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THE CHARACTERISTICS AND EVALUATION OF MUDFLOW FORMATION CONDITIONS IN THE TERRITORY OF NAGORNO-KHARABAKH

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This research investigates and evaluates the factors and conditions contributing to mudflow occurrences in the Nagorno-Karabakh (NK) Region. It identifies the primary origins of mudflows and categorizes areas prone to mudflows for zoning purposes. Additionally, the study outlines current trends in mudflow evolution. Furthermore, the research proposes a range of hydraulic engineering, preventive, and forest reclamation measures aimed at mitigating mudflow risks. Implementing these measures within the NK context has the potential to yield significant and beneficial outcomes in addressing mudflow-related challenges.

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***Keywords*:** mudflow, precipitation, hydrographic network, slope and acpect of the mountains, fragmentation, weathering, climate, relief, basin, landscape.

Introduction. The formation of mudflows represents a complex interplay of geological, geomorphological, and hydrometeorological factors. Mudflows are widespread across the territory of Nagorno-Karabakh (NK) with frequent occurrences observed particularly in the Eastern and Southern regions, where conducive conditions prevail.

Mudflow formation in NK is primarily linked to intense torrential rains or hailstorms. These phenomena are most prevalent at altitudes ranging from 500 *m* to 1500 *m*, coinciding with major agricultural areas. The resulting damage from mudflows poses heightened risks to food and food security. Therefore, it is crucial to thoroughly investigate and identify the key factors shaping mudflow characteristics in NK.

The primary aim of this study is to assess the level of danger posed by mudflows and propose effective countermeasures. This is essential in addressing the challenges posed by global warming and safeguarding the region against mudflow-related risks.

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Materials and Methods. This study utilized actual observations from meteorological stations within the territory of Nagorno-Karabakh as its primary data source. Additionally, the authors compiled maps depicting the geographical elements of the NK Region. Furthermore, climate change assessment and forecasting results, along with materials from existing studies on the subject, were incorporated. This study also considered research conducted in the study area over various years and different studies focusing on relief formation phenomena and related factors.

The methodological approach in this work relied on mathematical and statistical analyses, mapping techniques, and data analysis to provide a comprehensive understanding of mudflow formation conditions in NK.

Results and Discussion. Topographic features play a significant role in mudflow formation, with surface characteristics being key contributing factors. In NK, mudflows occur across almost the entire territory, particularly below 1500 *m* in altitude. This is due to the extensive surface area at these altitudes, making it a focal point for flow concentration from higher levels. Notably, this zone represents the most economically active region within NK.

The coefficient of horizontal fragmentation of the surface in NK is measured at 0.92 km/km^2, although certain areas such as the Lev and Tutkhun basins, Varanda and Karkar valleys, and the Southern and South-Eastern slopes of the NK mountain range exhibit higher coefficients ranging from 1.5 to 1.7 km/km^2 [1].

Approximately 13.2% of NK's surface area features slopes ranging from 3–7°, serving as accumulation zones for the solid components of mudflows. Furthermore, about 40% of the area comprises slopes up to 12°, while steep slopes (12–20°) account for 14.3% of the total area (Tab. 1). These findings highlight the varied topographic characteristics that influence mudflow dynamics across the NK Region.

Table 1

Indicators of groups of slopes of NK surface [1]

Relief type	Gradient of slope	Area	
		km^2	%
Flat land	<3	1874	16.4
Gentle slopes	3–7	1509	13.2
Moderately sloping	7–12	3063	26.8
Strongly sloping	12–20	3349	29.3
Moderately steep	20–30	1555	13.6
Very steep	>30	80	0.7
Total	–	11430	100

The slopes of mountains play a crucial role in mudflow formation, with the Southern slopes being particularly favorable. These slopes experience sharp fluctuations in heat and humidity, leading to sparse vegetation cover. Intensive wind blowing processes further contribute to the separation of a large amount of fragmental materials, making these conditions highly conducive to mudflow formation.

As indicated in Tab. 2, the study area is characterized by a prevalence of South-facing slopes (27.9%) and North-facing slopes (24.8%), with flat areas accounting for 5.2%. This diversity reflects the complex relief of the region. The configuration of the valley network significantly influences mudflow formation.

There exists a strong correlation between the shape (*K*) and perimeter (*C*) of primary mud basins and the connection direction (*D*) of the source channel, expressed as $K = C/D$.

Table 2

The areas covered by the inclinations of the mountain slopes [1]

Relief type	Unit of measurement	
	km^2	%
Flat land	590	5.2
North-facing slope	2835	24.8
East-facing slope	2505	21.9
South-facing slope	3190	27.9
West-facing slope	2310	20.2
Total	11430	100

In mud basins with a fan-shaped network, the form factor (*K*) exceeds 2.8 and approaches the value of π. For instance, the form factor of basins in several temporary watercourses (such as Chailakh, Sirik, Chorajjur, Banadzor, etc.) originating from the Southern slope of the Artsakh mountain range ranges from 2.82 to 2.90. Similarly, in some tributaries of the upper reaches of Varanda (like March, Shrsran, Krsnadzor), the form factor reaches 2.80 to 2.86.

On the contrary, in basins characterized by a feather-shaped valley network, the form factor (*K*) typically does not exceed 2.5. For instance, tributaries of several rivers originating from the Eastern slope of the Artsakh mountain range demonstrate varying form factors. In the Karkar valley, the form factor ranges from 2.65 to 2.75, including Ghaibali water, Piti River, and Patara. Meanwhile, for the Tartar tributary of Pghtoraget, the form factor is 2.82, and for Yeghisharakelots water, it is 2.60.

Understanding the formation of solid components in floods requires consideration of geological and geomorphological conditions. The area under study features diverse lithostratigraphic complexes ranging from the Middle Jurassic to the modern stage. These complexes comprise sedimentary, sedimentary-volcanic, volcanic, intrusive, and metamorphic rock layers, each with varying physico-chemical characteristics.

The presence of diverse lithostratigraphic complexes contributes to the intensive disintegration of heterogeneous rock layers and the accumulation of solid components in mudflows.

Mudstones are commonly found in areas containing clays, shales, argillites, siltstones, sandstones, tufabreccias, tufaconglomerates, and similar formations. Landslide processes are particularly active in rock formations, where the spreading direction intersects with the topographic surface or an active tectonic structure. Consequently, rocks on the steep slopes of Ororotsasar, Shikakar, Teksar, and Tovmasar chains undergo more significant erosion.

Tectonic fault lines, evident in the relief and often leading to the formation of landslide-prone sections with varied rock formations and steep slopes, are crucial areas prone to mudflows. Examples include the Tartar Region, the Southern slope of Okhtnaghbyur, Varanda, and other tectonic fractures. Depending on the lithogenic base, mudflow conditions are more favorable in folded, folded-block, erosional-alluvial, and overturned tectonic structures compared to tectonovolcanic and volcanoerosive relief conditions.

Hydrometeorological factors play a significant role in both the liquid and solid components of mudflows. The region experiences semi-arid climatic conditions, resulting in the formation of a substantial amount of debris material due to strong winds. In certain cases, this debris material accumulates to form a deluvial plume at the base of monoclines.

In nearly all river valleys in the NK, large fragments of fragile materials are present, and the sole condition required for mudflow formation is the presence of water. The quantity, intensity, duration, and condition of the soil are crucial factors in mudflow formation.

Some rivers' feeding sources exhibit high rainfall indicators, such as Kavart with 43%, Karkar in Stepanakert with 44%, Askeran with 50%, Vararak in Armenavan with 49%, Traget in Kosalar with 53%, Meghraget with 46%, Pataran with 55%, Varandan with 59%, Iskhanaget with 47%, and others [1, 2].

On average, the NK receives approximately 507 *mm* of precipitation, with the majority occurring during the warm months of the year. For example, Stepanakert receives 70% of its precipitation during these months, Martakert 68%, Martuni 70%, Shushi 67%, and so on. A significant portion of floods, about 80%, occurs during June and July [3].

The average temperature in the NK is 8.94℃. Between 1951 and 2015, there has been a notable increase in the average temperature by 1.05℃, coupled with a decrease in precipitation by 8.3%. This has led to changes in the spatio-temporal distribution of rainfall, an increase in the frequency of hot and cold waves, and a rise in the intensity and volume of rainfall. These shifts have rendered natural landscapes more vulnerable due to the combined influence of natural and anthropogenic factors [2, 4].

The liquid component of mudflows primarily originates from torrential rains. Even a 5 *mm* layer of precipitation with an intensity of 0.05 *mm*/*min* on bare slopes in undulating mountains can trigger a mudflow. Torrential downpours are usually brief and localized, with more than half having an intensity of 0.1–0.5 *mm*/*min*. Notable rainfall events include a recorded intensity of 9.4 *mm*/*min* at the Berdzor observation post on June 14, 2018, and 58 *mm* of rain in Stepanakert on June 16, 2018, within 2 *h* and 27 *min*, with the torrential part lasting 45 *min* and 42 *mm* falling in one place [5]. In 2023, on June 24, Askeran received 60 *mm* of rain within 3.5 *h*, on an already moisture-saturated surface.

Nagorno-Karabakh has experienced intense mudflows in various years, notably in 1934, 1940, 1948, 1950, 1952, 1957, 1958, 1963, 1966, 1968, 1969, 1972, 1974, 1975, 1984, 2018, 2022, and 2023. Some of these events have caused significant destruction. For example, the mudflow on October 27, 1957, resulted in considerable damage between the Horadiz–Mijnavan railway stations. It flooded areas, destroyed railway infrastructure, and displaced railway lines by 5 *m* in various sections. Unfortunately, specific information regarding the material damage caused by this mudflow in rivers Varanda, Ishkhanaget, and Tzhgporaget in Hadrut and Martuni Regions is not available [5].

In 1978, during a flood, Amaras was swept away, leading to the loss of 38 buffaloes. Moreover, during floods in 2006 and 2009, floodwater covered the bridge of the Red Market–Martuni highway with a height of approximately 1 *m*. The Varanda River has witnessed numerous mudflows resulting in the destruction of bridges and mills, the sweeping away of cattle, and causing human casualties.

Tab. 3 presents the dates and maximum discharges of several powerful mudflows that occurred in the rivers of Armenia in various years [1, 3].

Table 3

Characteristics of several mudflows that passed through the NK

N	River section	Catchment area, km^2	Mudflow time (day, month, year)	Maximum discharge, m^3/s
1	Karkar, Stepanakert City	238	20.06.1948	56.9
2	Karkar, Stepanakert City	238	16.06.1968	56.2
3	Karkar, Stepanakert City	238	20.06.1977	116.0
4	Karkar, Askeran City	783	03.07.1957	73.8
5	Karkar, Askeran City	783	11.06.1972	145.0
6	Karkar, Askeran City	783	07.07.1974	96.4
7	Khachen, Vanq village	175	07.07.1974	91.5
8	Qolatak right tributary of Khachen	12.5	03.06.1974	54.8
9	Varanda, Karmir Shuka village	166	25.05.1975	90.0
10	Ishkhanaget, Togh village	201	29.04.1934	41.3
11	Tartar, Qarvachar City	483	07.07.1974	52.0
12	Tartar, Vaghuhas bridge	1915	24.06.1978	110
13	Tartar, Sarsang village	2130	27.05.1966	230
14	Tartar, Maghavuz village	2160	30.06.1940	455
15	Tartar, Mataghis village	2460	30.06.1940	647
16	Tartar, Jermajur	2970	09.06.1956	15.2
17	Tartar, Qarvachar City	2640	01.08.1980	56
18	Lev, Tsaghkashen	363	06.06.1966	121
19	Tutkhun, near estuary	522	07.07.1963	104
20	Trghi, Maghavuz village	162	07.07.1963	96.6
21	Hakari, Berdzor City	1180	14.05.1974	106
22	Meghraget, Aygestan	77.1	20.06.1948	25.0
23	Patara, Patara village	77.1	20.06.1948	25
24	Taghot, Togh village	54.2	13.06.1968	8.78
25	Aghavno, Hak village	113	17.04.1974	25.5
26	Aghavno, Aghavno village	496	25.07.1982	55.2

The nature and condition of vegetation cover are crucial factors in the formation of mudflow phenomena. The flow coefficient is significantly influenced by meadow vegetation with a strong root system, as well as dense shrub and forest vegetation. These types of vegetation weaken the flow coefficient and reduce the likelihood of mudflows.

Approximately one-third of the study area is covered with forests and thick bushes, primarily occupying the Northern slopes, where mudflow phenomena are weakly expressed or absent altogether.

In contrast, vegetationless or sparsely vegetated areas on the Southern and South-Eastern slopes of the Artsakh mountain range, as well as the Southern slopes of several river valleys, not only fail to reduce the surface flow coefficient, but often contribute to the solid component of mudflows.

Human activity plays a significant role in mudflow formation in the NK Region, being as crucial as natural triggers. Unauthorized logging, degradation of pastures due to overgrazing, waste from mining activities, accumulation of construction and domestic waste, all contribute to the promotion of mudflows and the formation of mudflow-prone areas.

In the study area, mudflows originate from various mudflow foci, which are vital components of the mudflow basin and the primary sites, where mudflow formation occurs. Alluvial mud pockets develop on the slopes of catchment funnels and gather in the thalwegs and beds of temporary watercourses. Moreover, outcrops are formed at the base of steep slopes in narrow erosional valleys.

Moraine mudflow centers in the NK's territory are linked to the Ris and Vyrm glaciations, which left moraine mounds ranging from several meters to 15–20 *m* high. These mounds consist of silt, sand, and boulders and are located in the Mkhatik, Syunik volcanic plateau, and Mravasar mountain range above 2600 *m*. These moraine mounds become triggers for mudflows when water courses interact with them [6].

Active wind-slope mudflows are associated with the Meiotis pontine volcanic and volcanic proluvial strata. These formations occur in the watershed of Vorotan and Hakaru (Goris Formation) and on the left bank of Hakaru (Hakaru Formation). These strata serve as abundant sources of solid material for mudflows.

Landslide-slide mud pockets are extensively distributed and are primarily located along tectonic fault lines, serving as areas, where seismogravitational landslides propagate. These pockets are found in the valleys of Tartar, Varanda, Karkar, Khachenaget, Khonashen, and several other rivers and streams. The landslide masses descend into the riverbed sections, contributing to the solid component of mudflows or becoming integral parts of them [7].

Meridian mudflats consist of alluvial-proluvial formations from meridian fault lines of varying composition and height, including outcrop cones. These formations are characteristic of river valleys in folded mountains.

Anthropogenic mudflows are linked to human activities such as mining, road and aqueduct construction, deforestation, and similar practices. These activities can create new mudflows and contribute to their formation.

From the point of view of the spatial distribution of mudflow phenomena, the areas of folded mountains and intermountain hollows of the republic are most favorable, where the Jurassic and Cretaceous mostly water-bearing rock layers, the Paleogene and Miocene volcanogenic-sedimentary lithostratigraphic complexes are exposed in various tectonic structures. On a complex lithogenic base, in semi-arid climatic conditions, in different altitudinal zones and landscapes, various foci of mudflows have formed. The foci of landslides and mudflows developed in the zones of tectonic rocks stretching in different directions are especially dominant. The area was divided into marzes, sub-regions, regions, and sub-regions based on the features of geomorphological processes of mud formation, mud parameters of flood basins. These are also included in the following scheme of mudflow basins of the NK (Tab. 4, Fig. 1).

Table 4

Scheme of circulation of mudflow basins of NK territory

<table>
<tr><th>Basin</th><th>Sub-basin</th><th>Region</th><th>Sub-region</th></tr>
<tr><td rowspan="3">Aras River basin</td><td>I. Middle course of Aras</td><td>1. Voghji – Hakari basins</td><td>a) Aghavno;
b) Hochants;
c) Shalua;
d) Susanasar;
e) Vorotan;
f) Choradzor;
g) Voghji;
h) Khachin-Tsopadzor;
i) Bardutagh;
j) Karmraget;
k) Khachgiaduk;
l) Little Hakaru.</td></tr>
<tr><td rowspan="2">II. Artsakh mountains</td><td>2. Sirik – Banadzor basins</td><td>a) Qarakhach;
b) Sirik;
c) Chaylakh;
d) Arakel-Banadzor;
e) Chghporaget;
f) Khudapirin.</td></tr>
<tr><td>3. Varanda – Ishkhanaget basin</td><td>a) Taghot;
b) Shnakar;
c) Ishkhanaget;
d) Varandai;
e) Amaras;
f) Khonashen;
e) Sev Djur,
h) Marts.</td></tr>
<tr><td rowspan="2">Kura River basin</td><td>I. Middile course of Kura</td><td>1. Tartar – Geran basins</td><td>a) Lev;
b) Tartar;
c) Tutkhun;
d) Trghi;
e) Pghtoraget;
f) Yeghish Araqelots;
e) Inji;
h) Sev Djur;
i) Geranget;
j) al Lich;
i) Upper Tartar.</td></tr>
<tr><td>II. Artsakh mountains</td><td>2. Khachen – Karkar basins</td><td>a) Upper Karkar;
b) Ghaibaliget;
c) Spitakadjur;
d) Meghraget;
e) Patara;
f) Salk;
e) Hilisi;
h) Pitsi River;
i) Kolatak;
j) Khachenaget;
i) Kavart;
l) Innmas Djur.</td></tr>
</table>

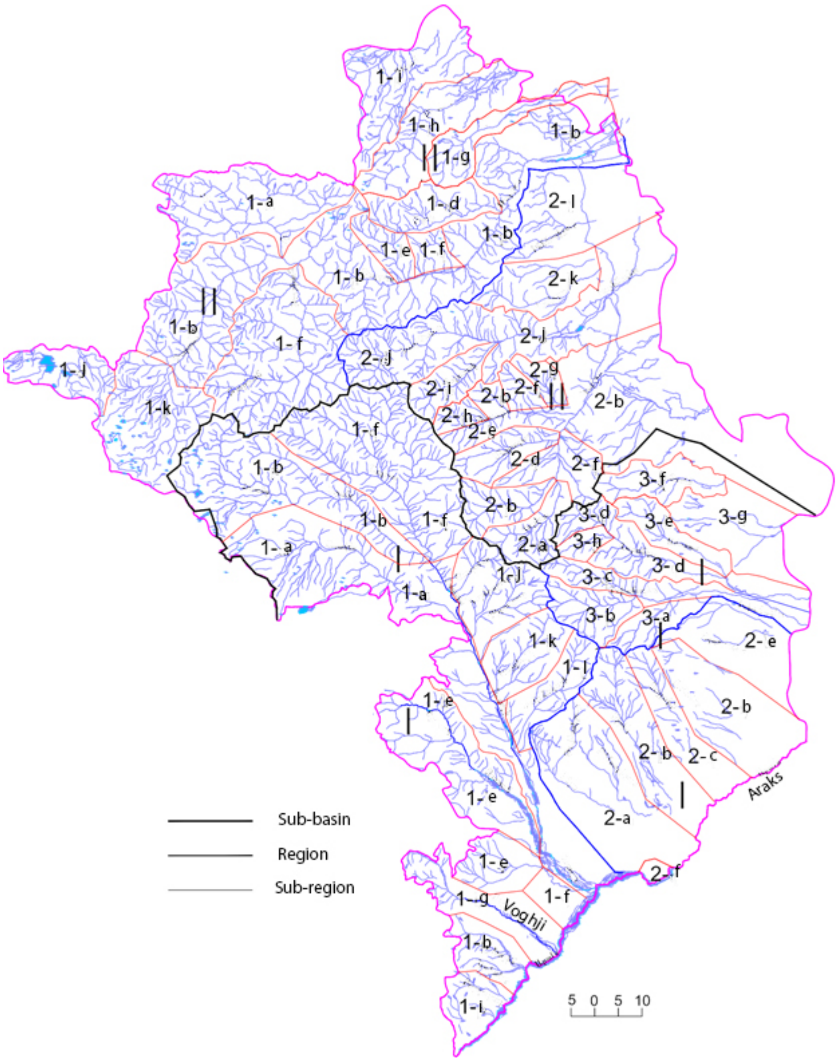

Fig. 1. The mudflow classification map of NK.

By combining the available materials and information about the mud basins of NK, and comparing them with the studies by K. E. Nazaryan's subdivision of the mud basins of the Republic of Armenia [2], the mud basins of the NK territory were divided into 3 classes at the current stage of study (Fig. 2):

1. *Strong Mudflow Basins*. These areas exhibit steep slopes and sparse vegetation, leading to the detachment of debris material from rocky and semi-rocky formations. With widespread heavy slope processes and a complex network of water flow concentration within the hydrographic system, a single mudflow event can yield 15000 m^3/km^2 to 35000 m^3/km^2. Basins such as Small Hakar, Amaras, Chakhmakh, Banadzor, Varanda, Tsopadzor, Sirik, and others fall into this category.

2. *Medium Mudflow Basins*. These areas feature extensive bedrock outcrops with limited vegetation, widespread debris distribution, and energetic wind blowing

and erosion phenomena. Mudflow in these basins can range from 5000 m^3/km^2 to 15000 m^3/km^2. Examples include the river basins of Chhgporaget, Chailakh, Ishkhanaget, Lev, Prtoghaget, and others.

3. *Weak Mudflow Basins*. These areas are characterized by dense vegetation, minimal wind and erosion phenomena, and a less developed hydrographic network. The mud yield from active surfaces involved in mud formation does not exceed 5000 m^3/km^2 during a mudflow event. Examples of weakly flood-prone areas include Shnakar, Kolatak, Trghi, Hochants, Shalua, Aghavno, and others. The absolute majority of mudflows in the territory of the republic are water-shale and they start mainly from the steep slopes of folded mountains.

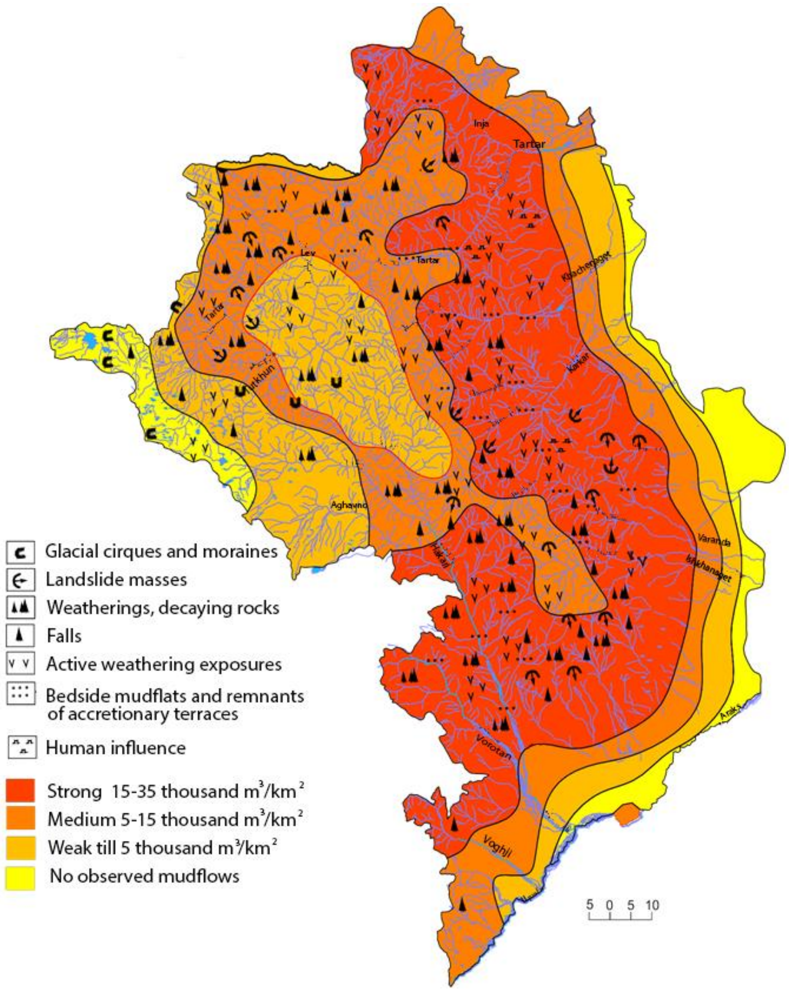

Fig. 2. The mudflow formation sources and mudflow intensity in NK.

Limestone mudflows have a limited distribution in the upper reaches of the Tartar and Hakaru basins. Some mudflows from the Southern slopes of the Artsakh mountain range are notable for their mud composition.

Conclusion. It is currently essential to develop the hydrometeorological monitoring network in the republic and align it with modern requirements. This is crucial for managing climate risks, planning regional development, assessing vulnerabilities in various economic sectors and ecosystems, and devising adaptation measures.

The NK is experiencing a gradual expansion of aridification, leading to the emergence of new mudflow centers. Additionally, the increasing anthropogenic pressure on landscapes is contributing to a clear rise in mudflow occurrences in the NK's territory. This expansion of mudflow phenomena is now an undeniable fact, making it imperative to implement measures to combat mudflow events.

It is imperative to consistently implement a sustainable policy for mudflow prevention and mitigation, along with comprehensive anti-mudflow measures.

One highly beneficial protective measure in NK's conditions is the construction of reservoir flood regulators. These regulators are designed to neutralize the destructive effects of mudflows and utilize the mudflow fluid that would otherwise flow aimlessly. This approach would be especially advantageous in arid areas. Similar to muflow protection hydraulic structures commonly found in Armenia's gullies, NK could construct dams, mud drains, mud removal canals, and coastal protection structures along flood channels.

Instead of building costly mudflow control and sludge catchment reservoirs in mudflow basins, expanding reservoirs in mudflow beds can be created to block mudflows and reduce their impact force.

To prevent landscape vulnerability under aridification conditions, it is crucial to implement proper agricultural practices, manage pastures effectively, prevent irrigation and road erosion, conduct phytomelioration works on mountain slopes, and regulate deforestation.

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ԼԵՌՆԱՅԻՆ ՂԱՐԱԲԱՂԻ ՏԱՐԱԾՔԻ ՍԵԼԱՎՆԵՐԻ ՁԵՎԱՎՈՐՄԱՆ ՊԱՅՄԱՆՆԵՐԻ ԱՌԱՆՁՆԱՀԱՏԿՈՒԹՅՈՒՆՆԵՐՆ ԵՎ ԳՆԱՀԱՏՈՒՄԸ

Ամփոփում

Աշխատանքում վերլուծվել և գնահատվել են Լեռնային Ղարաբաղի տարածքի սելավագոյացման պայմաններն ու գործոնները, առանձնացվել են հիմնական սելավային օջախները և դրանց բաշխումը հանրապետության տարածքում, դասակարգվել են սելավային ավազաններն ու հոսքերը դրանց շրջանացման նպատակով և բացահայտվել են սելավային երևույթների զարգացման միտումներն արդի փուլում: Առաջարկվել են նաև մի քանի ջրատեխնիկական, պրոֆիլակտիկ և անտառամելիորատիվ հակասելավային միջոցառումներ, որոնց կիրառությունը Լեռնային Ղարաբաղում կարող են արդյունավետ արդյունքների հանգեցնել:

В. С. САФАРЯН, Т. В. САФАРЯН, Г. С. ГАЛСТЯН

ОСОБЕННОСТИ И ОЦЕНКА УСЛОВИЙ ФОРМИРОВАНИЯ СЕЛЕЙ НА ТЕРРИТОРИИ НАГОРНОГО КАРАБАХА

Резюме

В работе изучаются и оцениваются условия и факторы, способствующие возникновению селей на территории Нагорного Карабаха. Выделены основные селевые очаги и классифицированы селевые потоки и бассейны с целью их районирования. Также выявлены современные тенденции развития селевых процессов. Кроме того, в исследовании предложен комплекс гидротехнических, профилактических и лесомелиоративных мероприятий, направленных на снижение селевых рисков. Реализация этих мер на территории Нагорного Карабаха потенциально может принести значительные положительные результаты в решении проблем, связанных с селями.