and peri-ridge parts of the territory [43].

Erosion processes are widely developed throughout the territory. They include sheet erosion, gully, lateral and bottom erosion of rivers. The activation of erosion processes on a regional scale is associated with the modern tectonic uplift of the Greater Caucasus orogen, estimated at rates from 2 to 14 mm/year [43]. Ascending movements increase the overall energy of the landform, which is already quite high. In high mountain areas, the length of the erosional pattern is 2.5–3.4 km/km^2, and the depth of local erosion bases reaches 1000–1500 m. Under these conditions, water flows are characterized by high speed (up to 3 m/s and more) and perform significant erosion activity [45].

The history of North Ossetia is replete with a sufficient number of facts testifying to the susceptibility of the territory of the republic to the destructive effects of almost all known types of dangerous geological, hydrometeorological, and biological processes that lead to the death of people and huge material losses, have a significant impact on the socio-economic situation and security of the territory of the republic.

The total average long-term economic damage to the republic from these dangers currently reaches 1% of the republic's GRP [11].

The cyclic nature of natural phenomena and processes creates conditions for the occurrence of emergencies that are typical for the territory of the republic. The following most significant hazardous natural processes, which are a manifestation of a number of factors (meteorological, hydrological, geomorphological), can be distinguished in Table 1, Figure 4 [11].

Table 1. Recurrence of the hazardous natural processes on the territory of North Ossetia-Alania (modified from the work of [11]).

Type of Emergency Situation	Return Period	Notes
Earthquakes	1/100 years	The catastrophic manifestation of the natural process is considered
Landslide processes	1/10–20 years	Annually, individual landslides depending on the structure
Mudflows	1/10–15 years	Individual mudflows at 5–7 years
Avalanche process	1/10 years	A number of avalanches occurs every year

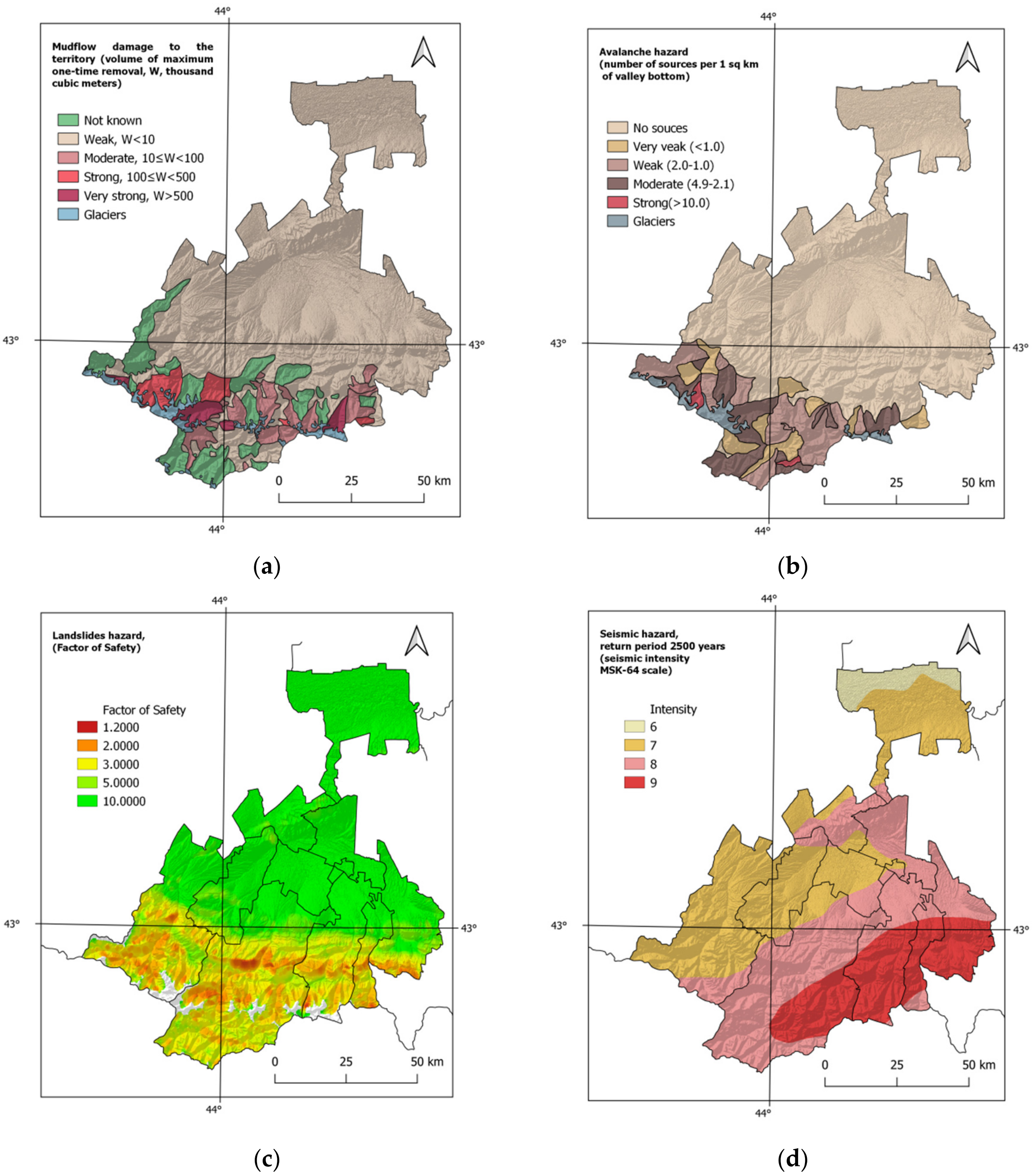


Figure 4. (**a**)Scheme of mudflow hazardous zones of North Ossetia-Alania; (**b**) scheme of avalanche hazard on the territory of North Ossetia-Alania [33]; (**c**) assessment of the potential landslide hazard of the territory of North Ossetia-Alania in the form of a safety factor F; (**d**) seismic hazard map of the territory of North Ossetia-Alania, intensity with 5% exceedance probability.

3.1. Mudflows

Mountainous Ossetia is one of the most mudflow-prone regions of the Central Caucasus. The strongly dissected topography, modern glaciation, high seismicity, huge reserves of loose-clastic material, and high moisture content create favorable conditions for mudflow formation (Figure 4a) [50]. A total of 60% of the territory of North Ossetia-Alania is subjected or may be subjected to the passage of mudflows of varying hazard levels. At the same time, huge damage is caused to settlements, agricultural lands and facilities, industrial enterprises, communication and power lines, sports and recreation facilities, and highways.

The following genetic groups of mudflow centers are developed: associated with the accumulation of loose-clastic material in the channels of temporary and small flows; associated with the damming of rivers and with the activity of modern glaciers.

Observations of mudflows in the main basins of the Mamisondon and Zrug rivers for the period of the last regular observations from 2004 to 2014 show a steady increase in the number of mudflows and their total volume (Figure 5).

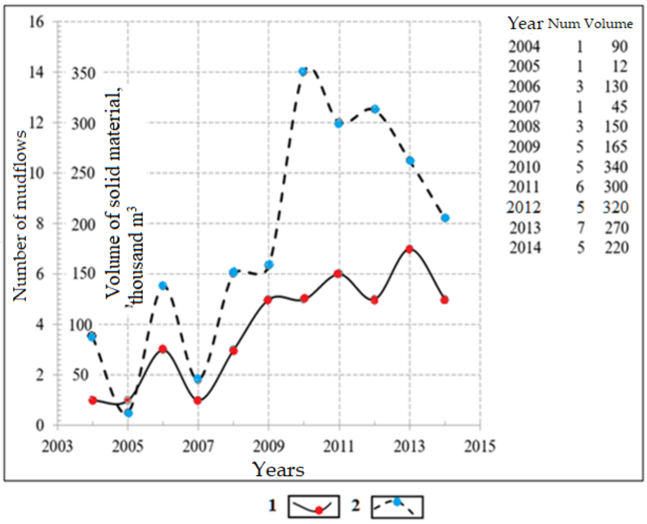


Figure 5. The frequency of mudflows in the basins of the Mamisondon and Zrug rivers by years for the period 2004–2014: 1—number of mudflows per year; 2—volume (thousand m^3) of solid material removal.

3.2. Avalanches

The altitudinal extent of climatic regions (plain, foothill, and mountainous) on the territory of the republic has a great influence on the nature of the occurrence and formation of snow cover. An analysis of the conditions of snow accumulation on the mountain slopes in the republic shows that there is a snow cover with a thickness of 40 cm or more in most of its mountainous territory. In practice, it has been determined that the existence of such a snow cover on slopes exceeding 15° causes avalanches [43].

An active zone of avalanches on the territory of the republic covers a wide range of altitudes from 1200 to 3800 m above sea level, with an average steepness of slopes from 15° to 76°. The highest relative height of the avalanching varies in a wide range from 1060 to 2060 m above sea level. The total number of avalanche sources on the territory of the republic is 688. The volume of snow carried by avalanches ranges from 500 to 1,500,000 m^3, and the maximum possible impact force of an avalanche on a fixed obstacle can reach 131 t/m^2. Each avalanche source on the territory of the republic produces an average of two avalanches per year, which indicates a high avalanche activity in the mountains of North Ossetia-Alania [43].

The duration of the avalanche period in the zone of the most active avalanche formation at altitudes above 2000 m above sea level can be up to 210 days (from November to

May). At the same time, the maximum development of avalanche processes is observed in January–February, and the minimum number of avalanches and the total volume of snow being removed falls on April–May since in most avalanche areas, the snow has already melted by this time. In the zone of average avalanche activity at lower absolute heights, the duration of the avalanche period is reduced to 90 days or less. At the same time, the maximum avalanches in this zone are usually observed in December–January. At the lower boundary of the zone of systematic avalanches, the period is usually 15–20 days [33].

3.3. Landslides

The landslide process is one of the many forms of geological matter evolution. The causes of landslides are divided into two groups: random (scholastic) and expected. The first group includes such fast-moving factors as precipitation, abrasion, erosion, earthquakes, and man-made factors. The regularity of the landslide process reflects the features and mode of rocks occurrence, tectonic disturbances that gradually develop in these rocks, and the appearance of stress fields in them. The ratio of both factors leads to the accumulation of anomalous stresses in rocks, which causes landslides.

Among 350 landslides explored in the mountains of North Ossetia, the following are distinguished by size: small (up to 1 thousand cubic meters), medium (up to 100 thousand cubic meters), large (up to 1 million cubic meters), and very large (with a volume of more than 1 million cubic meters). Examples of very large landslides are the Luar, Donifars, and N. Nar landslides.

The main factor of landslide processes activation is the excessive watering of the slopes, which occurs during snowmelt and heavy rains (Figure 6). A sharp increase in river runoff contributes significantly to the activity of landslides; as a result, the erosion and destruction of the frontal parts of landslides occur, which often leads to the displacements of the overlying masses, as was observed on the Luar landslide in 1984 and on the Matsuta landslide in 1991.

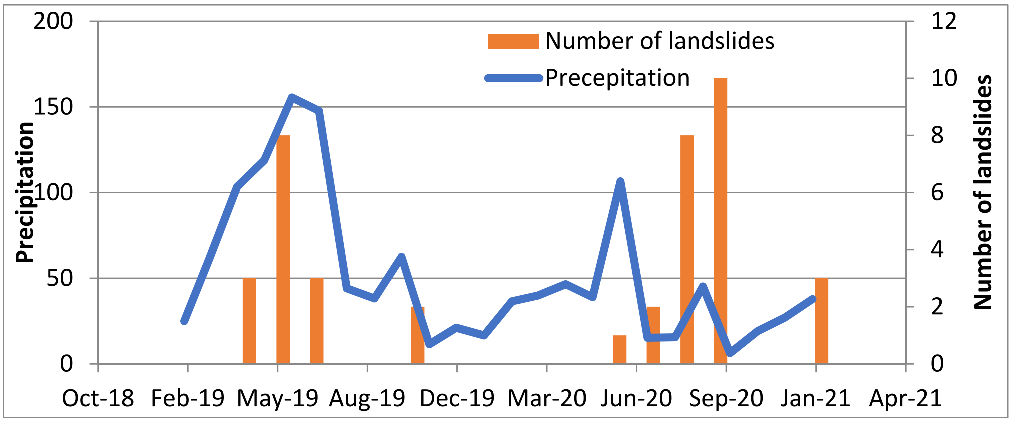


Figure 6. Monthly precipitation and the number of landslides in the Alagir region of North Ossetia-Alania in 2019–2020.

A noticeable increase in landslide activity is caused by seismic impacts associated with modern tectonic movements. In particular, the movements of the Matsuta and Donifars landslides in 1990 and the Ursdon landslide in 1993 are associated with tectonic movements. A retrospective analysis of the formation and large activation of landslides in the 20th century indicates that some of them are directly related to earthquakes (Dallagkau landslide, 1905; Korinskiy landslide, 1915; Turmonskiy landslide, 1981).

Slope stability was assessed for the territory of North Ossetia on a scale of 1:200,000. The average values of rock properties were used to identify the most hazardous zones for further detailed analysis. There was used the Scoops3D program, which makes it possible to assess the stability of slopes in a three-dimensional setting based on digital elevation models. The elevation model was built on the basis of SRTM satellite data. To perform calculations throughout the entire territory, a digital elevation model was compiled, the resolution was reduced to 200 m.

Scoops3D is a computer program developed by the United States Geological Survey (USGS) for analyzing slope stability across the entire digital landscape, represented by a digital elevation model (DEM). It detects large numbers and calculates the stability of 3D potential landslides covering a wide range of depths and volumes. Scoops3D uses a three-dimensional "column method" of limited equilibrium analysis to calculate the resilience of potential slope failures (landslides) with a spherical potential slip area. The approach was originally described in the work of [51]. The results of Scoops3D analysis show the minimum safety factor (stability index) for potential slip areas affecting each DEM cell throughout the landscape, as well as for volumes or areas associated with these potential damages of slopes.

Scoops3D allows the user to choose between two well-known geotechnical methods of the moment equilibrium for calculating the stability of a rotating surface. Bishop's method was used in our calculations. When performing a slope stability analysis, Scoops3D calculates the shear strength s on the test surface using the Coulomb-Terzaghi linear fracture rule [52].

Scoops3D calculates the safety factor F for a given test surface using moment equilibrium [52]. In general, all limited equilibrium methods (including moment equilibrium methods) define F as the ratio of the average shear strength s to the shear stress τ required for maintaining limit equilibrium along a predetermined test surface [53]:

$$F = s/\tau. \tag{2}$$

F values less than one indicate instability. A fixed 1/F ratio of the available shear strength is opposed to the shear stress at equilibrium (fundamental assumption of the method).

As a result, the assessment of the value of the safety factor F is obtained (Figure 4c) for each element of the terrain model (excluding boundary elements). For altitudes above 3500 m, the calculations were not performed (white zones in the figure). The sites characterized by the greatest danger (minimum F values) are located in the well-known areas-Tsey, Unal-Sadon, and Buron sites. In addition, separate point areas have been identified, which have not been previously studied due to their remoteness from infrastructure facilities. A detailed study of the properties of rocks and topographic survey (including the use of unmanned photogrammetry) will allow assessing their stability more accurately.

Rockslide-talus processes are widely developed in the mountainous part of North Ossetia-Alania. These processes cover almost all large outcrops in road cuts and on the slopes of valleys. In these areas, frequent falls of trees, large boulders, rubble, and whole blocks of loose formations are noted. With insufficient development of engineering protection of roads and other objects, rockslides lead to significant material losses [45].

Causes of rockslides under the conditions of sharply dissected topography and the presence of intensely dislocated rocks are the following: active geodynamic processes that are very typical for territories located at the junctions of megaplates; phenomena of accumulated seismic impact (natural and man-made); seismic impact; the mechanism of the influence of cracks on the side impact.

On the territory, any steep-sided (up to 50°–90°) section composed of rocks can be classified as rockslide-hazardous, but the most probable are the areas of powerful tectonic faults development (Tsey thrust and a series of tectonic faults of the southern slope-the Severny and Nar faults, Tib, Khalatsa, Zgil, and Saukhokh faults) and the zones of development of the newest discontinuous seismic dislocations as a way to relieve endogenous tectonomagmatic stresses [43]. Intensive manifestations of rockslide-talus processes occur in zones of concentration of tectonic disturbances, which are clearly manifested in seismic and electric fields.

3.4. Earthquakes

The high seismicity of North Ossetia-Alania is caused by a number of active regional faults of deep origin, among which one should mention the transcontinental fault of the meridional direction, which goes into the Earth's crust to a depth of 100–200 m and captures North Ossetia in the west, where there were earthquakes up to 9 points; further on, the North Caucasian subcrustal fault with a depth of 75 km, crossing a section of the territory of North Ossetia-Alania in the latitudinal direction, as well as the Ardon, Terek faults and the main thrust-crustal faults with a depth of up to 35 km, as well as a zone of deep shifts northeast-oriented, crossing the southeastern sector of the region with a depth of 30–40 km. Almost all seismic shocks of the last 50 years from 5 to 9 points were recorded within this zone [11].

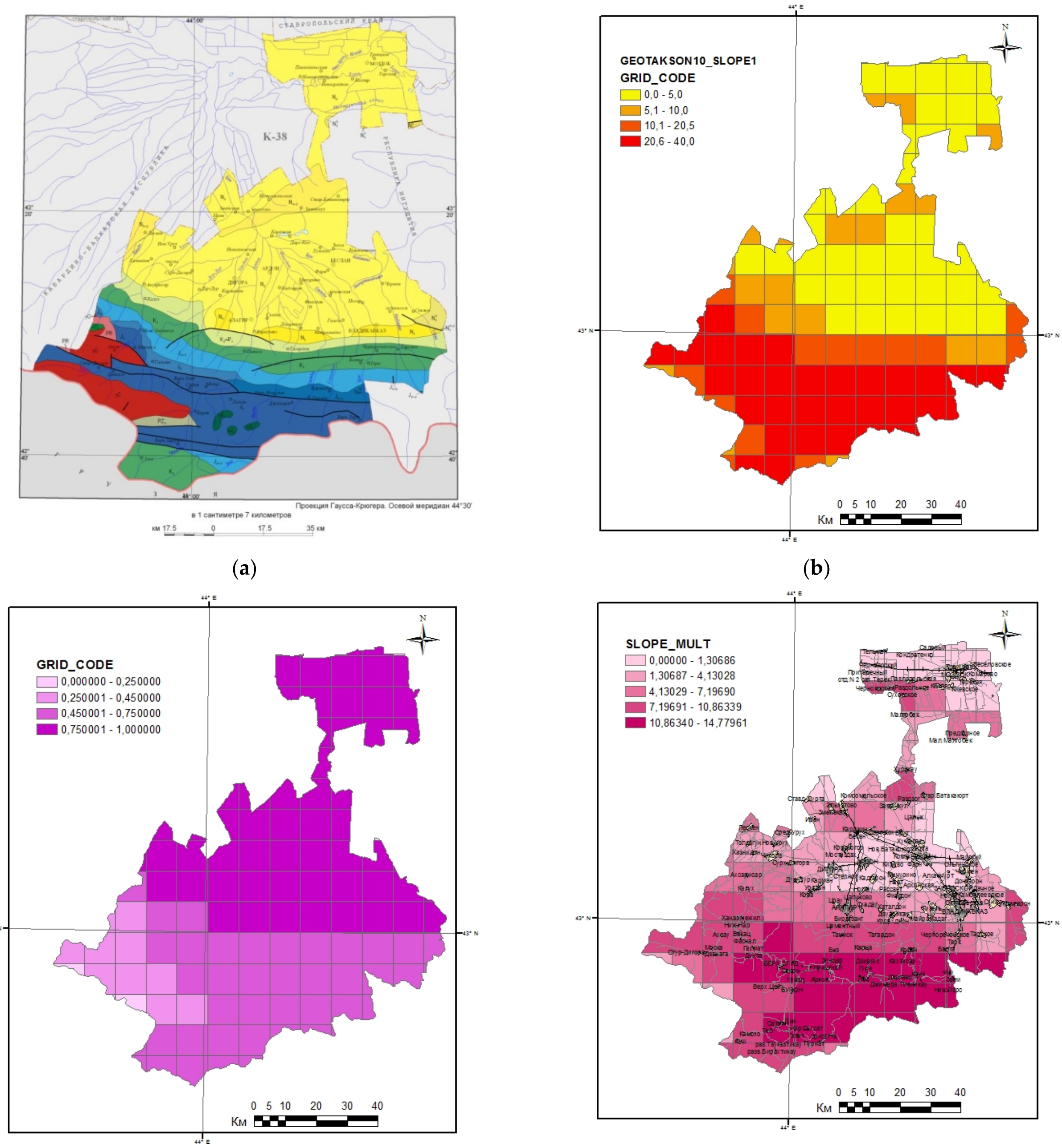
The probabilistic seismic hazard maps (the maps of detailed seismic zoning) have been constructed for the total area of North Ossetia on a scale of 1:200,000 with exceedance probability for a period of 50 years (standard time of building or construction durability!) with 1%, 2%, 5%, 10% in GIS technologies, which corresponds to the reoccurrence of maximum probable earthquake for a period of 5000, 2500, 1000 and 500 years. The longer the period of time, the higher the level of possible intensity. For a period of 500 years, only a small part will be occupied by the zone of 7 intensity earthquake, for a period of 1000 years–8 intensity and at 2500 years 9 intensity earthquake appearance, correspondingly. Cornell's approach, namely the computer program SEISRisk-3, developed in 1987 by Bender and Perkins (Bender and Perkins, 1987), was used for the calculations [53,54]. The maps of 5% probability are likely to be used for the large scale building, i.e., the major type of constructions, whereas the maps of 2% probability should be used for high responsibility construction (map is shown in Figure 4d). One can see great hazards in the south of North Ossetia on the map, where exists the increased level of seismic hazard (due to the powerful Vladikavkaz fault lying nearby).

4. Results

For a quantitative assessment of the environmental impact of geodynamic factors, a selection of all manifested geodynamic and climatic factors was made. The intensity of the impact of each of these factors on the environment is given according to a five-point system. At the same time, the rank is based not on the intensity of the shaking, but on the ability of one or another geodynamic factor to accelerate the denudation of rocks, to weaken their engineering properties, to develop Quaternary deposits, dangerous geological processes and, ultimately, accelerated changes in the environmental situation.

The maximum rank of the impact of an individual factor was determined based on the methodology of expert assessments [21,22] in the form of taking into account mass transfer (landslides-screes, mudflows, landslides, etc.), landscape and geomorphological changes (glacier movements, avalanches), long-term or short-term expected consequences (tectonic, volcano-plutonic manifestations, earthquakes, seismic dislocations). It is accepted that the impact on the environmental situation of N factors, each with an intensity of one rank or a single rank, corresponds to the least influence of the factor on the environmental state, and the level of the fifth rank corresponds to the greatest one, by analogy with the works of Zaalishvili V.B. [55,56].

The ratio (1) was used to calculate the risk R of impact realization. According to the developed approach, the set of conditions is divided into several levels of vulnerability. Each level corresponds to the values of hazards that form vulnerability. This classification is based on the experience of past earthquakes. In other words, as was noted above, we used the expert assessment. Further, each factor value was assigned its weight rating, also determined based on past experience. The following ratio was used to calculate the vulnerability rating (Table 2). Intermediate data and calculation results are shown in Figure 7.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. (**a**) Geological map of the North Ossetia-Alania territory (according to VSEGINGEI data); (**b**) rating index of relief slope angle; (**c**) rating index of geological structure; (**d**) integral rating index and location of settlements and infrastructure facilities.

Table 2. Rating indicators of factors of various nature.

Factor	Units	Vulnerability, D			WeightRating, W
		1	2	3	
Seismicity of the territory	Intensity, MSK-64	7	7–8	8	2.0
Geology	Category	I	II	III	0.5
Topography	Slope degree	<5°	5°–15°	>15°	1.0

According to the results of the rating assessment, two urbanized zones can be distinguished (Figure 7d):

(1) The zone of minimal impact is the flat northeastern part, built up with cities and industrial facilities. Beslan can be considered as the center of this zone because it is the optimal area for the development of the republic. The largest settlement on the territory of North Ossetia-Alania, Vladikavkaz, to a greater extent, is potentially exposed to natural impacts;
(2) The mountain part with the presence of historical settlements and objects associated with mining. This part is prone to the highest level of natural impact. The zone of the "Mamison" complex is also located in the zone of high impact.

For a quantitative assessment of the environmental impact of geodynamic factors, a selection of all manifested geodynamic and climatic factors was made; the intensity of the impact of each of these factors on the environment is given according to a five-point system. At the same time, the basis of the intensity degree is not the intensity of shaking, but the ability of the geodynamic factor to accelerate the denudation of rocks, weaken their engineering properties, develop Quaternary deposits, hazardous geological processes, and, finally, accelerate the change in the environmental situation.

The maximum point of the impact of a single factor is determined concerning the mass transfer (landslides, talus, mudflows), landscape and geomorphological changes (surge of glaciers, avalanches), expected long-term or short-term consequences (tectonic, volcano-plutonic manifestations, earthquakes, seismic dislocations). It is accepted that the impact on the environmental situation of N factors (each with an intensity of 1 point (single point)) is equal to the change corresponding to the stabilized platform development condition. It is necessary to note that when assessing the intensity degree of the geodynamic factor, an element of subjectivity is presented; however, increasing of factors leads to minimization of the total error for subjective approaches.

According to the complex of geodynamic factors observed on the territory of the projected complex, two tables have been developed. Table 3 shows the levels of the impact of geodynamic processes on the environmental state of high mountain territories depending on the geological and geomorphological conditions, and Table 4 represents ranking in points of the potential impact of geodynamic processes on the environmental state of high mountain territories according to the levels of their manifestation in various geological and geomorphological conditions.

Table 3. Levels of the impact of geodynamic processes on the environmental state of high-mountain territories, depending on the geological and geomorphological conditions.

No.	Types of Impact	Level of Impact			
		Weak	Middle	Hight	Regressive
1	Earthquakes in the near-field (R = 50 km), seismic intensity MSK	<6	6–7	7–8	8–9
2	Active fault zone (density in km/km^2)	0.01	0.02	0.03	0.04
3	Zone of intersection of sublatitudinal and submeridional faults from one to four and higher (number of crossings)	1	2	3	4
4	Fissure tectonics development zone, 0.03 to 0.10 km/km^2 and higher	0.03	0.05	0.07	>0.1
5	Zones affected by static geophysical, geochemical fields within an event radius of up to 50 km, distance in km: 10–20; 20–30; 30–40; 40–50	3	4	5	6
6	Manifestation zones of one to three or more seismic dislocation events within a structural block	1	2	3	3

Table 3. *Cont.*

No.	Types of Impact	Level of Impact			
		Weak	Middle	Hight	Regressive
7	Distribution of Quaternary formations at altitude intervals: 1700–2000 m; 2000–2300 m; 2300–2600 m; 2600 m and above	1700–2000	2000–2300	2300–2600	>2600
8	Soft bedrock (up to 50 MPa), exposure 40%; 50%; 60%; 70%; or more	40%	50%	60%	>70%
9	Erosion basis 1000 m or more, at altitudes of 2000 and above, taking into account glaciation	2000–2500	2500–3000	3300–3500	3500–4000
10	Erosion basis 500 m at altitudes of 1500 and above	1500–1700	1700–1800	1800–1900	1900–2000
11	Erosion basis up to 500 m at altitudes from 1500 m and below	1300–1500	1100–1300	1000–1100	>1000
12	Terrain surface inclination angles up to 15° according to genetic soil types:	landslide-scree	moraine deposits	debris flows	landslide
13	Terrain surface inclination angles 15°–20° according to genetic soil types:	landslide-scree	landslide-scree	debris flows	landslide
14	Terrain surface inclination angles >20° according to genetic soil types:	landslide-scree	landslide-scree	debris flows	landslide
15	Thickness of Quaternary deposits 0–5 m, at slope angles of 12°–25° and more	12–15	15–20	20–25	>25
16	Thickness of Quaternary deposits 5–12 m, at slope angles of 12°–25° and more	12–150	15–20	20–25	>25
17	Thickness of the Quaternary deposits more than 12 m, at slope angles of 12°–25° and more	12–15	15–20	20–25	>25
18	Number of mudflows, from one to 5 and more per season, volumes from 10 thousand m^3 and more	2	3	4	5
19	Landslides in the total volume for the year from 10 thousand to 2 million m^3	50	75	100	150
20	Landslides-scree up to 5000 m^3	75	100	150	200
21	Flat wash, area from 0.05 to 0.10 km^2 and more, per km^2	0.05	0.06	0.07	>0.1
22	Erosive activity of rivers from 1 to 5 m/hour of lateral erosion	1.0	2.5	4.0	5.0
23	Solifluction with vertical capture power from 1 to 4 m	1.0	2.0	3.0	4.0
24	Stream erosion on slopes of 200 or more	20	25	30	>35
25	Karst formation, from one to three or more manifestations per km^2 of area	1	2	3	>3
26	Avalanches, up to 4 or more descents per season	1	2	3	4
27	Glaciers and glaciers up to three or more flood-type events per area	1	2	3	>3

Table 4. Ranking in points of the potential impact of geodynamic processes on the environmental state of high-mountain territories and the levels of their manifestation in various geological and geomorphological conditions.

No.	Types of Impact	Weight Rating	Level of Impact			
			Weak	Middle	Hight	Regressive
	I Endogenous impact factors					
1	Earthquakes in the near-field (R = 50 km), seismic intensity MSK	5	1	2	3.5	5
2	Active fault zone (density in km/km^2)	3	1	1.5	1	3

Table 4. *Cont.*

No.	Types of Impact	Weight Rating	Level of Impact			
			Weak	Middle	Hight	Regressive
3	Zone of intersection of sublatitudinal and submeridional faults from one to four and higher (number of crossings)	4	1	2	3	4
4	Fissure tectonics development zone, 0.03 to 0.10 km/km^2 and higher	5	1	2	3.5	5
5	Zones affected by static geophysical, geochemical fields within an event radius of up to 50 km, distance in km: 10–20; 20–30; 30–40; 40–50	2	1	1	2	2
6	Manifestation zones of one to three or more seismic dislocation events within a structural block	3	1	2	3	3
II Lithological factors						
7	Distribution of Quaternary formations at altitude intervals: 1700–2000 m; 2000–2300 m; 2300–2600 m; 2600 m and above	3	1	1.5	2	3
8	Soft bedrock (up to 50 MPa), exposure 40%; 50%; 60%; 70%; or more	3	1	1.5	2	3
III Geomorphological factors						
9	Erosion basis 1000 m or more, at altitudes of 2000 and above, taking into account glaciation	4	4	3	2	1,5
10	Erosion basis 500 m at altitudes of 1500 and above	3	1	1.5	2	3
11	Erosion basis up to 500 m at altitudes from 1500 m and below	2	1	1.5	2	2
12	Terrain surface inclination angles up to 15° according to genetic soil types:	2	1	1	2	2
13	Terrain surface inclination angles 15°–20° according to genetic soil types:	3	1	1.5	2.5	3
14	Terrain surface inclination angles >20° according to genetic soil types:	4	2	2.5	3	4
IV Factors of exogenous and natural-climatic nature						
15	Thickness of Quaternary deposits 0–5 m, at slope angles of 12°–25° and more	2	1	1	1.5	2
16	Thickness of Quaternary deposits 5–12 m, at slope angles of 12°–25° and more	3	1	1	2	3
17	Thickness of the Quaternary deposits more than 12 m, at slope angles of 12°–25° and more	3	1	1.5	1.5	3
18	Number of mudflows, from one to 5 and more per season, volumes from 10 thousand m^3 and more	5	2	3	4	5
19	Landslides in the total volume for the year from 10 thousand to 2 million m^3	3	1	1.5	2	3
20	Landslides-scree up to 5000 m^3	4	1.5	2	3	4
21	Flat wash, area from 0.05 to 0.10 km^2 and more, per km^2	3	1	1	2	3
22	Erosive activity of rivers from 1 to 5 m/hour of lateral erosion	4	1.5	2.5	3	4
23	Solifluction with vertical capture power from 1 to 4 m	3	1	1.5	2.5	3
24	Stream erosion on slopes of 200 or more	3	1	1.5	2.5	3
25	Karst formation, from one to three or more manifestations per km^2 of area	3	1	1.5	2	3
26	Avalanches, up to 4 or more descents per season	5	2	3	4	5
27	Glaciers and glaciers up to three or more flood-type events per area	4	1.5	2.5	3	4
Sum of scores of all impacts/Percent of contribution		**95** **100%**	**34.5** **36.3%**	**48.0** **50.5%**	**64.0** **67.4%**	**91.5** **96.35%**

The ranking of the territory and its adjacent areas (about 400 sq. km) according to 27 geodynamic factors of endogenous, exogenous, and climatic nature is performed by squares of 4 sq. km (about 100 squares). In these tables, the maximum total level of influence of all factors (the sum of the weight ratings of the event) with simultaneous participation is 95 points. This value can be less by the weight level of the geodynamic factor that does not participate in the process. The environmental impact on a square is estimated by the ratio of the sum of points for this square to the potentially possible sum of the maximum determined points of the impact of the geodynamic factors involved in the process of environmental transformation.

Zoning of the environmental impact of the territory was carried out based on the obtained values of these relations, which are classified into four groups: 30–40%—weak impact; 40–55%—average impact; 55–70%—high impact, above 70%—regressive impact. When zoning the territory according to the level of environmental impact, the data of block differentiation of the territory and the development of active tectonic dislocations [57] of the Kazbek segment of the Greater Caucasus mega-arch were used. The scheme of the territory zoning according to the intensity of the environmental impact is shown in Figure 8. The site plots where the greatest observed environmental impacts are marked with a special dash.

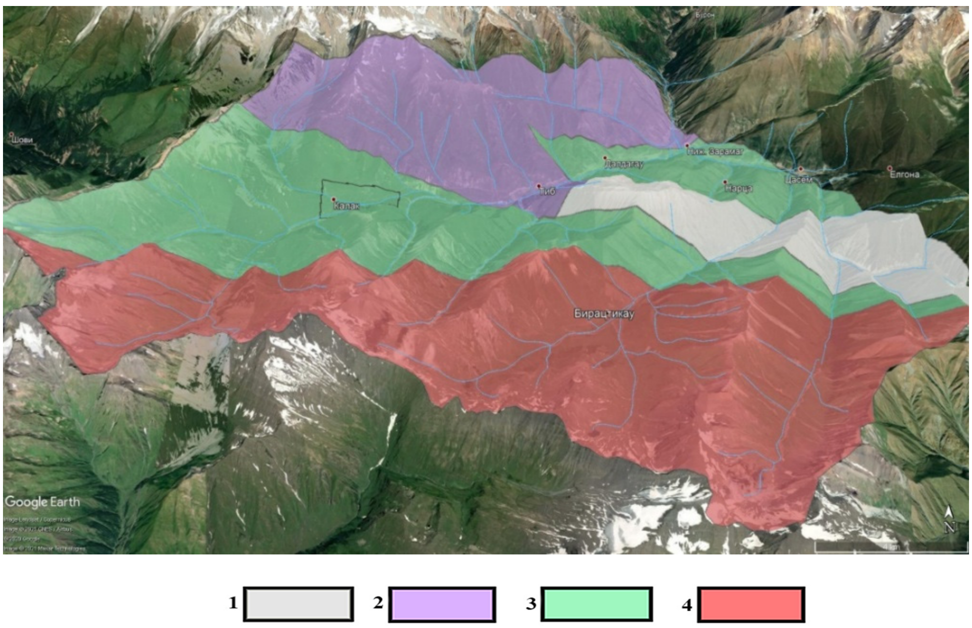


Figure 8. The scheme of the zoning of the environmental impact of the territory of the tourist and recreational complex "Mamison". Levels of environmental impact from geodynamic impacts: 1—weak; 2—average; 3—high; 4—regressive.

5. Discussion

Indicator structures that record the characteristic features of the impact of deep geodynamic energy on the environment are manifestations of the geodynamic situation as a cyclic stage of geological transformation, mountain building, volcanism, tectonic discontinuities, earthquakes in the form of local zones of origin of sources, seismic dislocations, dynamic impacts in the form of dislocations, the influence of physical fields and geochemical halos, and, finally, exogenous consequences for the environment of endogenous geodynamic activity (almost a complete set of genetic types of dangerous exogenous geological processes accompanying the tectonic structure). Exogenous dangerous geological processes typical for the mountainous territory are the following: mudflows, avalanches, landslides, glaciers, rockfalls, landslides, breakthroughs of open and closed water reservoirs, etc.).

It should be noted that during the weight contribution assessment of the geodynamic factor, an element of subjectivity is present to a certain extent. However, the more factors are used in combination, the more the total error for subjectivity approaches a minimum.

Based on the analysis of the results of studying the complex of geodynamic factors observed on the territory of the projected complex, two tables were developed.

Table 3 shows the quantitative characteristics of the impact of geodynamic processes on the environmental state of the site, caused by the lithological, geomorphological, endogenous, exogenous geological, and climatic factors. Table 4 shows the results of calculating the risk Ri of the impact of an individual factor with the potential Wi on the site and its environmental vulnerability Di on the corresponding factor.

Thus, the ranking of the risks of the potential impacts on the environmental state of high-mountain territories is realized according to the levels of their manifestation from lithological, geomorphological, endogenous, exogenous geological, and natural-climatic factors or conditions [58,59]. Given the interdisciplinary nature of the content of environmental and environmental problems, it is no wonder that both directions are so intertwined in scientific works that it is sometimes difficult to determine the solution of the problem of which discipline they are devoted. Traditionally, there is an idea that geoecology is an interdisciplinary direction, a kind of metascience, which summarizes all existing knowledge about the ecological state of the Earth, including environmental biology, although it is known that the biosphere partially determines the state of geoecology, forming the soil layer, participating in the transformation of the weathering crust; likewise, the geoecology affects the development and modification of living organisms.

Claims to the geographical orientation of geoecology can also be recognized as substantive when considering the consequences of environmental changes due to exogenous geological processes when landscapes and ecosystems change, but geography often does not have answers to changes in the environmental state of the environment caused by endogenous geological processes.

According to V.I. Osipov [60], the object of geoecology is the geospheric shells of the Earth, i.e., not only the lithosphere or geological environment, but also the hydrosphere, atmosphere, and biosphere. In this case, the subject of environmental science is the totality of all knowledge about the geospheres, including changes occurring under the influence of natural and technogenic factors.

The influence of geodynamic processes is considered only in the context of processes occurring in the geospheres of the Earth and affecting the environmental state at the boundary of the lithosphere and atmosphere.

Geodynamic hazard (endogenous and exogenous processes) is a threat caused by dangerous geological processes of an endogenous and exogenous nature, defined as the probability of a certain event or set of events manifestation in a given territory with a predictable intensity and within a given time interval.

The level of geodynamic hazard of the territory depends on the geodynamic activity of the lithosphere (endogenous geodynamics), the lithological composition of the sedimentary cover, the conditions for the interaction of the geological environment with the atmosphere, and climatic changes (exogenous geodynamics). Geodynamic and climatic processes determine the environmental state of the environment and the evolution of the Earth as a whole. Seismicity (rarely tectonic movements) and the exposure of the territory to exogenous processes [61–63], being the factors available to a person for research, are considered as the criteria for such an assessment. However, the relationship of even these two manifestations of the Earth's evolution at a subtle level (of a complex of physical fields-deformation, dislocation, electromagnetic, geochemical, and thermal fields) remains unclear.

An analysis of any exogenous natural geological process, regardless of the impact agent, shows that the object is being prepared for an event for a long time by endogenous geodynamic impact. Active tectogenesis, dislocation, tension, fracturing, fluid inflow, seismicity, magmatism, heat transfer, geochemical and geophysical fields are all agents that disrupt the structural bonds of the massif, increase porosity, contribute to intensive weathering and activation of erosion processes, affect the evolution of biota limited to a certain space [64].

Endogenous activity is a causative factor in the activation of exogenous processes, and one of the signs of this is the stable confinement of the latter to tectonic faults and nodes of discontinuous structures of different ranks, focal zones of seismic and volcano-plutonic activity [65,66], observed throughout the development of the alpine folding.

The state of endogenous geodynamics activity is manifested by lineaments of deep tectonic faults of the Caucasian strike (controlling outcrops of mineral springs), manifestations of earthquakes, folded dislocation of the massif, fracturing, geochemical and geophysical fields, seismicity, and a special indicator characteristic of the active state, i.e., seismic dislocations.

The level of impact on the environment of endogenous and exogenous geodynamic processes characterizes various genetic types of Quaternary formations widely developed over the area, forming numerous sources of dangerous exogenous geological processes. The surface topography, being a structure of endogenous manifestation, reflects many elements of tectonic activity expressed in geomorphology. With the introduction of technologies for remote sensing of the Earth's surface with different resolutions, the possibilities of mapping geological structures of different orders, including tectonic ones, have opened up.

One of the geomorphological indices characterizing the tectonics of a territory is the asymmetry factor [67], which is determined by the ratio of the area to the right of the mainstream to the entire catchment area. If the water system develops on terrain with homogeneous lithology and insignificant development of structural disturbances, the value of the asymmetry coefficient will be equal to 50. However, for the territory associated with active tectonic structures, the asymmetry coefficient will significantly differ from this value. This is due to the emergence of the Coriolis force in moving water systems, acting on the right banks in the northern hemisphere and, conversely, on the left banks in the southern hemisphere. With the general tectonic fragmentation of the basin part of the river, the displacement of the channel to the right will be the more noticeable, the more intense the tectonic processes are. According to the level of spatial asymmetry, it is possible to judge the degree of development of tectonic processes in the territory.

The main energy-conducting channels are interblock crustal tectonic faults, along which during the intrusion, a magma-fluid jet can manifest itself in different ways: it can penetrate by an intrusion, displace blocks, create conditions for earthquakes, break out, and erupt into a volcano.

The tectonic fault connects the lithosphere with the atmosphere with all ensuing consequences of the transit of gases and dissolved elements in upward and downward modes. In the downward stream, oxygen enters the lithosphere at the expense of the organic substances of the biosphere. In the upward stream, dissolved elements and volatile components, together with juvenile and mantle waters, move upward due to the energy of the convective flow of mantle jets.

Soluble and volatile elements of geochemical aureoles of concealed deposits crossed by a fault rise to the day surface along tectonic faults; they may contain vapors of heavy and radioactive elements.

Experimental studies of modern movements of the Earth's crust carried out on geodynamic polygons of different purposes defined two types of geodynamic movements: cyclic with different duration periods and trends, maintaining a constant direction for long periods. Both types of geodynamic movements influence the safety of surface structures and underground space objects. Intense local anomalies of vertical and horizontal movements are associated with fault zones of various types and ranks [68,69]. These anomalous movements occur cyclically and sometimes have pulse character, against the background of trend tectonic movements; they are characterized by high-amplitude displacements (up to 50–70 mm/year), are spatially localized in intervals of 100–1000 m, have a periodicity of manifestation from 0.1 to one year and have a pulsating and alternating directivity.

Manifestations of alternating geodynamic movements in active tectonic structures lead to the liquefaction of the rock mass in the tectonic zone [70].

The whole range of observed cyclic alternating and trend movements indicates that the main property of the geological environment, especially in fault zones, is its continuous movement. Movement acts as a form of existence of the geological environment. In this regard, the role and place of modern geodynamics in the fundamental sphere of Earth sciences is difficult to overestimate, but its role in solving practical problems of ensuring the safety of objects associated with the development of territories with active neotectonics is even more important.

6. Conclusions

The stable confinement of manifestations of hazardous exogenous geological processes to active deep tectonic disturbances and associated fissure tectonics of the post-glacial manifestation of neotectonic activity confirms the concept of the decisive role of endogenous processes in the activation of exogenous processes and in the intensification of changes in the environment.

Impacts of endogenous factors (ruptures, fracturing, earthquakes, static stresses, seismic dislocations, deformations) on rocks are enhanced due to the influence of changes at the material, structural-textural and molecular levels due to physicochemical and geophysical agents accompanying endogenous factors, which leads to a weakening of the structural bonds of the rock and destruction under the influence of atmospheric agents.

Signs-indicators of a mechanical, geochemical, geophysical, hydrogeological nature, accompanying geodynamic factors, are used as a methodological basis for determining and localizing geodynamic factors by solving direct or inverse problems.

The cause-and-effect dependence of the development of exogenous geological processes and environmental changes on the activity of endogenous processes in the work is the author's concept, and it is confirmed in a stable spatial relationship between endogenous and exogenous processes.

Geophysical methods have shown high efficiency in identifying regional faults, manifestations of neotectonic activity (expressed by the development of fissure tectonics), and seismic dislocation zones.

Typical geodynamic processes were determined, and there was assessed their level of impact, considering geological, lithological, endogenous, exogenous, geomorphological conditions and factors of the natural and climatic nature of development, ranked according to their maximum calculated impacts on the environmental situation, the sum of which represents the potential of the expected environmental impact on area unit.

For the Mamison node, the algorithms for the interconnections of geodynamic processes are compiled on the assumption of a simultaneous multi-factor or single-factor impact on the environmental situation.

On the basis of the obtained data, a schematic map of zoning of the environmental impact of the territory of the tourist and recreational complex "Mamison" (which includes four rather extensive zones with different values of environmental impacts) was compiled.

The environmental state of the territory before the design decisions for the organization of the tourist and recreational complex "Mamison" is determined by the activity of natural processes, practically without the influence of any technogenic and man-made factors.

Geodynamic and climatic factors of influence on the geoenvironment create the danger of excessive environmental impact and disruption of its equilibrium state under anthropogenic impacts, which must be taken into account in designing.

Author Contributions: Conceptualization, D.M. and V.Z.; methodology, D.M. and V.Z.; software, D.M., A.K. and O.B.; validation, V.Z. and O.B.; formal analysis, D.M., V.Z. and O.B.; investigation, D.M., V.Z., O.B. and A.K.; resources, D.M.; data creation, D.M. and A.K.; writing—original draft preparation, D.M. and V.Z.; writing—review and editing, V.Z.; visualization, D.M. and A.K.; supervision, V.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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