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The History of Mudflow Processes Research in Georgia (on the example of Kakheti)

Tinatin Nanobashvili*

1 Department of Geography, The Faculty of Exact and Natural Sciences, Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia,

* Corresponding author: tinatin.nanobashvili@tsu.ge

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Abstract

Georgia, as a mountainous country, provides favourable conditions for the development of mudflow processes. The study of these processes is essential for their effective management, the reduction of damage, the prevention of casualties, and the preservation of undisturbed areas within the country's already limited land resources. Research on mudflow processes in Georgia dates back more than a century. The earliest investigations were rather primitive in nature and were primarily aimed at identifying events that had already occurred, rather than analysing their formation or attempting prediction. This article examines how the scientific approach to mudflow research has evolved over time. It is mainly based on documentary research and the analysis of published sources, and it outlines the objectives of mudflow studies at different historical stages, as well as the criteria used for subsequent classification. The first descriptive reports on turbulent processes along the Georgian Military Road were published in 1891 in the Proceedings of the Russian Geographical Society. S. Rauner's work Southern Caucasus Silt Flows and Their Regulation was published in the Forestry Journal (issues 1–2) in 1903. Notably, this publication described not only the mudflow of the Duruji River that occurred on 23 May 1899, but also the mudflows of the Stori and Kisiskhevi rivers. It also addressed certain protective measures, primarily forest melioration and the terracing of valley slopes. At the beginning of the 20th century, specifically on 30 August 1906, information on the passage of the Duruji River mudflow through Kvareli appeared in the monthly meteorological bulletin of the Tbilisi Physical Observatory. Whereas early studies were purely descriptive, by the 1940s the focus had shifted towards the geographical aspects of mudflows, with increasing attention paid to their origin and to mitigation measures. In later studies, attempts at prediction also became apparent. At the same time, greater emphasis was placed on understanding the process itself. A landslide, as a geodynamic category, is determined by a complex combination of multiple factors.

Keywords: Mudflow Processes, Classification of mudflow, Criteria of classification, Genesis, Result

Introduction

The study of mudflows in Georgia spans more than a century. The earliest investigations were rather primitive in nature, focusing primarily on documenting events that had already occurred rather than examining their formation or attempting prediction. The first descriptive accounts of mudflow processes along the Georgian Military Highway were published in 1891 in the Proceedings of the Russian Geographical Society. Research on mudflows in the Kakheti region dates to approximately the same period. In 1903, *the Forestry Journal* (issues 1–2) published S. Rauner's article *Debris Flows of Transcaucasia and Their Regulation. Notably*, this paper described not only the mudflow of the Duruji River that occurred on 23 May 1899, but also those of the Stori and Kisishkevi rivers, while also discussing certain protective measures—primarily forest reclamation and the terracing of valley slopes. At the beginning of the 20th century, specifically on 30 August 1906, reports on the passage of a Duruji

River mudflow through Kvareli appeared in the monthly meteorological bulletin of the Tbilisi Physical Observatory.

In general, mudflow events occupy a prominent place among modern geomorphological processes in the Kakheti region, representing the culmination of a complex denudational system. Their activity often causes significant material damage to the economy. Since the 19th century, destructive natural hazards have attracted considerable attention in Kakheti. Numerous expeditions and research activities have been undertaken, and various measures for combating such processes have been developed. The results of these efforts have been published in a large number of geomorphological and geological studies.

The development of mudflow foci in Kakheti is facilitated by its continental climate, characterised by large diurnal temperature amplitudes; the frequent recurrence of dry, drought-prone periods occasionally replaced by heavy rainfall; and the high degree of dissection of mudflow catchment basins—predominantly of Badlands morphology—against a backdrop of pronounced hypsometric variation. Other contributing factors include the absence of soil and vegetation cover, the exposure of rocks that are easily weathered and eroded by surface runoff, and, most importantly, the intensive development of landslide–gravitational processes both within the catchment and along the flow channel. Anthropogenic factors also play a significant role in mudflow formation, including unsystematic deforestation, tree felling on slopes, and improper transportation practices.

This article presents the results of mudflow research in the Kakheti region and, based on the accumulated material, discusses the potential long-term tendencies in the development and reactivation of such hazardous processes.

Methods and Materials

To study the formation of mudflow processes in Georgia, a document and literature review method was applied. This involved a content analysis of documentary sources and, more specifically, a detailed examination of hazardous events characteristic of individual municipalities within the Kakheti region.

With regard to the sources themselves, it should be noted that while early research was limited to descriptive accounts, by the 1940s discussion of the geographical aspects of mudflows had come to dominate. In the case of the Kakheti region in particular, it is important to emphasise that systematic study of the problem began only in the second half of the 20th century. Prior to this period, sources directly addressing the hazardous characteristics of Kakheti—and especially its mudflow processes—were scarce.

From the second half of the 20th century, alongside issues of environmental protection and natural resource use, special attention was devoted to the study of mudflows and landslides, in parallel with other modern geomorphological processes. During this period, research on mudflows in Kakheti was conducted by the Vakhushti Institute of Geography of the Georgian Academy of Sciences and the Georgian Geographical Society, the Scientific Research Institute of Hydrotechnics and Melioration of Georgia, the Sector of Hydrology and Engineering Geology, the Transcaucasian Hydrometeorological Research Institute, and the Geological Department under the Georgian Academy of Sciences. A substantial body of both published and archival material was accumulated at that time. Particularly noteworthy is T. Kikilashvili's work *The Main Factors Causing Mudflows in the Duruji River Basin* (1949).

In the spring seasons of 1952 and 1953, in connection with the engineering–geological planning of the main canal of the Upper Alazani irrigation system, A. Fokon and E. Ramishvili studied landslide phenomena on the eastern slope of the Tsova (Tbatana) Range in the Pankisi Gorge and on the south-western slopes of the Tsiv–Gombori Range, extending from Mount Shakhvetila to the town of Sighnagi. G. Changashvili published a series of works, including *Geomorphology of the Right Bank of the Alazani River Basin (Upstream from Bakurtiskhe) (1954), Mudflows and River Channel Variability in the Right Bank of Inner Kakheti (1955), Mudflows and Measures for Their Control in the Left Bank of the Alazani River (1962), On Modern Geomorphological Processes in the Vicinity of the Sioni Reservoir (1975), and The Causes of the Mudflow of 14 June 1977 in the Telavi District (1978)*, among others. In 1967, G. Changashvili also published A Geomorphological Study of the Right Bank of the Alazani River Basin (Upstream from Tsnori), which represents the processed results of data collected during field geomorphological research conducted in 1952, 1953, 1954, and 1960.

In 1958, T. Kikilashvili and M. Kordzakhia published *On the Issues of Mudflows (Mudflow Torrents) in the Alazani River Basin. In the same year, V. Lezhava published Mudflows on the Right Bank of the Alazani River from the Source to the Vantiskhevi, and Sh. Kipiani authored Modern Geomorphological Processes and Phenomena in the Duruji River Basin.*

For the scientific value of this article, the processing of the above-mentioned sources was of particular importance for analysing the formation and characteristics of mudflow processes both in Georgia as a whole and specifically in the Kakheti region.

Results

From the 1940s onward, scientific literature shifted its focus from mere descriptive accounts toward analyzing the mechanisms of mudflow formation and identifying measures for their mitigation. In subsequent years, attempts at prediction also became evident. Equally important was the study of the process itself. Mudflow, as a geodynamic category, is determined by a complex interplay of multiple factors.

The term *"seli"* (or *"sili"*), which entered Georgian literature directly from Russian without translation, is in fact of Arabic origin: *"sail,"* meaning a turbulent streams. Over time, many synonyms for the term emerged. In France, where the first works on such phenomena were published, these torrents were called *"torrents,"* literally meaning mountain streams; in Switzerland and Austria, the terms *"wildbach"* (wild stream) and *"mure"* were used; in the United States, *"mudflow," "mudavalanche,"* or *"rock-mudflow"* became common; and in Japan, expressions such as *"yamanatsunami"* (mountain wave) or *"dosekiro"* (mud torrent/stream) were adopted.

In Georgia, the Russian *"seli"* was soon replaced. Besarion Kavrishvili proposed the term *"ghvartsopi"* (mudflow), which clearly reflected the rheological nature of this geodynamic process. Being an authentically Georgian word, it quickly secured a rightful place in geographical literature. At the same time, local designations also appeared in other Caucasian countries - for example, *"ikhi"* in Kabardino-Balkaria.

From all these terms, it becomes clear that a mudflow refers to a water-sediment stream composed of fine-grained material as well as large rock fragments, characterized above all by its scale and dynamism. Mudflows are marked by sudden onset, considerable magnitude and volume, high concentrations of coarse debris within the flow, and very high velocity - reaching several meters per second. In many cases, mudflows cause powerful destruction and devastation within only a few minutes. For this reason, in scientific-popular and literary works they are sometimes referred to as *"black death."*

Over the past century, during which mudflow research has intensified, numerous attempts at classification have emerged. Given that the formation and development of mudflow processes are conditioned by an extremely complex set of geographical and geological factors, different units have been emphasized for classification. As a result, scientific literature has accumulated a wide variety of mudflow classifications, often quite distinct from one another. Some researchers have prioritized their genetic origin, thus distinguishing between natural and anthropogenic mudflows.

Throughout the 20th century, the study of mudflow processes in Georgia was largely linked to the "all-Soviet" period. Consequently, the approaches of the Russian scientific school, which were disseminated in a centralized manner, are of particular importance. For this reason, it is essential to address the tendencies that emerged in the 1930s. In Russian scientific literature, several attempts at mudflow classification appeared, among which the works of E.P. Konovalov, A.I. Sheko, R.D. Kurdin, I.V. Vinogradov, S.M. Fleishman, and B.F. Perov are noteworthy. In the Georgian school, the contribution of M.S. Gagoshidze to mudflow research should also be emphasized. A brief review of each classification will allow us to analyze how evaluation criteria and methodological approaches in mudflow studies evolved, and what shortcomings or advantages each scientist's role entailed.

E.P. Konovalov, in presenting a genetic classification of mudflows, considered water as the single most important and mudflow-forming factor. His classification was based on the role of water in mudflows, and he identified the following genetic types:

1. Mudflows caused by heavy rainfall, or simply torrential mudflows/debris flows;
2. Mudflows resulting from the intensive melting of snow and ice;
3. Mudflows caused by the rupture of water bodies: a) glacial lakes, b) non-glacial lakes, c) artificial reservoirs;
4. Mudflows of complex origin, formed by two or more factors, e.g., the combined effect of rainfall and meltwater.

At the time this classification was developed (1938), knowledge about mudflows was still quite limited. However, its main shortcoming lay in the fact that under this approach, one and the same mudflow could be assigned to two different types, which is entirely unacceptable in classification. Equally problematic was that in distinguishing the first and second types, the defining criterion was the triggering factor, whereas in the third type the classification was based on the mechanism of origin. These are not equivalent approaches. It is also difficult to accept that natural and anthropogenic origins were combined within the third type (Konovalov, 1938).

As for A.I. Sheko's classification, the author identified four main groups of mudflow source formation: 1) accumulation of solid material in temporary and minor streambeds; 2) river damming; 3) modern glaciers; 4) volcanic activity. It should be noted that, as with Konovalov's classification, there was no uniform genetic approach in defining the main groups, and once again, the same mudflow could simultaneously be placed in two different groups (Churinov and Sheko, 1971).

R.D. Kurdin proposed a universal scheme for classifying mudflows. His classification was based on four criteria: the nature of mudflow formation, the structural-rheological model of the mudflow, its composition, and its intensity and destructive power. Since the most important components of mudflows are water and solid material, he conditionally divided them into two categories. According to water supply, the following subgroups were distinguished: 1) rainfall-fed, 2) snowmelt, 3) glacial, 4) outburst. According to solid material supply, the following subgroups were identified: 1) slope-derived, 2) collapse-landslide, 3) channel-derived/streambed-type, 4) morainic. However, this classification also had its shortcomings, as the water and solid components of a mudflow cannot truly be separated from one another. The destructive force of a mudflow results only from the unity of these two parts, and only this unity can properly be termed a mudflow (Kurdin, 1973).

With regard specifically to the Kakheti region, until the 20th century almost no literary sources on destructive natural processes are available. From the beginning of the 20th century, research on such processes acquired a local character, which explains the limited number of sources, focusing only on the mudflows of the Duruji, Stori, and Tsiviskhevi rivers. In this regard, S. Rauner's 1903 publication is particularly noteworthy, as it describes the Duruji River mudflow that destroyed the village of Kvareli on 23 May 1899. Reports on the passage of the Duruji mudflow through Kvareli on 30 August 1906 are also preserved in the monthly meteorological bulletin of the Tbilisi Physical Observatory, noting that the mudflow destroyed houses and fences along its path, washed away orchards, vineyards, and farmland, and killed both people and livestock

In the subsequent period, despite the scarcity of available geographical data, the study of destructive natural processes gradually took on a scientific character. These issues were studied by Tbilisi State University, the Scientific Research Institute of Hydrotechnics and Melioration of Georgia, and other institutions.

In recent years, the remote sensing method has taken on a significant role in process research. Based on the analysis of landscape-indicative features, remote sensing materials have revealed the spatial characteristics of landslides, the locations and timing of mudflow passages, time and other related phenomena.

An examination of ongoing mudflow processes in the Kakheti region reveals that, at present, approximately 250 mudflow-prone rivers have been registered in the target area, posing direct threats to the population, infrastructure, and engineering structures. In reality, however, the total number of channels susceptible to mudflow transformation is nearly five times greater.

In the Duruji River and, more broadly, within the Kakheti sector of the Greater Caucasus, high-density (1.8-2.5 g/cm^3) boulder-mud structural-rheological flows typically form, particularly under conditions conducive to the development of catastrophic mudflows. This explains why the composition of boulder-mudflow currents often includes massive boulders (2-5 meters or more in diameter) within transit-accumulation zones, and sometimes even transported into accumulation areas. The mudflows of the Duruji River place the town of Kvareli and its infrastructure at great risk. At present, the most optimal and effective protective measure for the residents of Kvareli against mudflows is considered to be a 7 km long embankment, the project for which envisaged the construction of a 15-20 m high earthen dam, the periodic cleaning of the river channel, and the use of the excavated material to increase the dam's height (Tsereteli, et al., 2001).

The mudflow processes formed in the Telaviskhevi river are typical of all mudflow-transformed rivers on the slopes of the Tsiv-Gombori Range, characterized by fan-shaped spreading. Whenever mudflow-generating rainfall occurs, the formation of mudflow currents is inevitable - the greater the precipitation in the form of torrential rains, the proportionally higher the risk of hazard. A classic example of this is the mudflows formed in the Telaviskhevi river on 14 June 1977, triggered by torrential rainfall of up to 80mm within three hours. Mudflow processes developed simultaneously in 8 tributaries of the river basin, of which 5 produced landslide-outburst flows. In total, the mudflows transported up to 1 million m^3 of boulder-mud material, of which about 300 000 m^3 was deposited in the cone area on which the town is situated. To prevent the recurrence of such hazardous mudflow processes in the Telaviskhevi river, in 1978 a debris-trapping permeable structure was constructed (Tsereteli et al., 2002).

Kurilla and Fubelli's article (2022) discusses the development of a global debris-flow susceptibility model, in which a large number of environmental parameters must be considered. Although debris-flow behaviour and controlling factors are inherently local phenomena, the analysis based on the Maximum Entropy (MAXENT) model demonstrates that a global model performs particularly well when evaluating cumulative susceptibility outcomes in the medium, high, and very high classes. In the Kakheti region, the intensity of debris-flow occurrence is reflected in the table and mapped distribution presented below (Table 1, Fig. 1).

Table 1. Mudflow ratio by municipalities

Municipality	Mudflow
Akhmeta	0.580
Gurjaani	0.839
Dedoplistskaro	0.250
Telavi	0.700
Lagodekhi	0.515
Sagarejo	0.426
Sighnaghi	0.476
Kvareli	0.545

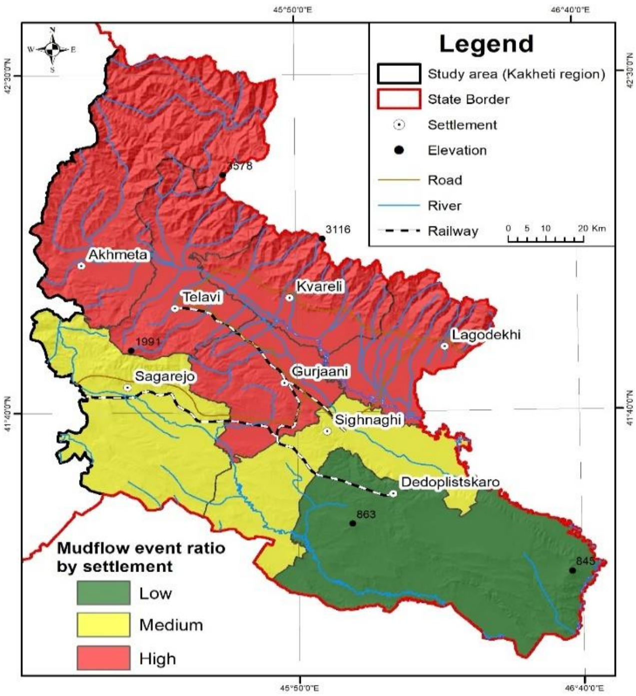

Figure 1. Mudflow event ratio by settlement, Data source: Department of Geology, National Environment Agency (2024)

Beyond the description of the current situation, it is particularly important to identify the expected changes in climate, as this will enable the anticipation of natural hazard risks. In Georgia, a major contribution to the study of mudflow processes was made by geomorphologist Emil Tsereteli. Under his leadership, the general scheme (1988) of geological conditions for the development of mudflow processes was prepared. A geological report was also developed as a model, focusing on climate-resilient practices for managing floods and flash floods in the Rioni river basin. Under Emil Tsereteli's guidance, the scale of mudflow processes' dependence on climate was studied, along with an attempt at forecasting based on this approach. Below, we present the projected climate change trend for 2020–2050, developed by the Caucasus Environmental NGO Network (CENN), which subsequently serves as the basis for the long-term forecasts of natural hazard risks and the tendencies of development-reactivation of hazardous processes in individual municipalities of the Kakheti region, prepared at the Geological Department of the National Environment Agency under Emil Tsereteli's leadership.

Of the 289 settlements in Akhmeta Municipality, 15 (i.e., 54%) fall within the natural hazard risk zone. Of these, 5 settlements are classified in the high-risk category, 19 in the medium-risk category, and 17 in the low-risk category (Gaprindashvili et al., 2021). For Akhmeta Municipality, the forecast relative to the baseline period (1960-1990) is negative: for 2021-2050, = -2.704, with a deviation coefficient of Kdef. = -0.011. In the case of daily torrential rains, which have a particularly strong impact on the activation of mudflow processes and flash floods, the forecast for 2021-2050 is positive at +1.539, with a coefficient of Kpos. = +0.14, while for 2071-2100 it is negative at = -1.012, with a coefficient of Kdef. = -0.09. Based on these data, it can be assumed that the long-term forecast of geological process activation trends will remain at the same background level as observed to date.

Among the geological hazardous processes affecting the normal functioning of the city of Telavi, the only major threat is posed by periodically formed mudflow processes in the Telaviskhevi river basin. The long-term climate change forecast for Telavi is as follows: For intra-annual precipitation deviations: 2021-2050 shows a deficit of -8.572, with a deviation coefficient Kdef. = -0.01. For daily torrential rainfall with average recurrence: 2021-2050 is 0.387, with Kdef. = -0.095; and 2071-2100 is -1.942, with Kdef. = -0.249. According to the forecast of geological hazards, compared to the previous period, the expected trends remain below the background level (Gobechia et al., 2009).

In Gurjaani Municipality, according to the 2000 Geological Information Bulletin, 12 settlements were located within the geological hazard risk zone; by 2014, this number had increased to 26 (hazard risk coefficient 0.65). According to the 2021-2100 forecast, climate change in the territory of Gurjaani Municipality will show a deficit relative to the baseline period. The deficit deviation of average annual precipitation is projected to be = -9.343 for 2021-2050, with a deviation coefficient Kdef. = -0.014, and = -17.677 for 2071-2100, with Kdef. = -0.051. In the case of torrential rainfall: for 2021-2050 the value is = -0.450, with Kdef. = -0.36; and for 2071-2100 it is = -1.632, with Kdef. = -0.0002. It may therefore kobe assumed that with such coefficients of atmospheric precipitation, the tendencies of geological process activation will remain below the background level of the previous period.

In Sagarejo Municipality, 21 settlements - representing 47% of the total number of settlements - were located within the geological hazard risk zone (of which 10 were in the medium- and high-risk categories). This indicates that within the territory of Sagarejo Municipality, vulnerability to geological hazards has increased, with a risk coefficient of 0.3. According to the climate change projections developed for Georgia by specialists of the National Environment Agency for the periods 2021-2050 and 2071-2100, Sagarejo Municipality is expected to experience a deficit relative to the baseline period (1960-1990). Specifically, for annual precipitation deviations: = -8.676 for 2021-2050, with Kdef. = -0.015, and = -18.329 for 2071-2100, with Kdef. = -0.032. For the average number of days with torrential rainfall: = -0.68 for 2021-2050, with Kdef. = -0.048; and = -1.240 for 2071-2100, with Kdef. = -0.22. It can be assumed that, given the negative coefficients obtained, the trends in the development of geological hazards will remain below the baseline level.

In Sighnagi Municipality, 14 settlements (64% of the total) were located within the geological hazard risk zone, of which 5 (22%) were in the medium- and high-risk categories. According to the trends in process development in relation to climate change, as assessed by specialists of the Hydrology and Meteorology Department of the National Environment Agency, the average annual precipitation changes for Sighnagi Municipality are projected to remain in deficit compared to current levels. Specifically, for 2021-2050 the value is = -9.789, with Kdef. = -0.012; and for 2071-2100 the value is = -16.031, with Kdef. = -0.02. For the recurrence of daily torrential rainfall, the forecast relative to the baseline period is also negative: = -0.699 for 2021-2050, with Kdef. = -0.09; and = -1.240 for 2071-2100, with Kdef. = -0.156. Based on these data, it can be assumed that the long-term forecast of geological hazard development trends will remain below the background level observed to date.

The population and infrastructure of Kvareli Municipality are threatened only by mudflows transformed on the southern slopes of the Caucasus, along with the associated bank erosion and flooding they cause. Accordingly, of the 22 settlements, 13 are located within the mudflow hazard risk zone (risk coefficient 0.6), of which 4 fall into the high- and medium-risk categories (coefficient 0.18). For the periods 2021-2050 and 2071-2100, the intra-annual deviations of atmospheric precipitation that provoke geological processes in Kvareli are projected to show a negative balance relative to the national baseline. Specifically, intra-annual precipitation deviations are = -9.576 for 2021-2050, with Kdef. = -0.01, and = -18.043 for 2071-2100, with Kdef. = -0.020. Regarding the average number of days with torrential rainfall: = -1.212 for 2021-2050, with Kdef. = -0.097, and = -4.716 for 2071-2100, with Kdef. = -0.461. It can therefore be assumed that, given the significant precipitation deficit projected for both intra-annual totals and torrential rainfall, the tendencies of geological hazard activation in this period will remain below the background levels of previous periods.

Of the 64 settlements in Lagodekhi Municipality, 38% are located within the geological hazard risk zone. Among them, 20% fall into the medium- and high-risk categories (risk coefficient 0.2), and all are associated with mudflow processes, flash floods, and/or riverbank erosion. Long-term forecasts indicate that in the territory of Lagodekhi, the deviations of atmospheric precipitation that provoke geological processes will have a negative balance. Specifically, the intra-annual precipitation deficit will be = -9.776 for 2021-2050, with Kdef. = -0.01, and = -16.639 for 2071-2100, with Kdef. = -0.017. Regarding the average number of days with torrential rainfall: = -1.540 for 2021-2050, with Kdef. = -0.173; and = -4.716 for 2050-2100, with Kdef. = -0.48. It can therefore be assumed that, given such coefficients of atmospheric precipitation, the tendencies of geological hazard activation will remain below the background level of the previous period.

Dedoplistskaro Municipality is the only territory in the Kakheti region where geological processes pose no significant threat, apart from bank erosion along the Alazani and Iori rivers and seismic activity. According to the climate change projections developed by specialists of the National Environment Agency for the periods 2021-2050 and 2071-2100, the average annual precipitation deviations relative to the multi-year average will remain in deficit: = -7.219 for 2021-2050, with Kdef. = -0.008, and = -12.178 for 2071-2100, with Kdef. = -0.015. The average number of days with torrential rainfall recurrence is also projected to be negative: = -0.224 for 2021-2050, with Kdef. = -0.027, and = -0.451 for 2071-2100, with Kdef. = -0.054. It may therefore be assumed that, given the deficit coefficients obtained, the tendencies of geological hazard activation in Dedoplistskaro Municipality will remain below the background level observed to date.

Since destructive natural processes in Kakheti represent one of the pressing issues of state significance, it is hoped that future research will be further deepened and yield better results.

Discussions

The results of this study align with earlier classifications and observations of mudflows by Konovalov (1938), Sheko (1971), and Kurdin (1973), all of whom emphasized the central role of hydrological triggers but differed in their methodological criteria, often leading to overlaps in typology. Georgian scholars, including Changashvili (1954, 1955, 1962, 1975, 1978), Kikilashvili (1949), Kipiani (1958), Lezhava (1958), and later Tsereteli and colleagues (1978, 1985, 2001), extended this knowledge to the Kakheti region, highlighting both the geomorphological drivers and the severe socio-economic consequences of events such as the 1899 and 1906 Duruji mudflows or the 1977 Telaviskhevi disaster. Our findings confirm these historical insights: despite projected long-term precipitation deficits across municipalities, extreme short-duration rainfall remains sufficient to trigger destructive flows, particularly in highly dissected catchments like those of the Greater Caucasus and Tsiv-Gombori slopes. Thus, the Kakheti case underscores a broader pattern noted in both Soviet-era and modern literature: declining climatic means do not equate to reduced hazard, and risk management must integrate structural defenses with ecological and monitoring-based approaches.

On the global scale considering the modern approaches, recent literature has increasingly focused on cross-continental differences in debris-flow behaviour. For instance, Kurilla and Fubelli (2022) demonstrated that a single global debris-flow susceptibility model - particularly the MAXENT approach - can perform as well as or better than continent-specific models when evaluated across five statistical frameworks and fourteen environmental predictors. Complementing this large-scale perspective, Schöffl et al. (2022) provided high-resolution empirical insights from Illgraben, Switzerland, showing substantial intra- and inter-event variability in flow resistance based on pulse-Doppler radar measurements, thereby challenging assumptions of constant resistance in traditional modelling and proposing a new dimensionless scaling framework. At a more fundamental level, Coussot's monograph *Mudflow Rheology and Dynamics* (1997) offers the theoretical basis for understanding mudflow rheology and open-channel behaviour, linking constitutive equations to applied flow dynamics.

Conclusion

In conclusion, it should be emphasized that in all the classifications discussed in this article, mudflows are considered as one of the most complex geodynamic processes, formed through the interplay of multiple geographical and geological factors. The main focus has been placed on their intrinsic nature, and the attempts at classification have been grounded in this understanding - whether based on their origin, the course of the process, or the stage of dissipation, i.e., the accumulation phase. The classifications developed thus far have been largely attempts at ranking processes, without sufficient attention to the mudflow as a phenomenon. Distinguishing between process and phenomenon is crucial in the study of mudflows. For us, a mudflow is significant precisely as a phenomenon, since in practice we analyze the consequences of its occurrence. This should not be perceived merely as the statement of a past fact, but rather as recognition of the mudflow as an event that alters the geo-ecological state, affects the human living environment, and in many cases poses a direct threat to human life. For this reason, under modern approaches, the study of mudflows must include geo-ecological evaluation. It is of particular importance to assess the environmental impacts of mudflow phenomena and to classify them by ecological hazard in the context of sustainable environmental development.

As for the target location, the Kakheti region ranks among the most complex areas in Georgia in terms of the scale of mudflow development, recurrence frequency, economic damage, and hazard risk. More than half of its territory falls within the very high and high mudflow hazard categories (with coefficients of 0.6-0.9) (Tsereteli & Tsereteli, 1985).

The degree of activation and hazard risk of mudflows in Kakheti, against the backdrop of an extremely sensitive geological environment, depend entirely on climatic variability and on the magnitude of spatial and temporal deviations in intra-annual torrential rainfall. In this regard, for mudflows transformed in the Kakheti sector of the Greater Caucasus, daily precipitation exceeding 50 mm, and for those formed on the slopes of the Tsiv–Gombori Range exceeding 30–40 mm, must be followed by the immediate implementation of preventive measures.

These results underline the importance of viewing mudflows not only as geomorphological processes but as geo-ecological phenomena with direct societal implications. In the case of Kakheti, the evidence clearly shows that hazard levels remain high, making continuous monitoring and integrated management essential for reducing future risks. The global modeling approach discussed in the article is clearly applicable to regions such as Kakheti, where debris-flow activity is both frequent and intense.

Competing interests

The author declares that she has no competing interests.

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Mr. Emil Tsereteli was twice included in the list of the world's top 100 scientists compiled by the Cambridge International Biographical Centre. His contribution is invaluable - not only to the study of mudflow processes in Georgia and the development of various scientific methodologies, but also to practical activities and the training of future specialists who, in turn, have made significant contributions to the study of natural hazards.

ORCID iD

Tinatin Nanobashvili https://orcid.org/0009-0001-0601-0344

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