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Baltica

BALTICA Volume 37 Number 1 June 2024: 15–23
https://doi.org/10.5200/baltica.2024.1.2

Landslide and erosion processes in the high-mountain areas of the Greater Caucasus, Azerbaijan

Ilham Ildirim oglu Mardanov

Mardanov, I.I. oglu. 2024. Landslide and erosion processes in the high-mountain areas of the Greater Caucasus, Azerbaijan. *Baltica*, *37 (1)*, 15–23. Vilnius. ISSN 1648-858X.
Manuscript submitted 12 October 2023 / Accepted 19 March 2024 / Available online 22 April 2024

Abstract. This article presents the findings of ecogeomorphological studies conducted in the high-mountain belt of the southern slope of the Main Caucasus Range by utilizing satellite imagery. The investigations reaffirmed the dynamic nature of exogenous relief-forming processes evident in slope surface conditions and the diverse array of natural landscapes in high-mountain regions. The data acquired facilitated the development of measures aimed at enhancing the natural environment and guiding future land use practices. Through this research, various factors contributing to degradation processes were identified, enabling the pinpointing of erosion-prone areas on both slopes of the Greater Caucasus and the formulation of what we believe to be the most optimal anti-erosion measures scheme. Analysis of satellite imagery revealed that some river basins originating from the southern slope of the Main Caucasus Range exhibit the most pronounced soil and vegetation degradation processes.

Keywords: *landscapes; degradation of soils; satellite images; Main Caucasus Ridge; slope; morphosculptures; hypsometric*

Ilham Ildirim oglu Mardanov (geography.sumqayit@mail.ru) *http://orcid.org/0000-0002-1263-185X*
Sumgait State University, Sumgait, Azerbaijan Republic

INTRODUCTION

The natural conditions of the Greater Caucasus, along with the processes occurring within it, exhibit a distinct altitudinal zonality. As highlighted by several researchers (Abduev 2010; Alizade, Tarihazer 2010, 2015; Mardanov 2011; Abduev 2011), this zonality is attributed to recent tectonic movements and the varied landscape complexes hosting diverse exogenous processes. The vertical zoning of the Greater Caucasus is shaped by contemporary tectonic forces, fostering diverse landscapes and driving exogenous processes. Notably, from the Jurassic period to the Miocene epoch, significant folding processes also contributed significantly to the formation of the Greater Caucasus, further enriching its geological history and topographical features. The reformation of landscapes has been significantly influenced by both endogenous and exogenous processes, including landslides, collapses, and debris movements. To mitigate potential catastrophic consequences associated with these dynamic processes, a thorough examination and analysis of the territory are imperative. Today, the territory is experiencing significant economic activity, particularly in tourism, highlighting the need to assess mountain landscapes for their resilience to intense anthropogenic impact. The primary objective of this study is to evaluate landscape diversity from the point of view of their resistance to intense anthropogenic impact within specified boundaries and determine the extent of soil erosion in mountain meadows across the select fragments of the highlands of the Greater Caucasus within Azerbaijan. To accomplish this goal, the study involves collecting soil samples from representative areas, interpreting satellite imagery, and creating detailed maps to facilitate effective environmental management strategies.

MATERIALS AND RESEARCH METHODS

Building upon prior studies assessing the natural conditions of the Greater Caucasus for economic

development and environmental protection, we have devised an optimal approach to evaluate the degree of degradation in mountain landscapes influenced by geodynamic processes. This method incorporates satellite imagery, visual observations, and laboratory analysis of collected samples (see Fig. 1).

The images utilized in this study were sourced from the Sentinel-2 satellite, which was launched for Earth remote sensing (ERS) by the European Space Agency in 2015. These images were captured as part of a global environmental and security monitoring initiative. The Sentinel-2 satellite series, along with other satellites within the programme, are specifically designed to monitor various aspects of the Earth's surface, including soil use, vegetation, forests, water resources, and can also aid in mitigating the aftermath of natural destructive events.

During the extensive research period, field observations were conducted and soil samples were collected from key areas exhibiting varying degrees of erosion, which were then subjected to laboratory analyses. The degree of soil erosion was assessed based on surface disturbance in mountain meadows and the reduction in humus content and other crucial compounds. The findings from visual observations and laboratory analyses indicated a correlation between erosion and slope incline, as well as the intensity of anthropogenic activities. It was further observed that the degree of erosion manifested as changes in image tone, with heavily eroded areas appearing lighter and gradually darkening as erosion lessened. Areas with abundant humus and well-established meadow vegetation exhibited the darkest tones. Leveraging these interpretative features and field research data, schematic and fragmentary maps of high-mountain meadows in the Greater Caucasus within Azerbaijan were compiled.

Fig. 1 The high-mountain territory of the Greater Caucasus within Azerbaijan as captured in satellite imagery. The black square delineates the high-mountain regions of the Shahdag and Gyzylgaya massifs, situated north of Mount Babadag and northeast of Mount Xanyaylaq. This area represents only a segment of the highlands in the Azerbaijani part of the Greater Caucasus, extending from northwest to southeast, spanning from the Georgian and Russian borders to the shores of the Caspian Sea

To evaluate the ecogeomorphological and soil erosion conditions, a comprehensive analysis of extensive factual data concerning various components of the natural environment in the highlands of the Azerbaijani sector of the Greater Caucasus was conducted. Satellite imagery facilitated the compilation of cartographic materials, identification of primary landslide and erosion relief features, and generation of digital relief models in landslide-prone areas. These efforts enabled the assessment of erosion levels and overall exodynamic hazards within specific study areas, as well as the exploration of potential soil conservation measures to enhance the state of high-mountain landscapes.

The research conducted utilizing satellite imagery, as carried out in several studies, has facilitated the ecogeomorphological zoning of the territory. This zoning aims to optimize economic activities within the area (Mamedov 2016; Mardanov, Yusifova 2017; Tarikhazer *et al*. 2023).

RESULTS AND DISCUSSION

Difficult relief conditions contribute to the development of erosion processes, resulting in the degradation of the upper fertile soil layer in mountain meadows and hayfields. These areas constitute a significant portion of the highlands in the Greater Caucasus.

The climate of a particular region plays a crucial role in the initiation and progression of exodynamic processes, with variations significantly influenced by the absolute elevations of the terrain, as highlighted by several authors (Akhundov 1978; Eyyubov, Ragimov 2003). In the progression of natural destructive processes, morphometric indicators play a significant role, particularly the slope inclinations, which are notably characteristic of the southern slope of the Greater Caucasus. This aspect has been extensively studied by numerous Azerbaijani scientists (Alizade 1984; Piriev 1986; Alizade 2004; Kuliev 2006; Mammadov *et al*. 2017). Additionally, tectonic characteristics and rock composition of the slopes are pivotal factors in exogenous relief formation. The presence of rocks susceptible to external influences results in their accelerated degradation, intense denudation, erosion, and disruption of ecological balance in mountainous regions. This assertion is supported by an analysis of existing thematic maps.

Exodynamic processes disrupt the integrity of natural complexes, leading to the fragmentation of

mountain-meadow and mountain-forest landscapes into distinct segments. These processes also give rise to the formation of mudflow centres, particularly prevalent in the mountain-meadow and mountain-forest landscape belts of the Greater Caucasus, especially along its southern slope. These centres pose significant hazards to the lives of the local population residing in these areas.

Within the highlands of the Greater Caucasus, landslides, screes, and placer deposits play a significant role in exogenesis, with numerous scientific studies dedicated to exploring their causes and landscape characteristics (Alizade *et al*. 2015; Mardanov *et al*. 2018; Guliyeva *et al*. 2019). The pronounced intensity of exodynamic processes is evident in the landscapes of landslide-flows that develop in high-mountain areas. The fragmented materials from these processes, as well as those from screes and placer deposits, contribute to an increased risk of mudflow hazards within riverbeds (Abduev 2014).

It is imperative to reiterate that the geological and geomorphological conditions of this territory, characterized by high relief energy resulting from steep slopes and extensive surface dissection, contribute to the frequent occurrence of mudflows, particularly evident in a segment of the Main Caucasus Range covering the basins of the Kishchay and Kyungyutchay rivers. These rivers are identified to be among the most prone to mudflows. Consequently, intense exodynamic processes serve as the primary landscape and soil-forming factors in this area.

The nature of exodynamic processes in the high-mountain zone exhibits unique characteristics in the south-eastern extension of the Greater Caucasus. Here, the relative flatness of the peaks, in comparison to the central part of the range, does not diminish the intensity of natural destructive processes. This phenomenon is attributed to both endogenous factors, such as heightened tectonic activity and seismicity, as well as exogenous factors. Notably, the intensive development of pasture and hay farming significantly contributes to these processes. Within this region lie prominent peaks such as Babadag (3629 m), Garadag (3649.9 m), and Asad (3471.0 m), where denudation processes are prominently manifested within the subnival zone (see Fig. 2). Adjacent to Mount Asad lies a group of Goturnokhur lakes, wherein the active transfer of loose clastic material to their bottoms can lead to fluctuations in water levels and alterations in shape, resulting in various environmental consequences.

Strongly dissected surfaces are clearly visible on satellite images and occupy large areas in the territory adjacent to the bed of the Garachay River and on the slopes of the Babachay River valley, as well as the Girdymanchay River, representing a potential mudflow hazard. In this area, the rocky-nival belt primarily forms as barren areas devoid of soil and vegetation encroach upon high-mountain meadows due

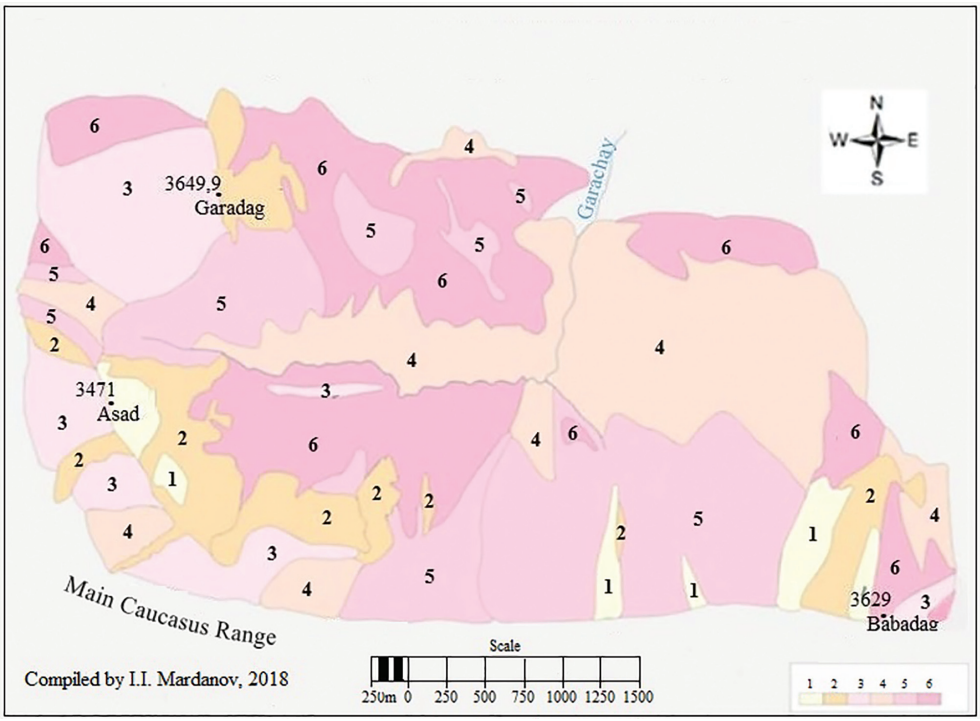

Fig. 2 Schematic map illustrating the subnival-nival belt surrounding the peaks of Asad (3471.0 m), Garadag (3649.9 m), and Babadag (3629 m). **1**. Solid snowfields. **2**. Snowfields with rock outcrops. **3**. Strongly dissected slopes of the subnival zone with rock outcrops, screes and snow patches. **4**. Strongly dissected slopes of the subnival zone with rock outcrops and screes. 5. Tongues of snowfields covering the slopes of rocks. **6**. Smoothed slopes of the subnival zone, occasionally covered with patches of snow

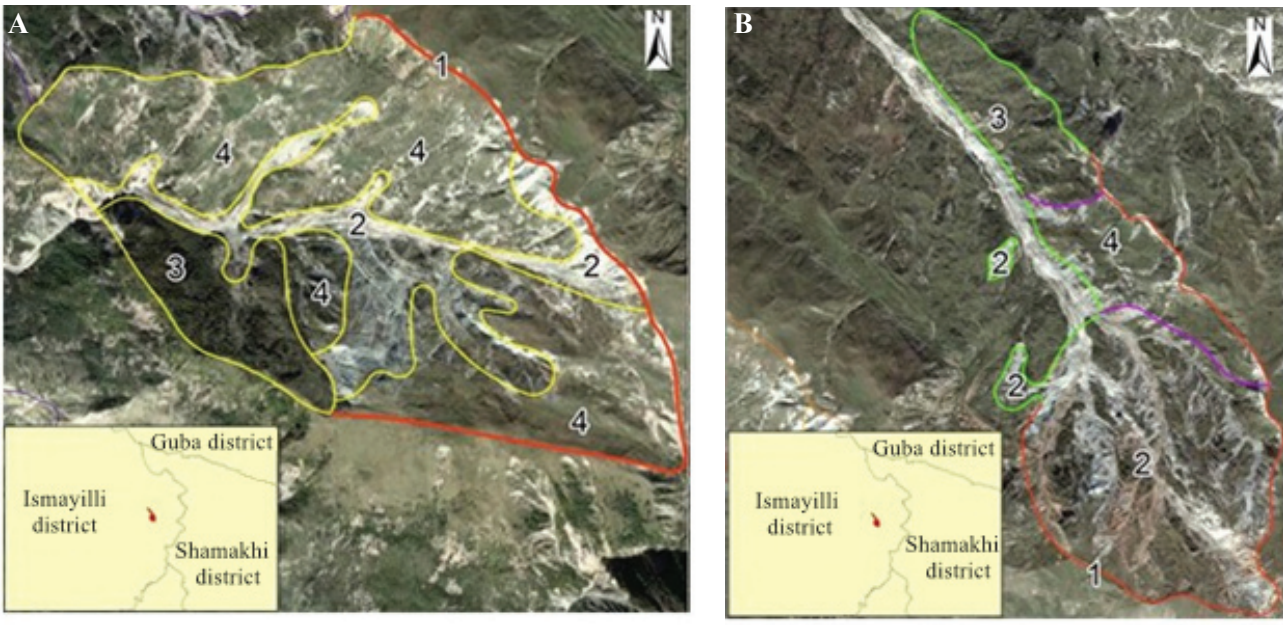

Fig. 3 Depicted branches of the Garauzchay landslide-flow (A and B), expanding to encompass new areas, distinguishable by their lighter phototone, delineating them from adjacent mountain-forest and mountain-meadow landscapes. The image, sourced from Google Earth, has a resolution of 1 meter and was captured on 29 September 2012. Key features include: 1 – edge of separation, 2 – fresh landslide deposits, 3 – landslide body covered with forest and shrub vegetation, 4 – landslide body covered with meadow vegetation

to the extensive erosion caused by intensive pasture development.

Continuous snowfields are limited in extent, predominantly found near the peaks of Babadag and Asad, while tongues of snowfields are widespread, covering the bottoms of ravines and potholes.

The study of landslide processes in this area is of significant interest, with the Garauzchay landslide-flow serving as a notable example. Originating at an altitude of 1900 meters above sea level on the western slope of Mount Matur in the Girdimanchay River basin, it extends to the valley of the Garauzchay River. This landslide-flow spans a length of 2 kilometres, with a width ranging from 10 to 50 meters. The surface of the landslide-flow exhibits numerous puddles, cracks, ridges, bushes, and fresh landslide materials. Comprising several branches, this landslide-flow converges in the valley of the Garauzchay River, forming a cohesive mass.

A digital relief model and a satellite image of this section of the Main Caucasus Range, which exhibits relatively lower elevation compared to its central part, reveal the characteristics of the landslide. Originating in the lower part of the mountain-meadow belt, the landslide forms several branches, including those that have emerged in recent years, visibly depicted by the light tone of emerging cracks in the satellite image. The landslide's surface topography is complex within a steeply sloped area, attributed to the alternating nature of rocks with varying resistance to geodynamic energy and the region's high seismicity. Particularly distinctive are the amphitheatre areas characterized by fresh landslide materials and dissected by ravines. Vegetation, primarily shrubs, is sparsely observed in such areas, with their development reflecting the degree of surface stabilization (see Fig. 3).

The progression of erosion processes along the resultant cracks and in bare areas within the amphitheatre region may lead to the displacement of substantial debris into riverbeds, precipitating mudflows that breach these accumulations.

The significance of these processes for the population's safety is underscored by the fact that this territory, home to numerous historical landmarks and situated in close proximity to the country's capital, is heavily engaged in economic activities, notably in the tourism industry.

A notable example of soil erosion is observed in the spur of the Main Caucasian ridge Khanyaylag, situated in close proximity to the city of Sheki, a significant historical and cultural centre of Azerbaijan. The high-mountain section of this ridge towers above the city, and the progression of these erosion processes poses a threat not only to Sheki but also to the surrounding areas. The examination of the soil-erosion map of the mountain-meadow belt in this region, compiled based on satellite imagery from 2017, reveals that areas with a low degree of erosion cover a considerable expanse. However, the ongoing development of soil and vegetation degradation processes in such territories could lead to their escalation to areas with moderate and severe erosion (see Fig. 4).

Numerous researchers have emphasized the vulnerability of the soil cover in the Greater Caucasus, as well as other mountainous regions, to anthropogenic influences (Poklar 2020; Tarikhazer 2022; Mamedov, Tarikhazer 2023).

The research conducted enabled the development of a comprehensive scheme outlining anti-erosion measures tailored to the specific relief conditions, climatic characteristics of the mountain-meadow belt, and the degree of surface erosion. This scheme takes

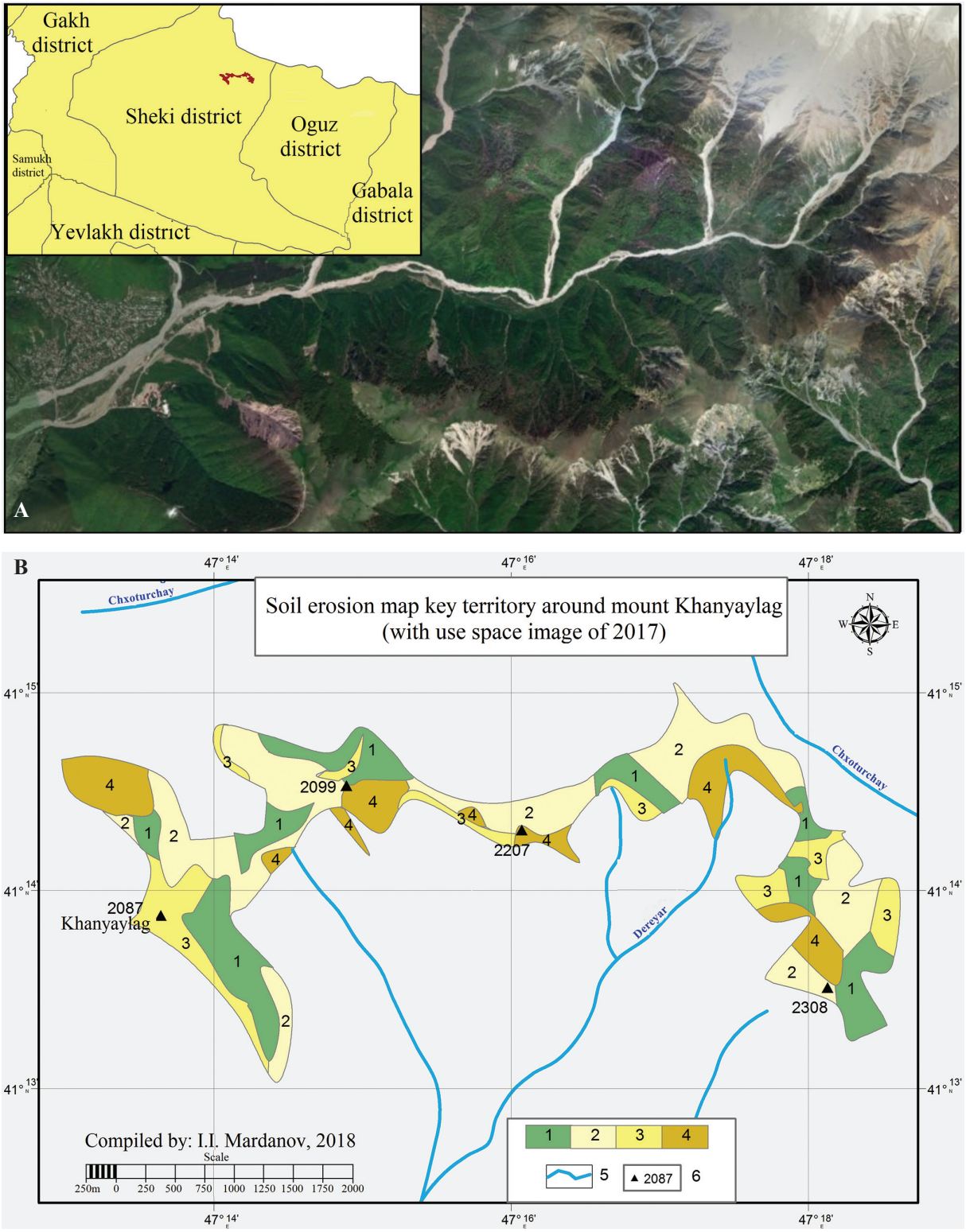

Fig. 4 A soil erosion map of a key area around the top of Khanyaylag (2087 m), compiled from the interpretation of a satellite image taken from the Sentinel-2 satellite, with a resolution of 10 meters: A – image of the study territory, B – map of the territory. Legend: 1 – non-eroded areas, 2 – poorly eroded sites, 3 – mid-eroded sites, 4 – strongly eroded sites, 5 – river, 6 – peak. Compiled by I.I. Mardanov, 2018

into consideration the characteristics of meadow vegetation and the patterns of soil erosion development associated with pasture farming on both the southern and north-eastern slopes of the Azerbaijani sector of the Greater Caucasus (see Table 1).

In neighbouring countries, ongoing research endeavours focus on assessing the extent of anthropogenic influence on the state of mountain natural complexes (Voskova *et al*. 2021).

The conclusions drawn from numerous studies conducted over the years across the mountain-meadow belt of the central part of the southern slope of the Main Caucasus Range consistently highlight human economic activity as one of the primary factors contributing to erosion, particularly linear erosion. Intensive grazing of livestock on steep slopes and in hollows, as well as repetitive traffic along the same routes, leads to the destruction of the turf layer and loosening of the soil. Subsequent precipitation then gradually washes away the soil, resulting in the formation of shallow gullies.

Over many years, the repeated movement of livestock and precipitation cause the gradual deepening and widening of gullies. This process is expedited by the increased steepness of the slopes of the Greater Caucasus, as heightened slope angles intensify washout and erosion. Our research into the genesis of ravines in the mountain-meadow belt of the southern slope of the Main Caucasus Range has revealed a significant intensity in gully formation within the study area. Based on a detailed genetic study of ravines during a period of numerous studies, the stages of their development were determined. Initially, erosion is gradual due to a high anti-erosion resistance of the upper soil horizon. The upper layers of soil, fortified by roots and rich in organic matter, which binds soil aggregates, exhibit slow erosion. Conversely, the underlying horizons, with lesser organic content, are unstable and erode rapidly. Once the upper stable horizon undergoes erosion and destruction, gullies with depths of 30–40 cm form. Subsequent erosion intensifies, marking the initial stage of ravine formation. Under favourable conditions, these gullies progress into ravines. Ravines typically range in length from 100 to 1800 meters, widths up to 300 meters, and depths up to 150 meters, with slopes reaching angles of 45º–50º.

The tops of gullies in the profile initially exhibit a triangular shape, which later transitions to a trapezoidal form. It's important to note that unlike in arable land where gullies or potholes are typically levelled during ploughing, this does not occur in the mountain-meadow belt. On the contrary, under the impact of intensive grazing and transhumance, gullies undergo gradual erosion and deepening, leading to rapid transitions between different stages of their development. Moreover, the intensity of gully formation and the development of ravines are significantly influenced by the nature of the underlying rocks.

Our research indicates that during the development phase, distinct variations are observed at the bottoms of ravines due to the presence of rocks exhibiting varying degrees of resistance to erosion. For instance, in the basin of the Kishchay River, which flows from the southern slope of the Main Caucasus Range on the outskirts of the village of Kish, ravines known as "Kavan Sarmasy" are formed. These ravines feature drops at their bottoms, attributed to the alternating layers of limestone and clayey shales in this area. The territories of the mountain-meadow belt abound with ravines within the basins of the Kurmukhchay River above the villages of Sarybash and Ilisu, the Shinchay River in the area of the Salavat Pass, and the Mukhakhchay River in the vicinity of the village of Suvagil.

The properties of the underlying rocks influence

Table 1 Scheme of anti-erosion measures in the high-mountain belt of the Greater Caucasus

Degree of erosion	Measures
Non-eroded	A) Implementing regulations on cattle grazing and utilizing a pen system
	B) Adopting conservation regimes and monitoring the biological diversity and chemical composition of soil and plant groups
Slightly eroded	A) Constructing protective dams in steep areas (150–200 meters), thereby mitigating surface runoff and furrow formation, and implementing park mode strategies
	B) Implementing measures to improve surface conditions, such as grass seeding, clearing scree and placer materials, and preventing runoff and furrow formation
Medium-eroded	A) Implementing fertilization and constructing protective dams in grasslands on the north-eastern slope of the Greater Caucasus, temporarily halting grazing activities, reclaiming ravines, and ceasing their further development
	B) Constructing protective dams on the southern slope of the Greater Caucasus to prevent ravine development, ameliorating existing ravines, and terminating cattle grazing
Strongly eroded	A) Halting livestock grazing, constructing hydraulic structures to mitigate surface runoff, and preventing ravine development while ameliorating existing ravines
	B) Seeding grass on gently inclined plots, primarily on northern slopes less susceptible to heavy rainfall impacts

not only the intensity of the development of ravines, but also the shape of their cross-section. In the mountain-meadow belt of the southern slope, the ravines, as usual, have a spherical shape in plan and an arcuate shape in profile, which is due to the presence of easily eroded rocks and the convex shape of the entire southern macroslope of the Greater Caucasus.

In the upper part of the mountain-meadow belt and subnival zone, where the soil cover is in the initial stage of development in the form of separate spots of alpine carpets, erosion processes are mainly due to a strong dissection of the relief (4–5.5 km/km^2).

Actually, the mountain-meadow belt within the study area is represented by alpine and subalpine subbelts and covers a strip of mountains with intensely dissected relief within the altitude range of 2000–3000 m. In some places, the border of subalpine meadows is noticeably reduced, which is associated with the cutting down of the upper border of forests. In some parts of the basins of the Kurmukhchay, Shinchay and Kishchay rivers, mountain-meadow, grass subalpine vegetation is lowered to altitudes of 1600–1700 m.

The total area of mountain meadows within the basins of these rivers amounts to 138.0 km^2, out of which 62.6 km^2 are nearly entirely affected by soil erosion, presenting barren areas that serve as sources for mudflow formation. These basins experience the most intense soil erosion processes in the Greater Caucasus. In certain parts of these basins, particularly along the Kurmukhchay River, subalpine variants of mountain meadows situated below 2200–2000 meters elevation, covering an area of 12.1 km^2 (in the vicinity above the village of Sarybash), are almost entirely devoid of soil cover, manifesting as bare slopes exhibiting intense linear erosion.

CONCLUSIONS AND RECOMMENDATIONS

The degradation processes affecting the soil and vegetation cover of the mountain-meadow landscape belt and rock-nival complexes in the highlands of the Greater Caucasus have multifaceted impacts on human life in these regions. Soil erosion development results in a depletion of vegetation species within mountain meadows and hayfields, leading to a reduction in the quantity of forage grasses available. This subsequently affects the quality of meat and dairy products sourced from livestock returning from summer pastures to the lowland areas, where a majority of the country's population resides.

Research examining the extent of erosion of mountain-meadow soils in the most degraded section of the Greater Caucasus highlands, particularly in its central region, revealed that a larger proportion of the area comprises slightly eroded regions, covering an expanse of 106.50 km^2. This accounts for approximately 32.29% of the total area. Moderately eroded areas occupy 72.44 km^2, that is, 21.87%, and the area of highly eroded soils is 77.8 km^2, that is, 23.59%. Indeed, the area of moderately eroded and highly eroded soils is less than the area of slightly eroded soils, but with the further development of erosion processes, their area may increase to dangerous values. The area of non-eroded lands, which constitute only 8.02% of the total area, may also decrease.

On the south-eastern slope of the Greater Caucasus, the area of slightly eroded mountain-meadow soils is already more than 180.88 km^2, which occupies 45.93% of the total area. The area of highly eroded soils is also more significant – 140.2 km^2, which is 35.60%. This indicates the need to determine territorial priorities when organizing anti-erosion measures.

Degradation processes lead to the deterioration of landscape situation and the emergence of landscape elements uncharacteristic of the mountain-meadow belt and new geomorphological conditions (Tarikhazer *et al*. 2021; Tarikhazer 2020).

The erosion process can cause surface water to infiltrate into the pores of rocks, rather than the soil, and thereby cause the accumulation of groundwater, which is an important factor in landslides.

The degradation of mountain-meadow surfaces and deforestation significantly heightens the risk of mudflows, posing a crucial constraint on the development of various economic sectors in this region. Consequently, continuous monitoring of the condition of soil and vegetation cover is imperative, alongside the construction of more robust protective structures to mitigate these risks.

Currently, in the highlands of the Greater Caucasus there is an increase in tourism activity, and the highlands of the Azerbaijani part of the Lesser Caucasus still have a longer perspective in this regard. In the high-mountain zone, the establishment of winter recreation centres, the development of hiking trails, and the organization of mountaineering competitions are fostering a new realm of human activity that engages the local population, alongside the traditional economic sectors of the region. However, the expansion of tourism activities necessitates thorough research into the potential environmental impacts and risks. Consequently, many countries with thriving tourism sectors are actively engaged in modelling complex scenarios and formulating strategies to address them (Popović *et al*. 2021).

The degradation processes affecting high-mountain landscapes can lead to population migration from areas deemed unfavourable due to exodynamic factors, thereby exacerbating social challenges in lowland regions and major cities.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the anonymous reviewers whose insightful comments and suggestions greatly contributed to the refinement of this manuscript.

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