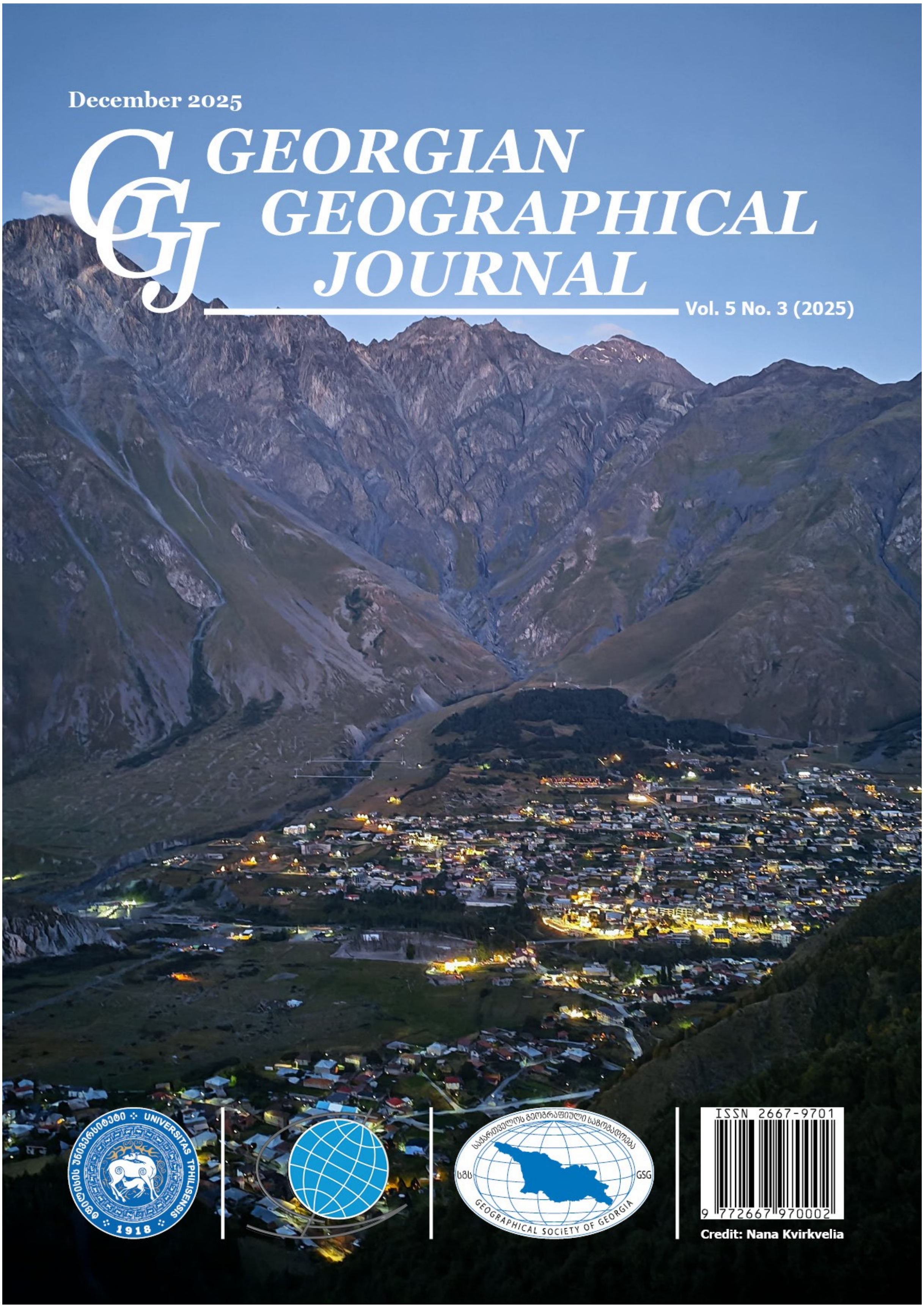

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Rural Depopulation in Georgia's Mountain Regions: Research Priorities in the Context of the 2024 Population Census

Editor-in-Chief's Note

The depopulation of rural and mountain regions represents one of the most serious long-term challenges facing Georgia's spatial, social, and economic development. Among these regions, Racha stands out as an area where population decline has been both rapid and persistent, affecting settlement viability, local economies, and cultural landscapes.

The relevance of this issue is underscored by the completion of Georgia's **2024 Population Census**, the first comprehensive demographic assessment conducted in the country in a decade. The census provides an essential empirical foundation for reassessing demographic trends, regional disparities, and development challenges across Georgia. For mountain regions such as Racha, the new census data offer an unprecedented opportunity to align scientific research with updated national evidence and policy needs.

In this context, the research project *"**The Depopulation of Rural Settlements in Racha: Spatio-Temporal Changes and Modern Problems**"*, implemented at the Vakhushti Bagrationi Institute of Geography with the support of the Shota Rustaveli National Science Foundation of Georgia, addresses one of the most pressing territorial challenges of our time. By combining statistical analysis of long-term demographic change with interdisciplinary fieldwork conducted directly in rural communities, the project seeks to move beyond descriptive population figures and toward a deeper understanding of the social, economic, and spatial mechanisms driving depopulation.

Preliminary insights from the research reveal a complex picture. On the one hand, limited economic diversification, infrastructural constraints, and sustained youth out-migration continue to undermine population retention. On the other hand, the relatively high educational level of the remaining population indicates the presence of significant, yet underutilized, human capital. These findings highlight that depopulation is not solely the result of geographical remoteness but also reflects structural development gaps that require targeted, evidence-based interventions.

The Georgian Geographical Journal considers research on rural depopulation and mountain regions to be of strategic importance, particularly at a moment when new census data allow for more precise and policy-relevant analysis. Future research directions should focus on spatial modelling of demographic change, comparative studies across mountain regions, and the integration of census data with local-scale qualitative research.

By fostering dialogue between empirical research and national demographic monitoring, this journal aims to contribute to a more informed and balanced discussion on regional development, territorial cohesion, and the future of Georgia's rural landscapes.

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

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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

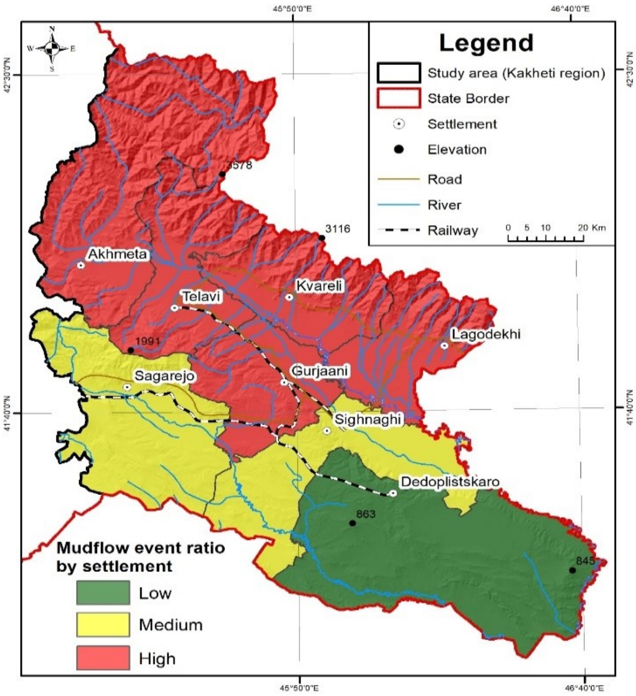

Figure 1. Mudflow event ratio by settlement, Data source: Department of Geology, National Environment Agency (2024)

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.

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Integrating GIS and Kernel Density Estimation for Multi-Hazard Risk Assessment of Potential Onshore Pipeline Failures

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Abstract

This paper introduces a newly developed risk-assessment framework that combines Kernel Density Estimation (KDE) with Geographic Information System (GIS) technology to analyze multiple hazards, including earthquakes, floods, landslides, mud volcanoes, and soil erosion, for the Baku-Tbilisi-Ceyhan pipeline in Azerbaijan. By integrating hazard-specific parameters into a unified risk matrix, each hazard's contribution is weighted, refined, and aggregated to produce a spatially explicit, combined risk map. KDE smooths hazard intensities and reveals overlaps among different risk factors. The resulting high-resolution maps enable more targeted prevention and response measures, guiding planners and stakeholders toward effective pipeline protection strategies. Although the model can demand computational power, it remains scalable and flexible, allowing for adaptation to additional hazards or expanded geographical areas. Furthermore, the methodology underscores the importance of cross-validation in setting KDE bandwidth and in calibrating hazard weights to ensure reliable outputs. Preliminary testing indicates that this integrated model improves the clarity of risk data, highlights areas needing immediate attention, and supports resilience planning across the pipeline corridor. This work can be applied more broadly to critical infrastructure projects in regions where multiple hazards coincide, thereby aiding decision-making processes for disaster risk reduction and sustainable development. Future research will focus on refining statistical models for inter-hazard correlations and incorporating machine learning for predictive analytics. The framework stands as a tool to maintain pipeline integrity in the face of evolving environmental threats.

Keywords: GIS, Kernel Density Estimation, Risk Matrix, Pipeline Integrity, Multi-Hazard Risk.

Introduction

Strengthening the durability of Azerbaijan's oil and gas infrastructure against natural disasters is a critical priority for researchers and industry stakeholders. Pipelines that transport hydrocarbons, while integral to national and transnational energy supply, are especially vulnerable due to the volatile nature of their contents. A failure can lead to irreparable environmental damage, human casualties, and costly socioeconomic disruptions (Lerche et al., 2014). The growing reliance on pipelines for interregional energy exchange, coupled with the apparent increase in natural disaster frequency, has underscored the need for comprehensive risk assessments (Krausmann et al, 2011). These assessments must extend beyond purely technical criteria to include geopolitical and environmental considerations, reflecting the international implications of pipeline failures and the cross-border nature of catastrophic events.

Climate change adds further complexity by intensifying extreme weather events and altering hazard patterns, placing critical infrastructure under unprecedented levels of stress (Zio, 2016). As natural disasters become more frequent and severe, safeguarding pipelines requires a flexible and forward-looking framework capable of integrating diverse data sources, advanced modeling, and predictive analytics. This forward-thinking perspective enables risk assessments that anticipate future scenarios rather than merely responding to current conditions.

Developing robust methodologies to quantify and mitigate these risks is thus an imperative, particularly in regions like Azerbaijan where seismic activity, floods, landslides, and mud volcanoes pose substantial threats (Othman et al., 2023). With pipelines traversing extensive distances across varied terrains, even localized disruptions can have extensive consequences. Consequently, the scientific community must invest in innovative tools and interdisciplinary strategies that address physical vulnerabilities, regulatory complexities, and cross-border interdependencies. Adopting a multi-hazard approach allows for a holistic understanding of pipeline resilience, thereby guiding more effective risk management, informed policy-making, and international collaboration.

Notably, specific natural disasters recognized in Azerbaijan can directly impact onshore pipelines, highlighting the urgency for targeted, data-driven solutions (Amirova-Mammadova, 2018; Bagirov et al., 2019):

1. **Earthquakes:** Azerbaijan experiences substantial seismic activity due to its location in an earthquake-prone zone (Alizadeh et al., 2017). Sudden ground movements or shifts can displace or fracture pipelines. Any rupture in a pipeline carrying hydrocarbons may cause leaks and, in severe instances, lead to explosions or fires.
2. **Floods:** Flash floods or prolonged heavy rainfall can result in rapid water accumulation and significant soil erosion[1]. High-velocity water flows may directly damage exposed pipeline segments, while erosion can undermine the structural support of buried pipelines, increasing the risk of bending or rupturing.
3. **Landslides:** In mountainous or hilly terrains, landslides can occur, particularly following intense precipitation or seismic events[2]. The downward movement of rock and soil can bury pipelines or exert forces beyond their design limits, leading to material failure.
4. **Mud Volcanoes:** Azerbaijan is well-known for its numerous mud volcanoes (Kadirov et al., 2005). These geological formations can erupt violently, expelling hot mud and gases capable of overheating, encasing, or fracturing adjacent pipelines, ultimately causing leaks or more severe accidents (Panahi, 2005).
5. **Soil Erosion:** Continuous erosion, often accelerated by flooding or heavy rainfall, can gradually expose pipelines designed to remain buried (Othman et al., 2023). Without adequate coverage, pipelines become vulnerable to external impacts and stress that can lead to cracks or breaks.

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[1] Pipeline safety: Potential for damage to pipeline facilities caused by flooding, river scour, and river channel migration (2019). https://www.federalregister.gov/documents/2019/04/11/2019-07132/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-flooding-river-scour-and-river

[2] Guidelines for Constructing Natural Gas and Liquid Hydrocarbon Pipelines Through Areas Prone to Landslide and Subsidence Hazards (2009). https://rosap.ntl.bts.gov/view/dot/34640

6. **Corrosion (Environmental Degradation):** While not considered a conventional natural hazard, corrosion is a significant environmental threat to pipelines. Humid or saline conditions accelerate metal deterioration (Cheng, 2015), and if not detected, corrosion can thin pipeline walls, resulting in leaks or complete structural failure.
7. **Extreme Weather Conditions:** Severe weather events—such as powerful storms, lightning strikes, or extreme temperature fluctuations—can damage pipelines directly or trigger secondary hazards like landslides or floods (Katopodis et al., 2019). While pipelines are built to withstand local climate norms, unusually harsh conditions can exceed their tolerance thresholds.
8. **Wildfires:** High temperatures from wildfires can damage pipelines and their protective infrastructure (Novacheck et al., 2021). Moreover, the burning of nearby vegetation may contribute to soil erosion, further exposing pipelines to potential mechanical stresses.
9. **Ground Subsidence:** This phenomenon, caused by natural geological activity or human practices (e.g., mining, groundwater extraction), results in the gradual sinking of the ground surface (Oruji et al., 2022). Uneven subsidence can place bending stress on pipelines, increasing the likelihood of ruptures.

Typically, the practice is to represent the impact and risk values for each hazard individually on separate maps. A risk matrix serves as a visual aid, facilitating the evaluation of the cumulative risk level associated with different occurrences, including natural disasters. This matrix is instrumental in pinpointing the probability and potential impact of a given event, thereby allocating it a precise risk rating. However, the variety of natural disasters differs by location, resulting in a diverse set of risk maps. This diversity can introduce complexities in managing and interpreting the array of maps (Samany et al., 2022).

Using a combined approach helps streamline this complexity by integrating multiple risk factors into a unified visual representation, simplifying analysis and decision-making (Falcone et al., 2022).

To derive a combined risk value encompassing all-natural disasters, one could consider aggregating the distinct risk values (Fotios et al., 2022) for each disaster. However, this method presupposes that all these incidents occur independently, a condition that might not always hold true. The overall risk assessment can be significantly swayed by the interrelations and mutual influences existing between various natural disasters. Recognizing these interdependencies is essential in accurately determining the combined risk value.

To maintain the integrity of all assessed risk values, the individual combined risk scores are connected to beforehand computed and proportionately weighted risk values for each type of natural disaster.

A critical initial phase involves quantifying the risk (Gemma et al., 2022) tied to each possible natural disaster. This could involve analyzing historical data on the frequency of natural disasters like earthquakes, floods, wildfires, and so on, within a targeted area to gauge their probability.

The core objective is to create a robust, multi-dimensional risk assessment model that not only identifies potential risks but also quantifies them in a meaningful and actionable manner (Rasouli & Imrani, 2023). To achieve this, we will employ a risk rating matrix grounded in rigorous mathematical formulations, enabling a detailed and nuanced understanding of risk levels. This matrix will integrate various risk factors listed above to generate a composite risk score for pipeline systems in the context of natural disasters. By combining the spatial analysis capabilities of GIS with the mathematical rigor of risk score calculations, this research endeavors to offer a novel and practical tool for policymakers, engineers, and disaster management professionals.

The ultimate goal is to enhance decision-making processes, facilitate proactive risk mitigation strategies, and contribute to the resilience and safety of pipeline infrastructures in the face of increasingly unpredictable natural events.

Methods and Materials

In this research, we utilize adjusted risk matrices that correspond to each relevant hazard type - encompassing both classical natural disasters (e.g., earthquakes, floods) and environment-based threats (e.g., corrosion). Each hazard is weighted according to its relative impact on pipeline integrity. These weighted factors are then refined using Kernel Density Estimation (KDE) techniques, converting the collected risk scores into a 2D array (Gramacki, 2017). The data assigned to each cell within these matrices can be stored in any relational database (Nasser, 2018) or in straightforward file formats such as comma-separated values (CSV) or JSON. This flexibility enables seamless integration with popular

GIS tools like ESRI ArcGIS or QGIS, where the 2D risk arrays can be visualized, analyzed, and used to inform decisions on pipeline protection and maintenance.

2.1 Area of observation

This research area (Fig.1) situated within Azerbaijan, known for its susceptibility to various natural disasters such as earthquakes, landslides, floods, and mud volcanoes. This region is identified as the "valley of mud volcanoes" Moreover, satellite imagery revealed the presence of strong wind patterns and noticeable geological faults in the area.

2.2 Risk Matrix

When analyzing the effects of natural disasters on pipeline systems, employing a risk matrix is an essential step for illustrating the degree of risk. This study utilizes a standard 5×5 risk matrix (Figure 2), which classifies threats according to their likelihood (ranging from rare to nearly certain) and potential consequences (spanning from negligible to disastrous) (Blokdyk, 2018). By adopting a five-tier system, each hazard can be systematically plotted on the grid, where higher probability and severity correspond to higher risk values.

Although summing the individual risk values for all-natural disasters can yield an overall, aggregated risk score, this approach assumes complete independence among events, which is not always accurate. Correlations and interdependencies between different types of natural disasters can significantly alter the true combined risk. Accordingly, such factors must be considered when determining an aggregated risk value.

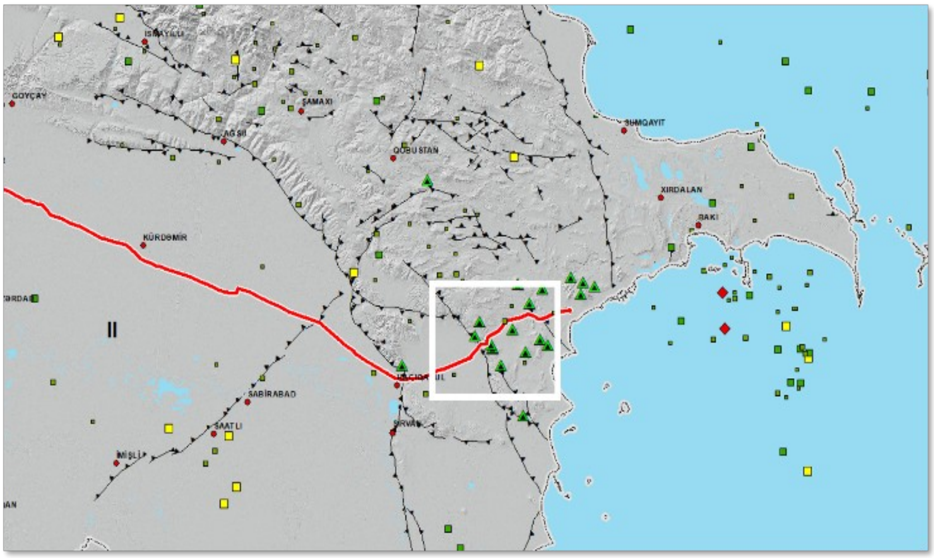

Figure 1. Area of observation

In spatial terms, each risk factor is mapped onto polygonal zones varying from as small as 50×50 meters to areas of several square kilometers (Han et al., 2010). These zones are categorized by risk level according to the matrix. Table 1 outlines a distribution framework for assigning integer or categorical values (e.g., “Low,” “Moderate,” “High”) to each zone based on local hazard intensity. This classification is a cornerstone for subsequent calculations in a GIS environment, ensuring that risk values can be systematically integrated with geospatial data. As a result, risk maps visualize both individual and aggregated hazards, thereby aiding in pipeline safety assessments and informing targeted mitigation strategies.

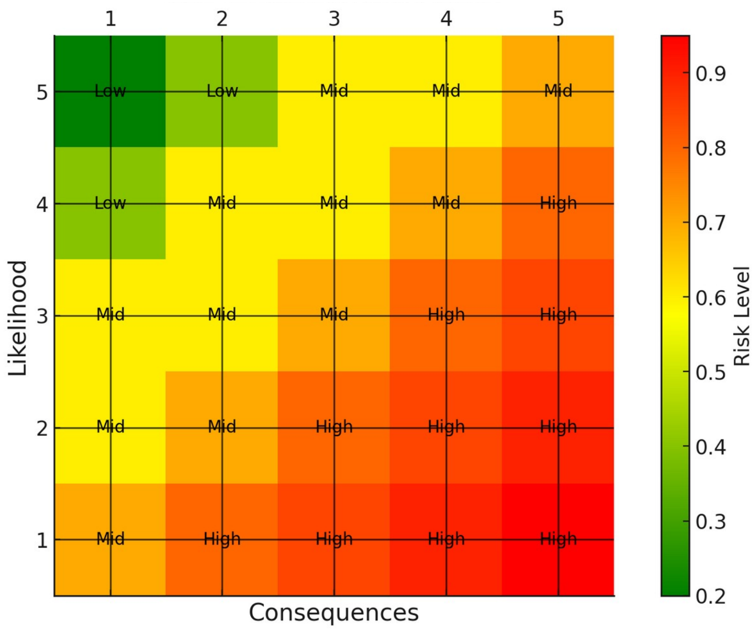

Figure 2. Risk matrix of 5x5 elements

Table 1. Distribution of risk levels according to ND factor

Natural Disaster	Risk Level (1-5, 5 is highest)	Description	Color
Landslides	4	Soil shifts in hilly or mountainous regions that have the potential to disrupt or harm pipelines.	Yellow
Earthquakes	5	Seismic activity or ruptures leading to significant damages	Red
Flooding	3	Lead to erosion or the accumulation of sediment	Yellow
Corrosion from soil chemistry	3	Specific soil environments may extend the corrosion, resulting in the deterioration of pipeline materials	Yellow

2.3 Determining the Risk Values

To address numerous hazard events, the contributions from each are consolidated into a unified risk score. We begin by computing the separate risk scores (R_i) for every hazard, following the formula:

$$R_i = L_i \times C_i$$

where $L_i$represents the likelihood and C_i denotes the impact of the i^{th} hazard. After determining the individual risk scores for each hazard (R_1,R_2, …, R_n), the average risk score (R_{avg}) is computed by the subsequent method:

$$R_{avg} = \frac{1}{n} \sum_{i=1}^{n} R_i$$

In this scenario, n represents the total count of hazards or events under evaluation. Averaging these values is one of several methods to consolidate the risk data, and it is particularly effective for the purposes of mapping. It's important to note that the risk scores will be visually differentiated using a color-coding system: scores ranging from 1 to 6 will be marked in Green, indicating low risk; scores between 7 and 12 will be highlighted in Yellow, signifying medium risk; and scores from 13 to 25 will be denoted in Red, representing high risk. Additionally, each specific value within these ranges could be represented by varying shades of the respective color, providing a gradient effect for more nuanced visualization Fig. 2.

Indeed, the method of calculating an aggregate risk score, as previously described, presumes that each hazard is independent and of equal importance, an assumption that might not hold true in more complex scenarios. To address this, our approach will integrate a weighting system, which allows for the differentiation in the significance of various hazards or the interdependencies between events. In this system, each hazard is assigned a weight (w_i) reflecting its relative importance or impact. These weights are typically values ranging from 0 to 1, with the sum of all weights equaling 1. This ensures that the overall significance of all hazards is proportionately distributed. Following the assignment of weights, the next step involves calculating the weighted risk score (R_{wi}) for each hazard. This is achieved by:

$$R_{wi} = w_i \times R_i$$

To obtain the comprehensive risk score (R_{total}), the process involves summing all the weighted risk scores for each hazard:

$$R_{total} = \sum_{i=1}^{n} R_{wi}$$

This total risk score is then categorized using the designated color-coding system based on its value:

$$\text{¿¿¿} \begin{cases} Green\ if\ 1 \leq R_{total} \leq 6 \\ Yellow\ if\ 7 \leq R_{total} \leq 12 \\ Red\ if\ 13 \leq R_{total} \leq 25 \end{cases}$$

This weighted approach enhances realism by recognizing that certain hazards (e.g., high-magnitude earthquakes) may be far more consequential than others (e.g., minor flooding). However, neither the averaging nor the weighted-sum methods inherently capture potential correlations among hazards—such as how an earthquake might trigger a landslide or how floods may exacerbate soil erosion. Capturing these interdependencies typically requires more advanced statistical or probabilistic models (e.g., Copulas, Bayesian Networks, or multi-variate correlation matrices[3]).

Despite these limitations, weighted risk calculations represent a practical, GIS-friendly means of consolidating disparate hazards into a single metric. By overlaying the final risk values on geospatial layers, decision-makers can pinpoint pipeline segments requiring greater inspection, maintenance, or protective measures. This approach also aligns well with advanced techniques, such as Kernel Density Estimation, which can further smooth risk values spatially and highlight high-risk clusters within the study region, supporting more robust and proactive risk management.

2. 4 Evaluation of 2D risk scores using Gauss kernel method

The 2D risk score for natural disasters can be evaluated using geospatial parameters, such as the magnitude of previous events (for earthquakes, landslides, etc.), proximity to fault lines, soil type, slope, and rainfall data (for floods and soil erosion). The method also assumes that each type of disaster has its own unique contributing factors. A Gauss kernel function[4] is often used in spatial data analysis because it is smooth, symmetric, and its value decreases with distance together with Kernel Density Estimation (KDE).

KDE is a non-parametric technique for estimating the probability density function of a random variable. When applied to risk levels, it allows you to smooth the risk measurements and find areas of high and low risk density. The equation (Equation 1.2) provides a smoothed estimate of the risk level distribution. From this, you could estimate probabilities of specific risk levels, find modes of risk (most common risk levels), or perform other analyses based on selection of kernel function for the KDE (Equation 1.1).

The Gaussian kernel is a common choice due to its smoothness and nice mathematical properties.

K(u) is the Gaussian kernel function, which decreases with the square of the distance from the center of the kernel (u), and f(x) is the kernel density estimate, which is an average of the kernel functions centered at each data point (Xi), with the bandwidth h which controls the amount of smoothing: a large h leads to more smoothing and a smaller h leads to less smoothing.

To apply this to measured risk levels, the data points (Xi) would be the measured risk levels, and the estimated density f(x) would give an estimate of the probability density of risk levels at each point in the risk range.

Equation 1.1: The equation for a Gauss kernel

[3] Multivariate correlations, https://numericalexpert.com/tutorials/statistics/multivarcorr.php

[4] The Kernel Cookbook, https://www.cs.toronto.edu/~duvenaud/cookbook/

$$K(u)=\frac{1}{\sqrt{2\pi}}e^{\frac{-1}{2}u^2}$$

Equation 1.2: KDE equation

$$f(x)=\frac{1}{nh}\sum_{i=1}^{n}K\left(\frac{x-X_i}{h}\right)$$

After collecting the data on historical ND, we can then calculate the risk scores per disaster category using minimal set of crucial input parameters:

1. Earthquakes:
   Variables:
- Magnitude (M) of the past earthquakes.
- Distance (d) to the epicenter of past earthquakes.

The risk score for earthquakes can be calculated as follows:

$$R(x,y)=\sum_i M_i\cdot e^{\frac{-d_i^2}{2\sigma^2}}$$

2. Landslides:
   Variables:
- Slope of the terrain (**S**).
- Soil moisture content (M).
- Distance (d) to previous landslides.

The risk score for landslides can be calculated as follows:

$$R(x,y)=\sum_i S_i\cdot M_i\cdot e^{\frac{-d_i^2}{2\sigma^2}}$$

3. Flooding:
   Variables:
- Precipitation (P) in the area.
- Distance (d) to water bodies such as rivers or lakes.

The risk score for flooding can be calculated as follows:

$$R(x,y)=\sum_i P_i\cdot e^{\frac{-d_i^2}{2\sigma^2}}$$

In these equations, σ is the standard deviation, controlling the spread of the Gaussian kernel, (x, y) are the coordinates for a specific grid cell in the GIS maps, R(x, y) is the calculated risk score at point (x, y), and the summation i is over all the relevant events or factors within a certain radius around point (x, y).

2.5 Applying the minimal safe distances

The minimal safe distance to the object (here the minimal distance to the linear part of pipeline) is a starting point to identify the way we calculate the offset for risk values. Minimal distance is a geometrical distance, a straight line. It varies from disaster factors, so let's integrate it (Dmin) into our equations:

1. Earthquakes:
   Variables:
- Magnitude (M) of the past earthquakes.
- Distance (d) to the epicenter of past earthquakes.
- Minimal safe distance to the epicenter of earthquakes (Dmin).

The risk score for earthquakes can be calculated as follows:

$$E(x,y)=\sum_i M_i\cdot e^{\frac{-(d_i-D_{min})^2}{2\sigma^2}}\cdot H(d_i-D_{min})$$

Here, H (di - Dmin) is the Heaviside step function. It is equal to 0 for di < Dmin (indicating no risk inside the safe distance), and 1 for di >= Dmin.

2. Landslides:
   Variables:

– Slope of the terrain (S).
– Soil moisture content (M).
– Distance (d) to previous landslides.
– Minimal safe distance to previous landslides (D_{min}).
The risk score for landslides can be calculated as follows:

$$L(x,y)=\sum_i S_i \cdot M_i \cdot e^{\frac{-(d_i-D_{min})^2}{2\sigma^2}} \cdot H(d_i-D_{min})$$

3. Flooding:
Variables:
– Precipitation (P) in the area.
– Distance (d) to water bodies such as rivers or lakes.
– Minimal safe distance to water bodies (D_{min}).
The risk score for flooding can be calculated as follows:

$$F(x,y)=\sum_i P_i \cdot e^{\frac{-(d_i-D_{min})^2}{2\sigma^2}} \cdot H(d_i-D_{min})$$

These equations will yield risk scores that are higher for locations closer to the dangerous object (beyond Dmin), and zero for locations within the safe distance. The more sophisticated approach is considering a gradual decrease of risk within the safe distance, instead of a sudden drop to zero (Section 2.5).

The results of evaluated risk scores (RS) of a single contributing factor for each type of disaster (e.g., a single earthquake, a single previous landslide, a single water body) using above equations can be found on Table 2:

Table 2. Risk scores per factor, 500 meters, 5 steps

Distance (m)	Earthquake RS (M=5, σ=500)	Landslide RS (S=2, M=0.5, σ=500)	Flood RS (P=100, σ=500)
200	0.891	0.577	19.2
700	0.706	0.353	14.12
1200	0.367	0.184	7.34
1700	0.135	0.067	2.7
2200	0.033	0.017	0.66

Here, M is the earthquake magnitude, S is the terrain slope, and M is the soil moisture content for landslides (not to be confused with M for earthquakes). P is the precipitation level. σ is the spread of the Gauss kernel, which is the same for all three types of disasters.

The risk scores were calculated using the updated equations from the “Section 2.4”, with Dmin equal to 200 meters. Note that for the distance of 200 meters, the risk scores are 0 because of the safe distance factor. The risk scores for distances beyond Dmin were calculated by substituting the given values into the equations. The calculations assume a specific value for each parameter, and the actual risk scores may vary greatly depending on these values.

The total risk function R(x, y) at location (x, y) would be the sum of these three functions:

$$R(x,y)=E(x,y)+L(x,y)+F(x,y)$$

The function R(x, y) will give us a single risk score for each location (x, y) that we can visualize on a 2D map. We can calculate this function for each cell in a 5×5 grid, and then color each cell based on its risk score to create a 2D risk map. This is used as a model for single cell area and actual risk maps would probably use a more sophisticated model and a much larger grid.

2.6 Splitting and scaling the grid

In multi-hazard GIS-based risk analyses, subdividing the area of interest from larger cells $(\Delta x, \Delta y)$ into smaller ones can greatly enhance the precision and interpretability of results. Each cell Gi, j represents a discrete spatial unit for modeling hazard intensity, vulnerability, and other relevant parameters. Adopting a finer cell size $(\Delta x_{small}, \Delta y_{small})$ has several advantages:

Increased Spatial Resolution.

Smaller grid cells capture more localized variations in elevation, land cover, infrastructure density, and other critical attributes. In mathematical terms, the number of cells N in a given region of area A scales approximately as $N \propto \frac{A}{\Delta x \times \Delta y}$. Hence, decreasing cell size yields a larger N, facilitating higher-resolution risk modeling.

Improved Risk Assessment.

By refining each cell's spatial dimensions, the risk matrix (or any comparable index) can more accurately depict local hazards. For instance, in a flood risk scenario, slight changes in elevation or land cover within a 2×2 km cell may significantly affect water flow and flood extent. A coarser 10×10 km cell $\left(\Delta x_{\text{large}}, \Delta y_{\text{large}}\right)$ would mask these localized variations, potentially underestimating or overestimating the actual risk.

Localized Analysis.

Disasters such as landslides or urban flash floods often affect small areas with disproportionately high severity. A finer grid enables targeted analysis of these hotspots, capturing the nuances of topography and land use that can influence the severity of impacts. This capability is crucial for large-scale disaster management strategies where local conditions can markedly change risk levels.

Detailed Mitigation Planning.

High-resolution grids reveal specific locations most prone to damage, supporting more efficient mitigation measures. Authorities can use these refined data layers to plan structural defenses (e.g., levees or retaining walls), allocate evacuation routes, and prioritize response resources, thereby reducing both immediate and long-term risk.

Enhanced Accuracy of Predictive Models.

Many computational models in hydrology, seismology, and other hazard-related fields use grid-based inputs. Smaller cell sizes often improve the fidelity of simulations, though at the cost of greater computational demand. By employing a grid of fine resolution, models can represent spatial heterogeneity more accurately, thereby yielding more reliable predictions of hazard behavior.

However, adopting smaller cells increases the computational burden, as the total number of cells N and the associated data complexity grow. Additionally, finer spatial resolution demands correspondingly detailed data inputs (e.g., higher-accuracy digital elevation models, land use surveys). In practical applications, the grid cell size is often a compromise between accuracy and available computational or data resources.

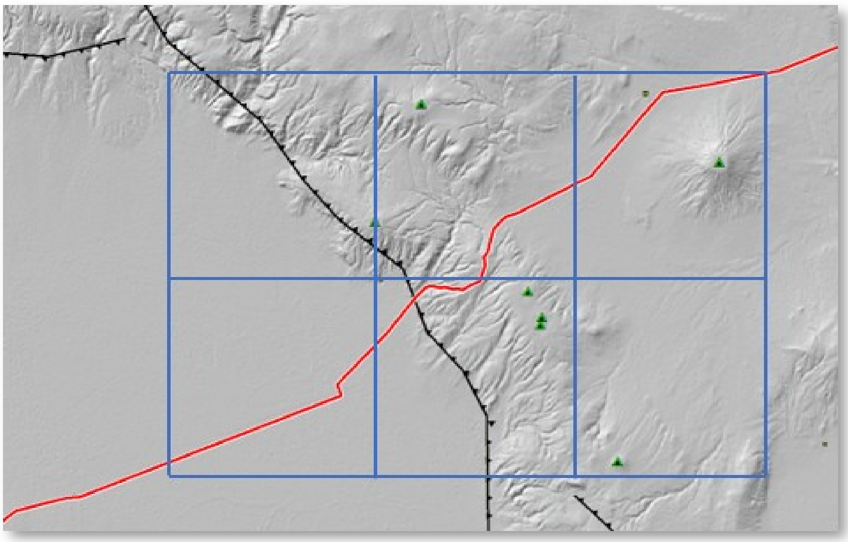

Figure 3. The area of interest with 3x2 cells, each 10x10 km

For example, Figure 3 may represent a coarser grid where each cell is approximately 10×10 km, capturing large-scale trends but providing only a coarse view of localized risk. Conversely, Figure 4 might illustrate a finer grid (2×2 km cells), capturing nuanced variations yet increasing both data density and processing time. Calibrating grid size becomes essential for balancing computational feasibility with the desired level of spatial detail. In many multi-hazard pipeline risk assessments, a moderate cell size is often chosen initially, followed by targeted refinement in critical zones where hazards overlap or infrastructure vulnerability is high. This approach ensures that risk maps reflect realistic spatial gradients without overwhelming computational or data-storage capacities.

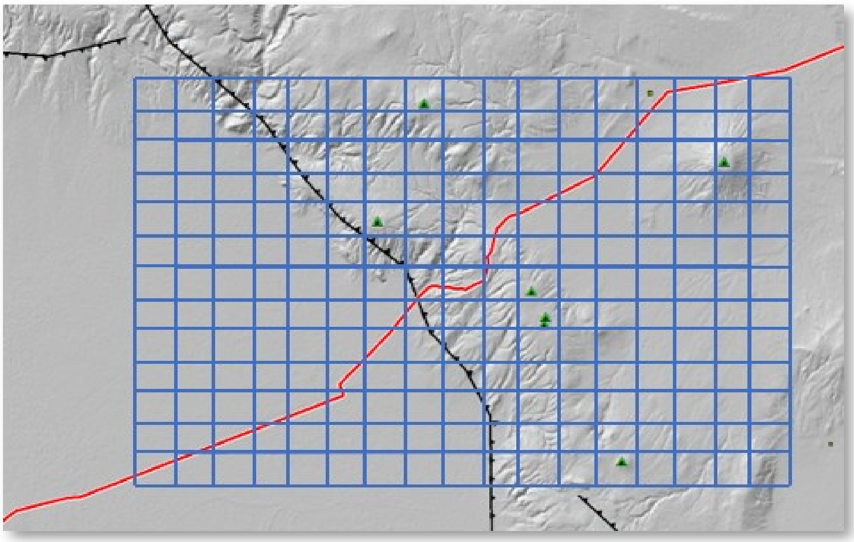

Figure 4. The area of interest with 17x12 cells, each 2x2 km

2.7 *Smoothing risk scores by categories*

When plotting discrete or granular risk values directly onto a map—especially when each value is subdivided into finer sub-scores—visual representations can appear patchy or irregular. To obtain a smoother, more continuous distribution of risk values across a two-dimensional space, Kernel Density Estimation (KDE) offers a robust solution. Under this approach, probability density functions are approximated for each designated risk category (e.g., Green, Yellow, Red), focusing attention on smaller, localized zones that require further scrutiny.

In this study, risk values lying outside the specified range of a given category are effectively excluded (or treated as zero) during computation. For instance, when constructing KDE surfaces for Green-category data, only points whose risk scores lie within the "Green" interval are included. Similarly, Yellow and Red categories are handled in separate density estimations, thus preventing extraneous data points from skewing results.

Mathematically, for the c-th category, where n_c data points $\left(x_i^{(c)}, y_i^{(c)}\right)$ satisfy that category's risk range, the two-dimensional Gaussian KDE can be written as:

Equation 2: 2D risk score using Gauss kernel

$$\hat{f}_c(x,y)=\frac{1}{n_c h^2}\sum_{i=1}^{n_c}\frac{1}{2\pi}e^{\frac{-1}{2}\left[\left(\frac{x-x_i^{(c)}}{h}\right)^2+\left(\frac{y-y_i^{(c)}}{h}\right)^2\right]}$$

Here, categorized risk levels per impact, where (n_c) is the number of data points in the (i)th category, (h) is the bandwidth parameter, (e) is the base of the natural logarithm and $x_i^{(c)}$ and $y_i^{(c)}$ are the nth pair of 2D data points.

This formulation assumes X and Y (the spatial coordinates) are independent variables in the Gaussian kernel, allowing for straightforward, radially symmetric smoothing. The choice of the bandwidth h is pivotal: smaller h values yield highly localized densities at the expense of potential overfitting, whereas larger h values give smoother distributions that may obscure important local variations. Bandwidth selection often leverages cross-validation or rule-of-thumb heuristics (Silverman, 2018).

By performing this KDE procedure separately for each risk category, the method generates multiple "layered" density surfaces that can then be visualized independently or composited. The resulting smoothed risk surfaces help highlight areas of greatest concern within each category and avoid the abrupt color transitions that simple, cell-by-cell risk mapping might produce. Consequently, decision-makers and analysts gain a clearer view of spatial risk concentrations, which supports more informed planning and more targeted mitigation strategies.

2.8 Data Processing

To streamline the risk analysis within a specified Area of Interest (AIO), a systematic methodology was devised, as summarized in Table 3. The determination of the AIO's minimum size - which was initially set at 1 km² - drew on a preliminary review of notable natural disaster events within Azerbaijan, ensuring that smaller-scale events would be captured. However, the AIO dimension is not fixed and may be recalibrated for different regions or urban areas where hazard intensity or infrastructure density warrants finer resolution.

Adapting AIO dimensions typically involves additional analytical steps. First, detailed hazard datasets (e.g., seismic zonation maps, flood extents, or landslide susceptibility layers) are reviewed to confirm the spatial extent and granularity of the events. Second, the potential impact radius of each hazard is considered - particularly if one hazard (e.g., flooding) tends to spread over a wider area compared to another (e.g., localized ground subsidence). Finally, socioeconomic or administrative factors, such as population centers or critical infrastructure corridors, may also inform the selection of a larger or smaller AIO.

Within each AIO, risk levels are determined by referencing previously established matrices for natural hazards (earthquakes, floods, landslides, mud volcanoes, etc.), environment-based hazards (e.g., corrosion), and their associated weights. The resulting risk scores are then aggregated spatially, allowing analysts to pinpoint critical hotspots. By adhering to the structured workflow shown in Table 3, one ensures uniformity across different AIOs, thereby facilitating consistent comparisons - even when hazard profiles differ.

Through this stepwise approach, researchers and decision-makers can maintain a clear audit trail of how risk scores are derived, updated, and mapped onto each AIO. This enables rapid re-evaluation if new hazard data emerge - such as revised seismic models or recent flood records -and fosters an adaptable framework suitable for a variety of planning or operational needs.

Table 3. Processing Steps for a Single AIO

Step	Description
1	Determine the AIO: The AIO should be centered around the pipeline to ensure accurate and proportionate GIS visualization of the event area and the pipeline's linear section
2	Identify (ND) and Adjust AIO Size: Identify NDs that could impact the AIO. The AIO's dimensions may be modified if an ND has a wider impact area. Concurrently, determine the risk parameters for each event and their relative weights concerning the pipeline.
3	Calculate Risk Matrices per Event: Develop risk matrices for each identified event, considering the specific risk parameters and weights.
4	Combine Risk Scores: Combine the individual risk scores from each event into a comprehensive risk score matrix.

This methodical approach ensures a thorough and systematic assessment of risks within a given AIO, allowing for a nuanced understanding of potential impacts on pipeline infrastructure.

2.9 Aggregated Risks

While the aggregated risk score provides a high-level view of the overall risk, it is still tied to the individual risk scores, and these can be used to understand the specific hazards in more detail. It's beneficial to consider both the aggregated and individual risk scores when planning interventions and communicating about risk. In terms of visualization of risk details in an aggregated form, the individual risk being stored as an entity within the relational database.

Many GIS frameworks providing the automation facilities (here ArcMap, QGIS and etc.) via scripting languages like Python, JavaScript. So, by adding the referential output per aggregated risk value (here individual colored cell) we can get the detailed information on certain cell of interest in a form of table 4 or other ways, like popup tooltips.

Table 4: Aggregated risk score for each location

Location	Earth-quake Risk	Land-slide Risk	Flood Risk	Mudflow Risk	Aggregated Risk

A	5.6	4.2	7.3	6.4	23.5
B	7.1	2.3	8.5	5.6	23.5
C	3.4	6.7	6.2	4.5	20.8
D	6.9	4.8	8.1	5.3	25.1
E	4.3	3.5	7.8	6.7	22.3

This table clearly shows both the individual and aggregated risk scores. By comparing the aggregated scores, we can see that location D has the highest overall risk, even though it may not have the highest risk for any individual disaster category. This is a good example of how aggregated risk scores can provide a different perspective than individual risk scores.

2.10 KDE and risk colors

The KDE method can be used to generate the smoothed, continuous distribution of the aggregated risk scores.

In this context, it would provide a way to understand the distribution of aggregated risk scores across the area of interest, identifying areas of high or low risk density. This could help to inform more granular risk management strategies or interventions, by focusing efforts where the density of high-risk locations is greatest.

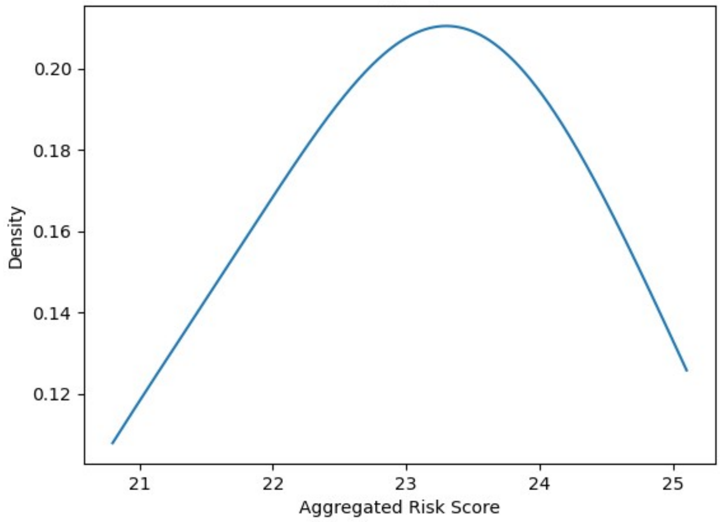

Figure 5. Histogram of Gaussian aggregated risk score

The Fig. 5 is a smoothed histogram (i.e., a probability density function) of the aggregated risk scores using a Gaussian kernel. The resulting plot shows the distribution of risk scores, with the y-axis representing the estimated density of each risk score.

This can help us to visualize how the risk scores are distributed and could potentially inform how we define the ranges for the 'Green', 'Yellow', and 'Red' risk rankings.

Then, the distribution of colours on the histogram be colorized based on colour ranges per risk score. On the example of given aggregated values from the table "Table 4", the risk ranking fall into 'Red' coloured risk score and be smoothed as a gradient of 'Red' colour. Following the calculation of the probability density function using the Gaussian kernel density estimation (KDE) technique, we visualize the distribution by creating a color-coded histogram plot (Fig. 6). Those gradients then be used to map smoothed aggregated risk values on final GIS maps.

This results in a spatial map where each location is coloured based on its normalized risk density, as estimated by the KDE. Darker colours indicate regions with higher risk densities.

In practical applications, this spatial risk map can be overlaid with other geographical features such as roads, buildings, and natural landmarks to provide a comprehensive view of the risk landscape. This can aid in identifying high-risk areas and prioritizing interventions.

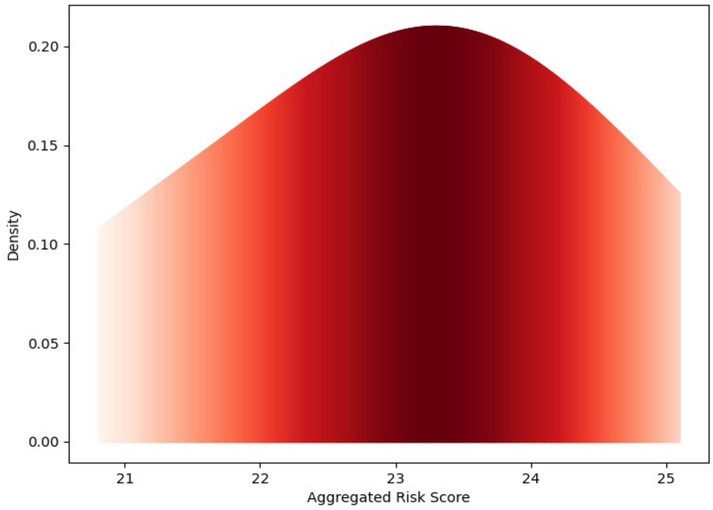

Figure 6. Gradient histogram of Gaussian aggregated risk score

2.11 Assessment challenges

In the process of assessing risks to pipeline infrastructure due to natural disasters, several challenges arise, particularly in accurately characterizing the impact of these events. A key aspect of this challenge is the need for a comprehensive definition of risk, which encompasses a clear understanding of the probability and dimensions of potential impacts. The challenges, listed in order of increasing complexity, include:

1. Identification and Evaluation of Risk Parameters: This involves pinpointing specific risk factors and assessing their potential impact. An example is evaluating the effects of earthquakes on pipelines, including subsequent NATECH events (Krausman et al., 2016).
2. Determining Appropriate Risk Weights for Each Parameter: Assigning the correct weight to each risk parameter is crucial for accurate risk assessment.
3. Choosing the Correct Granularity for the Area of Interest: This is essential to avoid oversimplification and ensure detailed risk analysis.

2.12 General steps for risk visualization

To visualize the spatial distribution of aggregated risk scores using the colorized histogram, we can employ a GIS framework. This allows us to map the risk scores onto a 2D map representation of the study area.

a. ***Define the study area***: Determine the extent and boundaries of the study area where the risk scores will be visualized.
b. ***Obtain the risk scores***: Collect or calculate the aggregated risk scores for each location within the study area.
c. ***Create a grid***: Divide the study area into a regular grid of cells. The size of each cell depends on the desired resolution for the visualization.
d. ***Interpolate the risk scores***: Assign each cell in the grid a risk score based on interpolation techniques such as inverse distance weighting or kriging. This step ensures that risk scores are assigned to locations that fall between the actual data points.
e. ***Colorize the grid***: Assign a color to each cell based on its risk score. Use a color scale or colormap that represents the risk levels of interest. For example, a colormap with shades of red can be used, where lighter shades represent lower risk and darker shades represent higher risk.
f. ***Generate the risk map***: Plot the colored grid onto the GIS map, overlaying it on relevant base layers such as roads, topography, or satellite imagery. This provides spatial context and aids in the interpretation of the risk distribution.
g. ***Include a legend***: Create a legend that clearly explains the color scale and risk levels associated with each color. This helps viewers interpret the risk map accurately.

h. ***Optional***: Add additional features: To enhance the visualization, you can incorporate other geographical features such as administrative boundaries, water bodies, or infrastructure that may be relevant to the risk assessment.

By following these steps, the colorized histogram-based visualization of aggregated risk scores can be extended to a GIS environment, allowing for a comprehensive and visually appealing representation of spatial risk distribution.

Results

The outcome of this study includes the successful implementation of GIS tools to create detailed visualizations of aggregated risk. A significant enhancement in our visualization technique was the incorporation of buffered zones along the pipeline route, which provided a more distinct delineation of risk areas (Petersen, 2020).

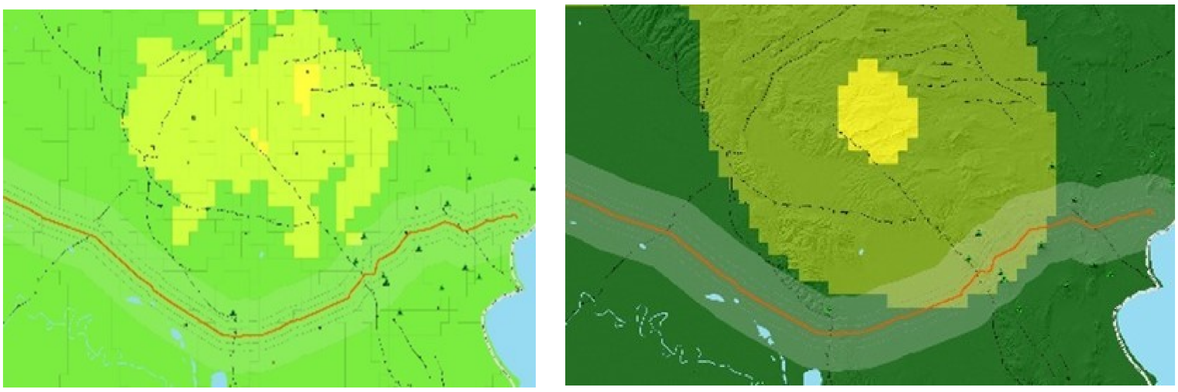

Figure 7-8. Coarse, CRS (left), KDE based, refined CRS (right)

The series of figures, from Fig. 7 to Fig. 10, illustrate the progression of refined combined risk scores (CRS) derived from various natural hazards within a relatively small region. The smallest unit of analysis, the AIO, covered approximately 2 km², while the entire region under assessment spanned about 100 km². The risk matrices developed were informed by a combination of data on recorded earthquakes, identified geological faults, and mud volcanoes.

The tools utilized for these visualizations were ESRI ArcMap 10.8 for mapping, output files generated (CSV files) with Python 3.8.

Discussions

In this study, we have navigated through the multifaceted challenges of assessing the risk to pipeline infrastructure from natural disasters. Our approach has been to meticulously identify and evaluate risk parameters, determine appropriate risk weights, and select the optimal granularity for the area of interest.

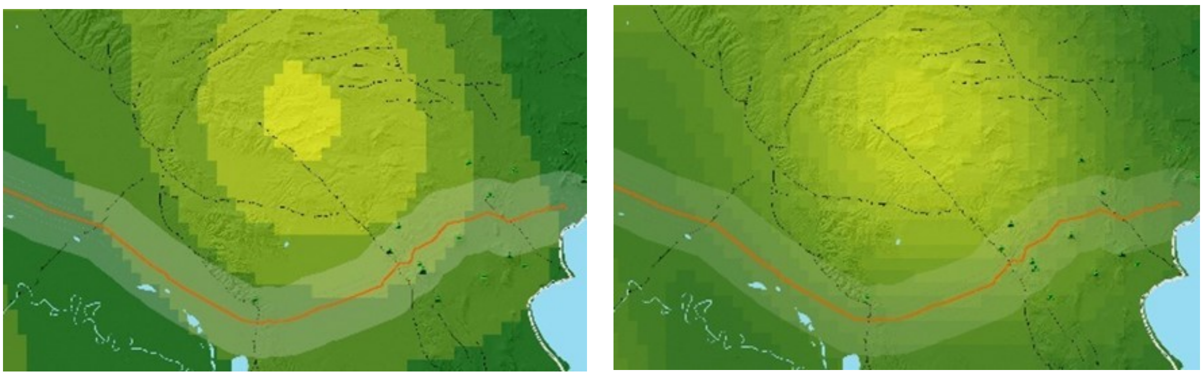

Figure 9-10. KDE based, smaller scale CRS (left), KDE based, fine-tuned CRS (right)

Implications of Findings: Our findings underscore the complexity inherent in assessing natural disaster risks to pipelines. The use of a three-dimensional risk assessment plot, as demonstrated in Figure 7 for earthquake impacts, provides a nuanced visualization of risk. This method allows for a more detailed understanding of how different risk parameters interact and affect the overall risk profile. The color-coded risk categories further enhance the interpretability of these risks, making the data more accessible for decision-makers.

The application of this methodology to other natural disasters reveals its versatility. However, it also highlights the increasing complexity when more parameters are involved. Each additional parameter requires careful consideration and integration into the overall model, underscoring the need for a robust and flexible risk assessment framework.

Challenges and Limitations: One of the primary challenges encountered in this study is the sensitivity of the KDE and color mapping to the choice of parameters, especially the bandwidth h. The selection of h is critical and must be tailored to the specific characteristics of the data and the objectives of the risk assessment. This sensitivity points to a broader challenge in risk assessment: the balance between accuracy and generalizability.

Furthermore, our approach assumes the independence of risk factors, which may not always hold true in real-world scenarios.

Future Directions: Looking ahead, there are several avenues for further research. First, exploring methods to incorporate the interdependencies between different risk factors would likely yield a more comprehensive and realistic risk assessment model. This could involve the development of more sophisticated statistical models or machine learning algorithms capable of handling complex, interrelated datasets.

Second, the adaptation of our model to a wider range of natural disasters would be beneficial. Each type of disaster brings its unique set of challenges and risk factors, and a versatile, adaptable model is essential for broad applicability.

Lastly, engaging with experts in geology, meteorology, and disaster management could provide valuable insights and data, enriching the model's accuracy and relevance.

Conclusion

This study has illuminated several key challenges in determining risk weights, which are crucial for accurate risk assessment in the context of ND and their impact on infrastructure. These challenges are summarized below:

1. ***Complexity of Risk Interactions***: ND often triggers or coincides with other events, complicating the assessment of combined risk impacts. Example: An earthquake increasing the likelihood of a landslide.
2. ***Data Scarcity***: The lack of sufficient data for rare or unprecedented risks introduces significant uncertainty in estimating probabilities and impacts.
3. ***Risk of Oversimplification***: Simplifying risk assessments can lead to underestimating the complexity and interactions of risks, potentially skewing the actual risk levels.
4. ***Model Dependence***: The accuracy of risk weights is directly linked to the efficacy of the risk assessment model. Inaccurate models can result in misleading risk weights.
5. ***Subjectivity in Risk Weighting***: Risk assessments can be influenced by individual or organizational risk tolerance, which varies widely. Balanced risk weighting often requires collective input from professionals or subject matter experts.
6. ***Evolving Risk Landscape***: Risks change over time due to environmental, technological, regulatory, and other factors, necessitating regular updates to risk weights.
7. ***Perception Bias***: Decision-makers' biases in risk perception can lead to overestimating or underestimating certain risks, influenced by factors like visibility, recency, or familiarity.
8. ***Quantifying Qualitative Risks***: Some risks are qualitative and difficult to quantify, such as reputational risks or the impact of regulatory changes, posing challenges in numerical risk weighting.

Advantages

The utilization of aggregated risk scores in assessing various types of risks offers several advantages, as outlined below:

1. ***Simplicity in Visualization and Interpretation***: Aggregated risk scores streamline the process of understanding risks by condensing multiple risk factors into a single, comprehensive score. This simplification aids in easier interpretation and visualization.

2. ***Enhanced Comparability***: These scores enable straightforward comparisons of overall risk across different locations or regions, which is invaluable for decision-makers in resource allocation and prioritization.
3. ***Holistic Risk Understanding***: Aggregated scores offer a broad overview of risk, capturing the cumulative effect of individual risks, especially when they interact or compound.
4. ***Effective Communication***: Communicating a single aggregated risk score is often more straightforward and accessible to stakeholders and the public than explaining multiple individual risk components.

Furthermore, the aggregated risk score can be tailored to align with the risk tolerance or appetite of the concerned entity. This adaptability allows for a more relevant and targeted risk assessment.

Using a risk matrix for aggregation effectively consolidates risks from various natural disasters into a single value. This comprehensive view is crucial for effective risk management, disaster preparedness, and resource allocation. However, it's essential to periodically update the risk matrix to reflect changes in the risk landscape due to factors like climate change, urban development, and population growth.

It's also important to recognize that the aggregated risk score is an indicative tool meant to guide, but not solely dictate, decision-making processes. Factors such as societal values, financial constraints, and political considerations should also be factored into risk management strategies.

Despite the challenges, our study successfully visualized risk in an aggregated form, using a single map with finely tuned risk scores. Regular review and updating of risk weights, expert involvement, and careful consideration of risk interactions are key components of this approach.

One notable finding is the model's applicability to other risk assessments using the same matrix representation and weight calculations. The flexibility of the model is further enhanced by the potential integration of the Kernel Density Estimation (KDE) method for fine-tuning outputs and the implementation of algorithms like the Moore neighborhood (Ilachinski et al., 2001) for relative AIO region risk score determination.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

All authors provided critical feedback and helped shape the research, analysis and manuscript.

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Seasonal Ice Caves of Georgia

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Abstract

This article examines the seasonal ice caves of Georgia, unique physical and geographical formations in which ice forms during summer and melts in winter. Similar phenomena, known as seasonal ice caves, occur in many countries worldwide and are characterised by ice accumulation during warm periods and comparatively higher internal temperatures during cold winters. This unusual behaviour has not yet been fully explained scientifically and is therefore often described by local populations as "mystical". The study presents case analyses of the Khorkhebi, Khiza, and Khikhadziri seasonal ice caves. The aim of the article is to raise awareness of the existence of seasonal ice caves among both the scientific community and the general public and to provide a foundation for potential future research collaboration.

Keywords: Natural freezers, seasonal ice caves, mystical caves

Introduction

Seasonal ice caves occur in various regions of Georgia and differ in both origin and morphological characteristics. Existing scientific research on seasonal ice caves (natural freezers) within the territory of Georgia is predominantly descriptive in nature (Kipiani, 1976; Kiknadze, 1963; Rakviashvili, 1965; Tsikarishvili et al., 2010; Ukleba, 1960; Pirpilashvili, 1960). Such caves were documented in Georgia as early as the 18th century. In Description of the Kingdom of Georgia (1745), Vakhushti Bagrationi discusses aspects of the practical use of seasonal ice caves. In particular, during hot summer periods, ice was cut into blocks and transported to the royal palace for various purposes, including the storage of food supplies for the army.

Figure 1. Coudersport Ice Mine

Despite their long-standing historical and scientific significance, the existence of these natural phenomena remains largely unknown to the general public. Most of the seasonal ice caves visited during the present study were found to be collapsed, filled with debris, and difficult to access. This highlights the urgent need for their systematic registration and documentation in order to preserve these natural features for future generations.

A similar seasonal ice cave was discovered in Pennsylvania in 1894. The cave is approximately 121 m deep, 2 m wide, and 3 m long. The ice that forms on its walls, often in the form of icicles, is generally clear and sparkling (Patowary, 2016). Initially, this cave-freezer was used for food storage; since 1900, it has been transformed into a tourist attraction and continues to be used for this purpose today (Fig. 1).

Methods and Materials

In 1987, Tavartkiladze and Kuznetsov developed a mathematical model of the physical process responsible for ice formation in seasonal ice caves, based on the spatial orientation of cave openings in relation to solar radiation (Tavartkiladze, 1987). However, these theoretical calculations were not supported by field observations. To validate the model empirically, continuous meteorological observations were required, which proved difficult at the time due to the absence of automatic weather stations.

Many years later, at the initiative of Professor Tavartkiladze, a group of scientists from the Institute of Geography (the authors of the present paper) conducted field investigations in three seasonal ice caves located in different physical–geographical and climatic conditions: the Khorkhebi, Khiza, and Khikhadziri freezers (Fig. 2). These field visits were carried out between 2009 and 2012 and enabled direct observation of the processes involved in ice formation (Fig. 3).

Figure 3. Khorkhebi natural seasonal ice caves

Results

The results of the initial visual observations indicated that ice formation occurs under varying physical–geographical and geomorphological conditions and develops as a result of the combined influence of climatic factors.

Despite their scientific importance, the existence of these natural phenomena remains largely unknown. Most of the seasonal ice caves examined during fieldwork were found to be collapsed, filled with debris, and difficult to access. This underscores the urgent need for their systematic registration and documentation to ensure their preservation for future generations.

All seasonal ice caves examined are developed within Upper Pliocene dolerite lavas and were formed as a result of tectonic or gravitational processes (Fig. 4).

A particularly notable seasonal ice cave is located in Tetritskaro Municipality, within the Ktsia–Khrami valley, approximately 2.5–3 km from the village of Kldeisi. The cave entrance is situated on the southern slope of the Bedeni Plateau. It is formed within Upper Pliocene dolerite lavas, among large lava blocks with volumes of 30–40 m³, created by tectonic or gravitational processes. Numerous narrow openings occur in this area. One of them—a relatively narrow (0.5–1 m wide) and low passage approximately 10–12 m long—leads to a small chamber 2–2.5 m high. Beyond this chamber, a narrow opening connects to a confined space of 3–4 m², where thick ice layers (0.4–0.5 m) are formed.

Narrow passages between the boulders facilitate the accumulation of cold winter air masses. In summer, water vapour condenses as warm external air mixes with cold air retained between the rock openings, resulting in the formation of crystal-clear ice blocks on the cave floor and ice crystals on the walls due to low temperatures.

During the expedition conducted on 5 August 2009, the air temperature at the cave entrance was 17.4 °C. At a distance of 7 m from the entrance, the temperature decreased to 7.2 °C, while in the ice-formation zone it reached 1.0 °C. In summer, ice is also present in other cavities between the boulders. Condensation and meltwater drain approximately 0.5 km from the cave, forming a spring locally referred to as a “glacial spring”, with a water temperature of 6.0 °C.

Figure 4. Entrances to the seasonal ice caves

Discussions

According to some researchers, heavy cold air masses accumulate in the depths of the cave in the winter, which freeze the latter when they touch the raised ground water level in the summer and form ice blocks. However, it is not clear how the correlation between ice strength and atmospheric air temperatures can be explained.

Our opinion is that narrow passages between boulders help to accumulate layers of cold winter air. In addition, by mixing warm air from outside and cold air trapped between the holes, water vapor condenses, creating ice boulders on the bottom of the freezer and ice crystals on the walls due to low temperatures.

Conclusion

It is assumed that the conditions for ice formation in seasonal ice caves depend on the topography and climatic characteristics of the area. Disruption of any of these components alters the natural rhythm of ice formation and its contributing factors, which can lead to the loss of this rare natural phenomenon and the potential destruction of the monument itself.

A scientific explanation of the processes occurring in seasonal ice caves and the development of a theoretical framework could, in the future, support the creation of energy-efficient refrigeration infrastructure. The practical implementation of the research results opens broad prospects for the development of energy-saving cold storage facilities, which can bring both public and social benefits.

Moreover, technological advancements in this field do not require above-ground construction or major alterations to the natural landscape. This approach can have a positive impact on both the environment and household economies.

Research in this field carries significant scientific and economic value; therefore, it is essential to promote and support further investigations in this area.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

T.K. and K.Ts. took the lead in writing the manuscript. N.B. was responsible for editing the manuscript V.G. collected the historical materials. All authors participated in the field trip, provided critical feedback, and contributed to the research, analysis, and preparation of the manuscript.

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Impact of Atmosphere Perturbation and Microcirculation on Tbilisi Thermal Regime

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Abstract

This paper investigates the thermal peculiarities of Tbilisi in relation to geomagnetic activity and local microcirculation features. The geographical setting of Tbilisi gives rise to the well-known "Tbilisi Hole" phenomenon, which strongly influences the spatial distribution of air temperature within the city. Geomagnetic storms represent major disturbances of the Earth's magnetosphere that occur when the solar wind interacts with the near-Earth space environment. The strongest storms are typically associated with solar coronal mass ejections (CMEs) and may take several days to reach the Earth. Geomagnetic indices constitute important parameters in weather forecasting methods. In this study, correlations between geomagnetic storms and air temperature in Tbilisi were identified using meteorological observations from the National Environment Agency (NEA) and data from NASA's Solar Dynamics Observatory (SDO) and the NOAA Space Weather Prediction Center. The results indicate that sudden decreases in air temperature occur predominantly on dates associated with geomagnetic storm events. In addition to the influence of geomagnetic activity, a key recommendation for reducing thermal stress in Tbilisi is the expansion of green cover in the city centre and on surrounding slopes. Nature-based solutions represent the most effective approach for achieving this goal and include measures such as green roofs, vertical vegetation, green corridors, and geoparks.

Keywords: Geomagnetic storm, Microcirculation processes, inversion, turbulence flow, atmosphere instabilities

Introduction

Understanding the thermal regime of large cities has become an increasingly important scientific and practical task, particularly in the context of ongoing climate variability, urbanisation, and the growing frequency of extreme weather events. Urban thermal conditions are shaped not only by large-scale atmospheric circulation but also by local factors such as relief, land cover, building density, and anthropogenic heat emissions. In complex topographic settings such as mountain basins and hollows, these influences are further modified by microcirculation processes, temperature inversions, and restricted air exchange, resulting in pronounced spatial and temporal temperature contrasts within relatively small areas.

In recent decades, urban climatology has increasingly focused on the interaction between atmospheric perturbations and local-scale circulation mechanisms. Numerous studies have demonstrated that synoptic-scale disturbances, including changes in atmospheric pressure patterns and variations in solar and geomagnetic activity, can modulate near-surface meteorological conditions, particularly in regions characterised by stable stratification and weak ventilation. In such environments, even short-term atmospheric perturbations may amplify or suppress local thermal anomalies, thereby influencing the intensity and persistence of urban heat accumulation.

The role of microcirculation in shaping urban thermal regimes has been widely recognised, especially in cities located in basins or enclosed relief forms. Local wind systems, slope flows, and valley circulations can either enhance heat removal or promote stagnation, depending on their structure and interaction with background atmospheric conditions. In the case of Tbilisi, the combined effects of the Tbilisi Hollow, surrounding mountain ranges, and the Mtkvari River valley create a highly sensitive climatic system in which small perturbations may lead to measurable thermal responses.

At the same time, growing attention has been paid to the potential influence of atmospheric and space-weather-related factors, including geomagnetic disturbances, on meteorological variables near the Earth's surface. Although the mechanisms linking geomagnetic activity and surface air temperature remain the subject of ongoing debate, empirical studies conducted in different regions suggest that such interactions may be detectable under specific geographical and climatic conditions. Cities characterised by persistent temperature inversions, limited vertical mixing, and strong radiative forcing are considered particularly suitable for investigating these relationships.

Within this broader scientific context, Tbilisi represents a valuable natural laboratory for studying the combined impact of atmospheric perturbations and microcirculation on urban thermal regimes. Its complex relief, frequent inversion conditions, pronounced intra-urban temperature contrasts, and sensitivity to both regional and local atmospheric processes make it especially relevant for integrated climatic analysis. Examining these interactions is not only important for advancing theoretical understanding but also has practical implications for urban planning, public health, and climate adaptation strategies in rapidly warming urban environments.

Tbilisi is located in the eastern part of Georgia, within the Tbilisi Basin, at elevations ranging from 380 to 700 m above sea level. The city's main artery, the Mtkvari River, divides it into two parts—the right and left banks—whose relief differs markedly. The right bank is significantly higher and steeper and is dissected by numerous small rivers and transversely oriented ravines. By contrast, the left bank is relatively flat, although dry ravines, locally referred to as lifeless ravines, are also present. Tbilisi is bordered to the north by the southern foothills of the Saguramo Range, to the east by the north-western section of the Iori Upland, and to the west and south by branches of the Trialeti Range.

The climate of Tbilisi is classified as subtropical semi-arid, with hot summers. The average air temperature in July is +24.4 °C, while the absolute annual maximum reaches 40 °C. Winters are cold, with a mean January temperature of +0.9 °C. The average annual precipitation is approximately 560 mm, with a maximum in spring and a minimum in winter. Northern and north-western winds prevail, although south-eastern winds are also frequent. Due to the city's relatively low geographical latitude, cloud cover is limited, and solar radiation is abundant and prolonged.

July is, on average, the warmest month of the year, with a mean maximum temperature of 29.9 °C. Tbilisi recorded its all-time highest temperature on 4 July 2017, exceeding the previous record by 0.1 °C. The former record had been set on 1 August 2000, when the air temperature reached 40.4 °C (Tatishvili et al., 2025).

A distinctive climatic feature of the Tbilisi Hollow is observed in winter under sunny, calm anticyclonic conditions, when air temperatures on the slopes of Mtatsminda are often 6–9 °C higher than those recorded at the meteorological station located at 459 m above sea level. Cold air descending from the surrounding mountains flows into the Mtkvari River valley, where, due to limited ventilation, it stagnates and further cools.

During winter, Mtatsminda remains warmer throughout the day than the city centre, whereas in summer it is comparatively cooler. At the same time, air humidity increases in the central parts of the city, fog frequently forms (with visibility reduced to 500–700 m), and an aerosol smog layer is almost always present (Khvedelidze et al., 2023). Microcirculation processes contribute to higher air temperatures in the city centre compared to peripheral districts. In both January and July, temperatures in central Tbilisi are 0.6–2 °C higher than those recorded in Digomi and Samgori. Wind speeds in the city centre are also lower (2.2 m/s in January and 2.1 m/s in July) than in the outer districts, such as Digomi (3.7 m/s and 5.2 m/s) and the airport area (5.4 m/s and 7.2 m/s).

Vertical air mixing in Tbilisi is weak (Tatishvili et al., 2024), and air movement is largely limited to slope winds. As a result, strong temperature inversion layers frequently develop, leading to the accumulation of dust and other pollutants and, consequently, to increased air pollution. Under these conditions, the intensity of long-wave radiation increases, while ultraviolet radiation decreases. Ultraviolet rays become concentrated in the near-surface layer, contributing to elevated levels of ground-level ozone, which has adverse effects on living organisms (Khvedelidze et al.).

Another important climatic characteristic of Tbilisi is the long-term persistence of an aerosol cloud during morning hours, clearly visible from the surrounding hills. This phenomenon is associated with temperature inversion, the effects of which vary depending on cloud cover, precipitation, and mist formation. The inversion layer forms a stable "cap" over the city that inhibits ventilation. Within the Tbilisi Hollow, a persistent upward airflow of relief origin develops; due to closed circulation patterns, this airflow does not dissipate over the surrounding mountains but instead changes direction and returns to the urban area.

Methods and Materials

Numerous studies have been devoted to the investigation of meteorological parameters in Tbilisi. Among the most recent are the works of Amiranashvili et al. (2023, 2024) and Aliyev et al. (2025), in which these parameters—particularly air temperature—are discussed in detail.

To conduct the present research, ground-based air temperature data from meteorological stations for the period 2014–2018 were used, together with satellite-based data obtained from NASA (NOAA Space Weather Prediction Center, n.d.; Sunspot Watch, n.d.; NASA Solar Dynamics Observatory, n.d.; NASA Earthdata, n.d.) and data provided by the NOAA Space Weather Prediction Centre.

Solar flares, coronal mass ejections (CMEs), and solar energetic particles (SEPs) are the primary drivers of space weather effects in geospace. Solar activity can be quantified using several indices or combinations of indices, including the sunspot number (WN) and the solar radio flux at 10.7 cm (F10.7), which reflect variations in the Sun's electromagnetic output. In addition, parameters such as the interplanetary magnetic field strength (B) and solar wind speed (v) at the Earth's orbit are used to characterise solar wind properties.

The geomagnetic activity index Kp has been continuously calculated since 1932 by the Helmholtz Centre Potsdam (GFZ). The Kp index is one of the most widely used geomagnetic indices and is designed to represent the level of geomagnetic disturbance on a global scale over three-hour intervals in Universal Time. To facilitate averaging, Kp values are converted from their quasi-logarithmic scale into a near-linear scale expressed in nanotesla, yielding the three-hourly ap index. The daily Ap index is then calculated as the average of the eight three-hour ap values.

Two main methodological approaches were applied in this study: (1) analysis of microcirculation processes using wind velocity equations, and (2) correlation analysis between meteorological parameters and geomagnetic activity.

Results

The wind velocity is a three-dimensional vector. Vertical component is much smaller compared to horizontal motion and can only be (10-20) sm/sec or more in intense convective motion. Such convective motions, however, often occur on bumpy, mountainous terrain. Therefore, in the mountainous terrain it is not acceptable to have wind zero divergence as allowed for a smooth surface. Experimental measurements of wind vertical velocity are associated with principal difficulties and therefore their evaluation using theoretical methods is necessary.

It is assumed that origin of wind velocity is conditioned only by surface friction and relief; it is defined from integration of continuity equation:

$$W = -\int_0^H \left(\frac{du}{dx} + \frac{dv}{dy} \right) dz \qquad (1)$$

The air flows are affected by upwind –downwind currents rising from relief considering of which is essential on any selected local polygon. Those currents define local circulations and peculiarities. After transformations the equation (1) obtains the following type:

$$W = \frac{1}{lp}\left[rot_z \tau + \frac{1}{\eta}(p ln \eta) H \right] \qquad (2)$$

The obtained equation is differing from already existing ones by the last member that reflects orographic loading [2].

$$W_0 = \frac{1}{l\rho\eta}(p, \ln\eta)H \qquad (3)$$

where H s atmosphere layer altitude and W0 reflects upwind flow velocity rising from orographic factor. After calculations W0 amounts 8,7sm/sec. that indicates that orographic factor is important. This fact is revealed on the formation of local wind in Mtkvari River gorge. In Mtkvari River gorge wind transfers in gradient wind and their directions coincide. Thus, we got one wind flow in the gorge that is much stronger than in other river basins (e.g. Rioni River). Such event is usually observed every day and is of orographic nature. We can use this factor to explain so called “Tbilisi Hollow” phenomena.

The calculated vertical orographic velocity calculated is about 12.64 sm/s. Air masses mainly move in only one direction along the Mtkvari gorge.

In Tbilisi Hollow, the origin of the closed mountain-valley circulation occurs, which is enhanced by the low vertical velocity (maximum two dozen cm/s). Obviously, such dynamics of the air flow

substantiates all the climatic features mentioned above in it. Since there is a constant upward current of relief origin, which, due to the closed circulation, does not disappear above the mountain, but changes direction and returns to the city

Discussions

The air masses generally move only in one direction - across the Mtkvari gorge (h = 4.12m). In the cavern there rises congested circulation that is enhanced by the deficiency of vertical velocity (max. 20sm/sec). Such flow dynamic justifies all the climate "phenomenal" peculiarities (Tatishvili, et.al. 2019).

The above discussed is one reason of Tbilisi thermal regime. Another process that affects temperature distribution is geomagnetic activity.

During a geomagnetic storm the high-latitude currents which occur in the ionosphere change rapidly, in response to changes in the solar wind. These currents produce their own magnetic fields which combine with Earth’s magnetic field. At ground level, the result is a changing magnetic field which induces currents in any conductors that are present.

The Sun-Earth environment has variables, which are changing on regular basis due to starbursts. These variables are the Kp, proton flux and E-flux. Sudden changes in these parameters may abruptly influence the environment of the Earth. If an E-flux hike is responsible for global warming, then an E- flux lowering may lead to snowfall, thunderstorms and erratic rainfall. The effect of earth directed CME would not only trigger the earthquake, but affect the whole environment of the Earth, including the destruction of ozone layers leading to climate change (Tatishvili, et.al. 2021).

The effect of Earth directed Coronal Mass Ejections (CME) from the Sun reveals a significant impact on the atmosphere and geosphere. It has been observed that there is a close relationship between Kp values (Planetary Indices) and particle flux (Electron flux and Proton Flux) with the CME. The response of the magnetosphere to interplanetary shocks or pressure pulses can result in sudden injections of energetic particles into the inner magnetosphere

In order to identify connection between geomagnetic activity and synoptic and circulation processes 2015-17 warm period (III-IX months) various synoptic and geomagnetic indices daily data (Sunspot Watch, n.d.) have been studied for Georgian conditions.

Table 1. Geomagnetic activity indices and meteorological elements daily data for 2015-17 warm period in Georgia

Geostorms		Insignificant cloudiness (700 hpa)		Showers. Thunderstorm	
Geomagn. index	Geomagn storm type	Number of events	Circulation processes	Number of events	Circulation processes
K4	Active	10	South-west wave	20	South-east wave South-west wave High pressure area High pressure area (1 event)
K5	Minor storm	25	South-west wave	10	South-east wave South-west wave
K6	Moderate storm	23	High pressure area (8 event)	8	South-east wave South-west wave
K7	Strong storm	4	High pressure area (3 event)	3	South-west wave
K8	Severe storm	1	High pressure area	-	

It is ascertained that during all magnetic storms south-west or south-east wave processes have been formed and strong storms create high pressure areas. Depending on the synoptic situation wave processes leads the formation of thunderstorm and heavy showers. In addition, through geomagnetic storms the direction of circulation processes may drastically be changed.

The obtained NEA ground and space observation data are used for correlation analysis. The obtained results depict that temperature sudden decreases occur mainly on those dates when geo storm happens despite season of the The obtained NEA ground and space observation data are used for correlation analysis. The obtained results depict that temperature sudden decreases occur mainly on those dates when geo storm happens despite season of the year (Fig 1-8).

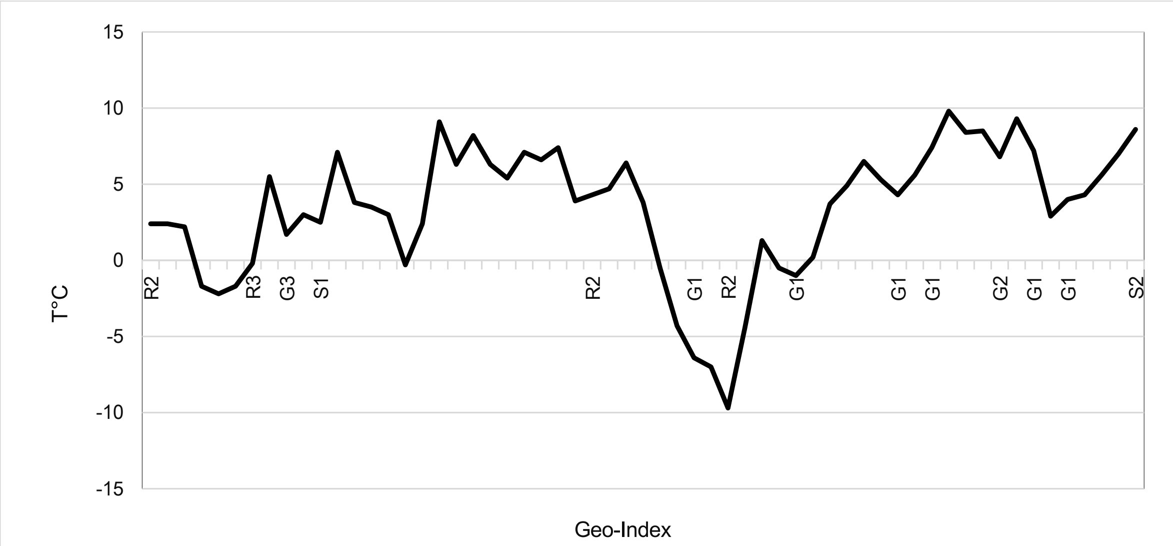

Figure.1. Correlation of temperature and kp geo index for 2014 (January and February)

Figure.2. Correlation of temperature and kp geo index for 2015 (June-August)

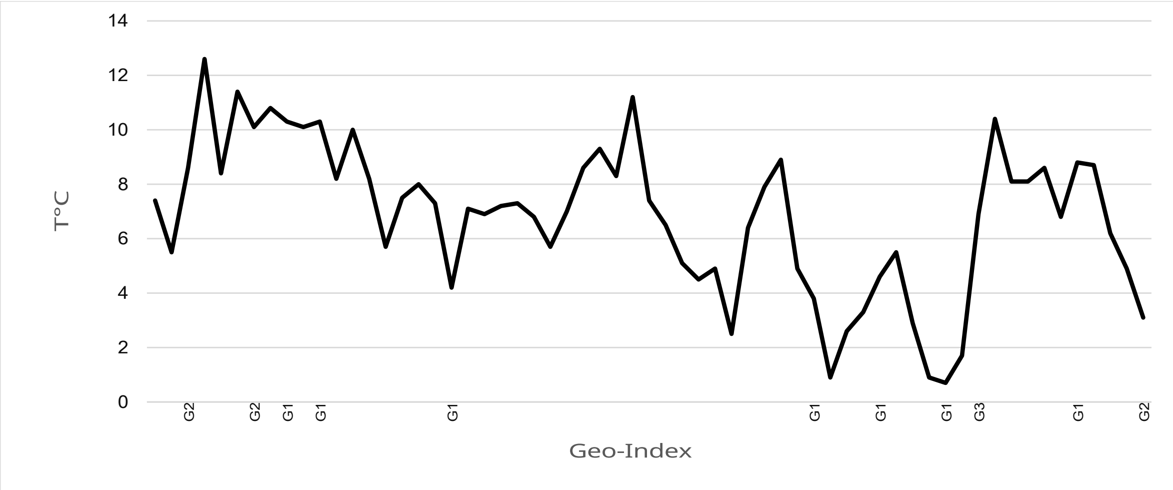

Figure.3. Correlation of temperature and kp geo index for 2015 (November-December)

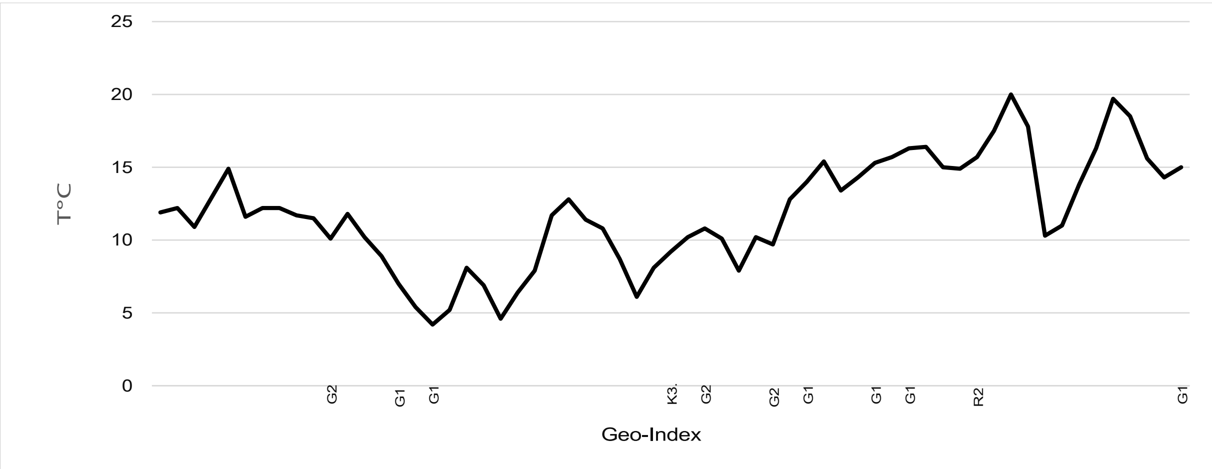

Figure.4. Correlation of temperature and kp geo index for 2016 (March-April).

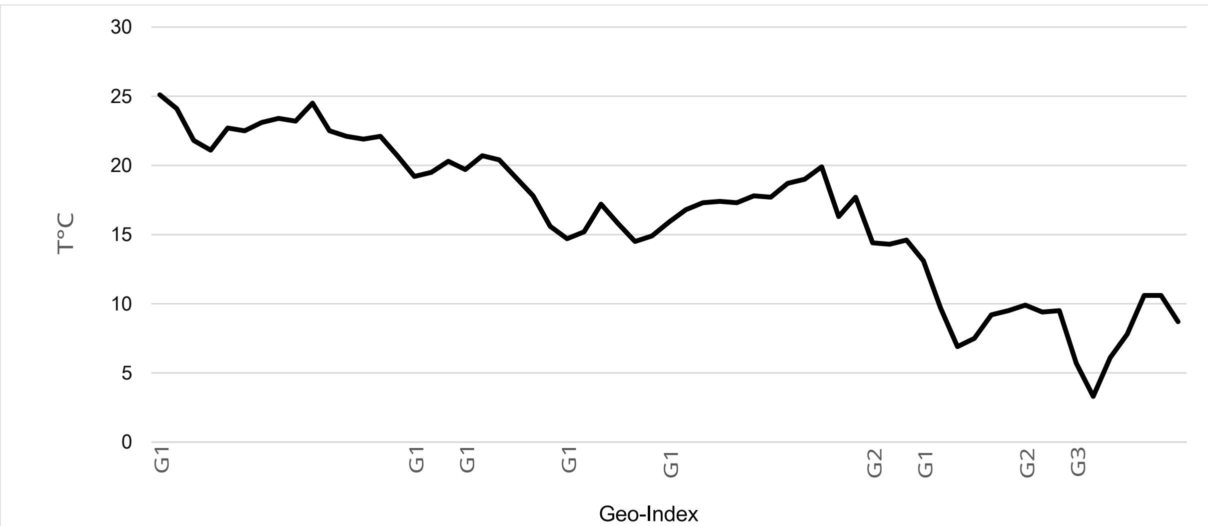

Figure.5 Correlation of temperature and kp geo index for 2016 (September-October)

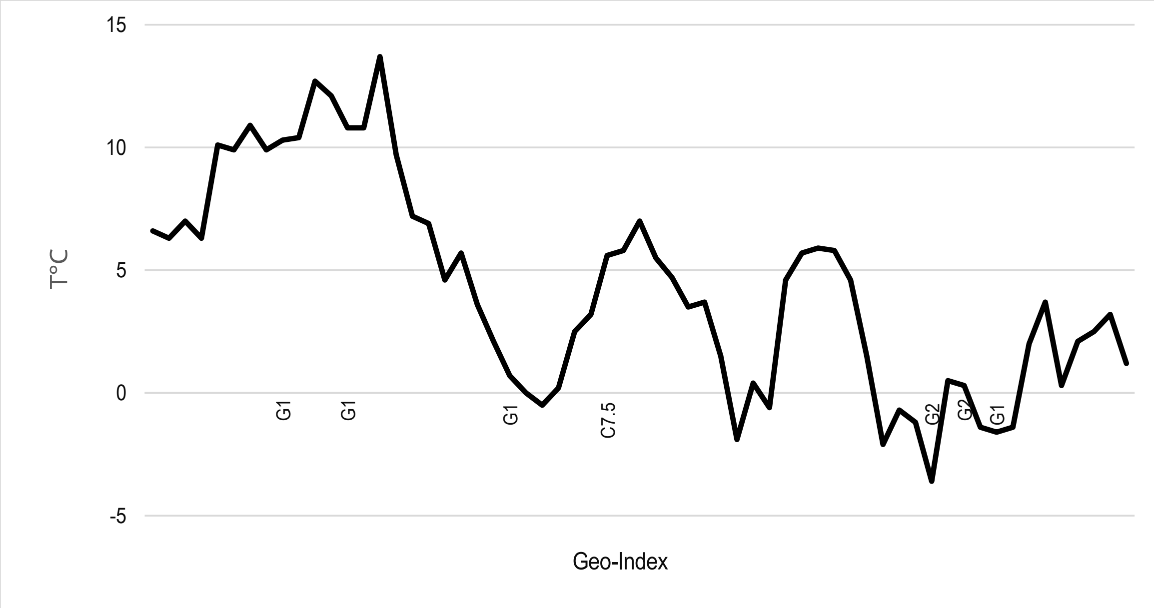

Figure.6. Correlation of temperature and kp geo index for 2016 (November-December).

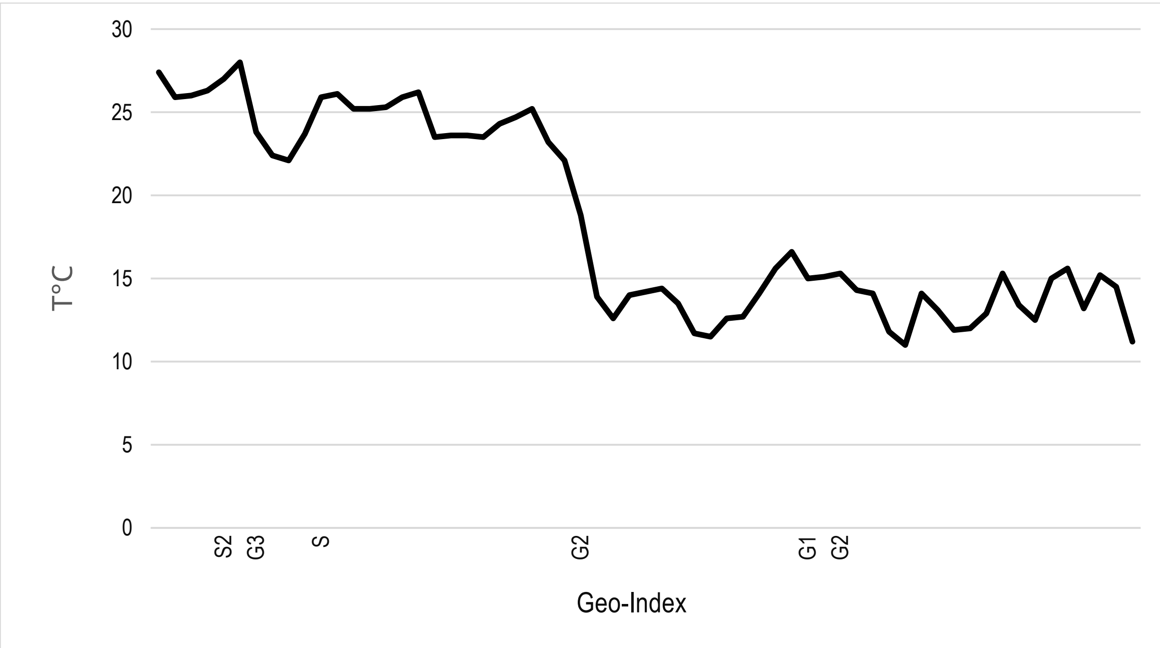

Figure.7. Correlation of temperature and kp geo index for 2017 (September-October).

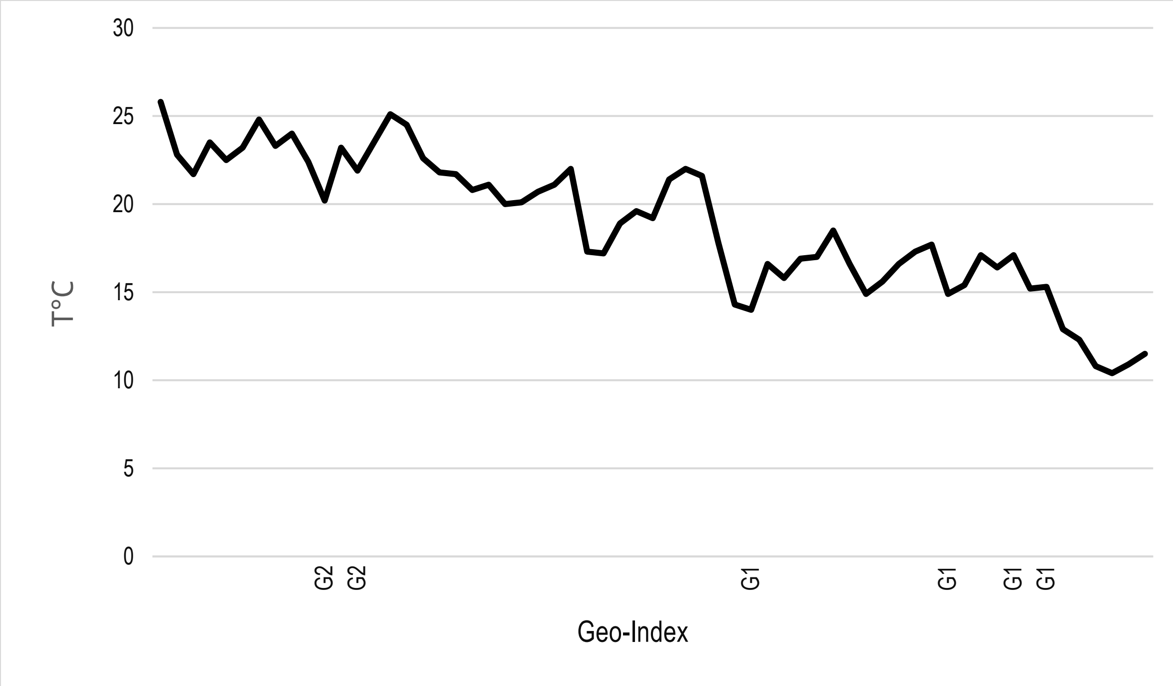

Figure.8. Correlation of temperature and kp geo index for 2018 (September-October)

Conclusion

The Vere River tragedy on 13 June 2015 is clear evidence of how upper atmosphere activity triggered geo-hazard. On this day, flash-flood on Vere River flooded part of Tbilisi city, destroyed buildings, infrastructure, Zoo, many Zoo habitats and 18 humans were dead. After analysing satellite data and synoptical situation it became clear what happened. During several days from 9 to 14 June 2 MEV high energy electrons penetrate atmosphere. The abundant amounts of electrons create stable clusters in lower atmosphere resisting precipitation infall. After they became so massive that couldn't resist gravitation the great amount of rainwater has been fallen out from clouds, causing flooding. The most of water properties are preconditioned by the fact that three component atoms aren't placed on one line. Negative charge prevailed on oxygen atoms part and positive on hydrogen. Thus, water molecule is electrically polarized. Among atoms and molecules acts force that always has attractive character. It is intermolecular dispersive or Van-Deer-Vaalse force. It is only one of the expressions of electromagnetic force. It acts among electrically neutral systems such as dipole or quadruple. In dipoles force reduces by r4 inverse proportional and in quadruple by r-6. It is not temperature dependent and its nature is quantum. By increasing dipole number their interaction increases (Tatishvili et.al. 2022)

1From analysing of historical records of meteorological observations and geomagnetic activity this correlation became more obvious. Many dangerous hydrometeorological event (flood, landslide) occurred over Georgian territory has driven by this activity, as the result of intensification of precipitation amount. Even hail processes intensification is the result of increasing atmosphere electricity and thunderstorm activity, that are produced by high energy charged particles intrusion into upper atmosphere.

These kinds of studies are essential in understanding of Earth magnetism and the Sun-Earth environment. It may be assumed that for weather forecasting the only existed numerical weather models aren't sufficient and they have to be enhanced by magnetic models to make forecasting more precise.

The main recommendation on how to make Tbilisi city cooler except the geomagnetic storm is to increase green cover in city centre and hill slopes. The best way for this action is Nature Based Solutions that include many possibilities such as green roofs, vertical vegetation, green troops, geo-parks.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

M. T. conceived of the presented idea, performed data processing, took the lead in writing the manuscript. N.B. performed data processing, took the lead in writing the manuscript T.K. and N.S, performed data processing. All authors provided critical feedback and helped shape the research, analysis and manuscript.

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Determining Parameters of Tbilisi's Winter Regime under Conditions of Climate Change and the Accuracy of their Determination

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Abstract

This study examines the winter temperature regime of Tbilisi, Georgia, over the period 1881–2018 using four analytical approaches: difference, linear, cyclic, and non-linear approximations. Nine temperature-related parameters were analysed, their probability density distributions were calculated, and the performance of each method was evaluated. The results indicate a gradual warming trend in average frosty-day temperatures and cumulative frost-related indices, accompanied by a decrease in the number of frosty days. Absolute minimum temperatures increased by approximately 0.5 °C over an 87-year period. The study demonstrates the usefulness of applying multiple approximation methods for assessing regional climate trends, particularly in areas with limited data coverage.

Keywords: Global climate, frosty days, winter regime

Introduction

Accurate assessment of winter temperature regimes at the regional scale is of particular importance under conditions of ongoing climate change, as winter temperatures strongly influence energy demand, ecosystem stability, hydrological processes, and the frequency of hazardous meteorological events. In mountainous and basin-shaped regions such as Tbilisi, winter thermal conditions are especially sensitive to both long-term climatic trends and local factors, including relief, atmospheric circulation patterns, and temperature inversions. Consequently, reliable identification of changes in winter temperature characteristics is essential for understanding regional manifestations of climate change and for supporting evidence-based adaptation strategies.

Recent advances in climate research increasingly emphasise the need to move beyond single-parameter analyses and to evaluate multiple temperature indicators simultaneously. Studies focusing on winter regimes often highlight not only mean temperature changes but also variations in extreme indices, such as the frequency of frosty days, absolute minimum temperatures, and cumulative frost intensity. These parameters are particularly informative in assessing shifts in climatic thresholds that affect infrastructure resilience, agriculture, and public health. However, the accuracy of their determination depends strongly on the analytical methods applied, especially when working with long-term observational series characterised by temporal inhomogeneities and data gaps.

Within the state of the art, a growing body of literature demonstrates that different approximation techniques may yield substantially different estimates of regional climate trends. Linear approaches remain widely used due to their simplicity and interpretability, yet they may fail to capture non-stationary or cyclic behaviour inherent in climate systems. Cyclic approximations attempt to account for periodic variability associated with solar activity, while non-linear methods allow for more complex temporal dynamics but introduce additional uncertainty related to model selection and parameterisation. The comparative evaluation of these methods has therefore become an important research direction in regional climatology.

In this context, the assessment of winter temperature parameters in Tbilisi provides an opportunity to examine not only the magnitude and direction of climatic changes but also the reliability of different methodological approaches used to quantify them. By analysing multiple temperature-related parameters and evaluating their probability distributions, it becomes possible to characterise the internal structure of the winter temperature regime and to assess the stability or transformation of its dominant modes. Such an approach contributes to the broader scientific effort to improve the robustness of regional climate assessments under conditions of limited observational coverage and complex local influences.

Determining the modern change of the Earth's global climate is still possible only theoretically, namely by building of energy-balance model. The main reason for this is the long-term (several decades) empirical data of the main air parameters, which can be used to determine the stability or change of the Earth's global climate are known only for less than one-tenth of the Earth's surface. If we take into account that the temperature change according to the regions is remarkably uneven (in some places there even cooling has taken place), it is clear that under such conditions the temperature of one tenth of the Earth cannot characterize the global change of the air.

As for the possibility of building energy-balance model of the Earth (together with the atmosphere), the fact that the energy system of the Earth placed in a vacuum is formed only at the expense of solar radial energy and climate parameters are mainly determined by this energy. Thus, the energy-balance model determines the Earth's energy potential, that is the ratio of received and released energies, which forms the global atmosphere. The energy potential, in addition to the intensity of the solar radiation energy, depends on the gaseous composition of the atmosphere and the ability of the subsurface to absorb the radiation energy. In a stable equilibrium of energy potential, the global atmosphere is unchanged. Under conditions of unstable equilibrium, the global climate experiences cooling or warming.

Determining regional climate changes in the same way as global weather is impossible. Because it is not the isolated system and neighbouring regions influence it. Determining their influence is difficult task. Regional climate can only be determined empirically. At present, the empirical data of ground surface temperature for a long time period in particular several decades, is used. As far as is known, the determination of regional climate changes is produced in four different ways:

1. Long (several decades) empirical data divided into three periods with the average temperature difference of the third and first periods (the so-called "difference" method);

2. Linear approximation based on the determination of the dynamic norm (Tavartkiladze 2010);

3. Cyclic approximation, where the periodic variation of solar radiation energy is taken into account.

4. With non-linear approximation, when the temperature change over time is modelled by a high-order polynomial.

In order to assess the change or stability of the regional, terrestrial temperature field, we take nine parameters characteristic of the temperature field (see below), determine their probability densities (thus uniquely characterizing their mode structure) and determine the accuracy of their calculation using the four mentioned methods.

Methods and Materials

The winter season (December–February) was selected because the effects of weather changes in Georgia are more pronounced during the winter than during the year, and it has a frosty period, which can be characterized by extreme deviations and better characterizes the weather changes than the average annual temperature.

Empirical data of Tbilisi winter temperatures for 1881–2018 were analyzed. Critical analysis of daily data and filling of randomly missed observations was carried out by the method of decomposition of the random function into natural-orthogonal coefficients (Obukhov 1960, Tavartkiladze et al. 2011, Tavartkiladze 2012, Tavartkiladze, et al. 2019, Tavartkiladze, et al. 2020, Bolashvili et al. 2024, Tavartkiladze, Bolashvili 2022, Tavartkiladze et al. 2023). To determine that every parameter of the air changes even slightly, an autocorrelation matrix of the parameters was built. Probability densities of each parameter were also calculated (Fig. 1).

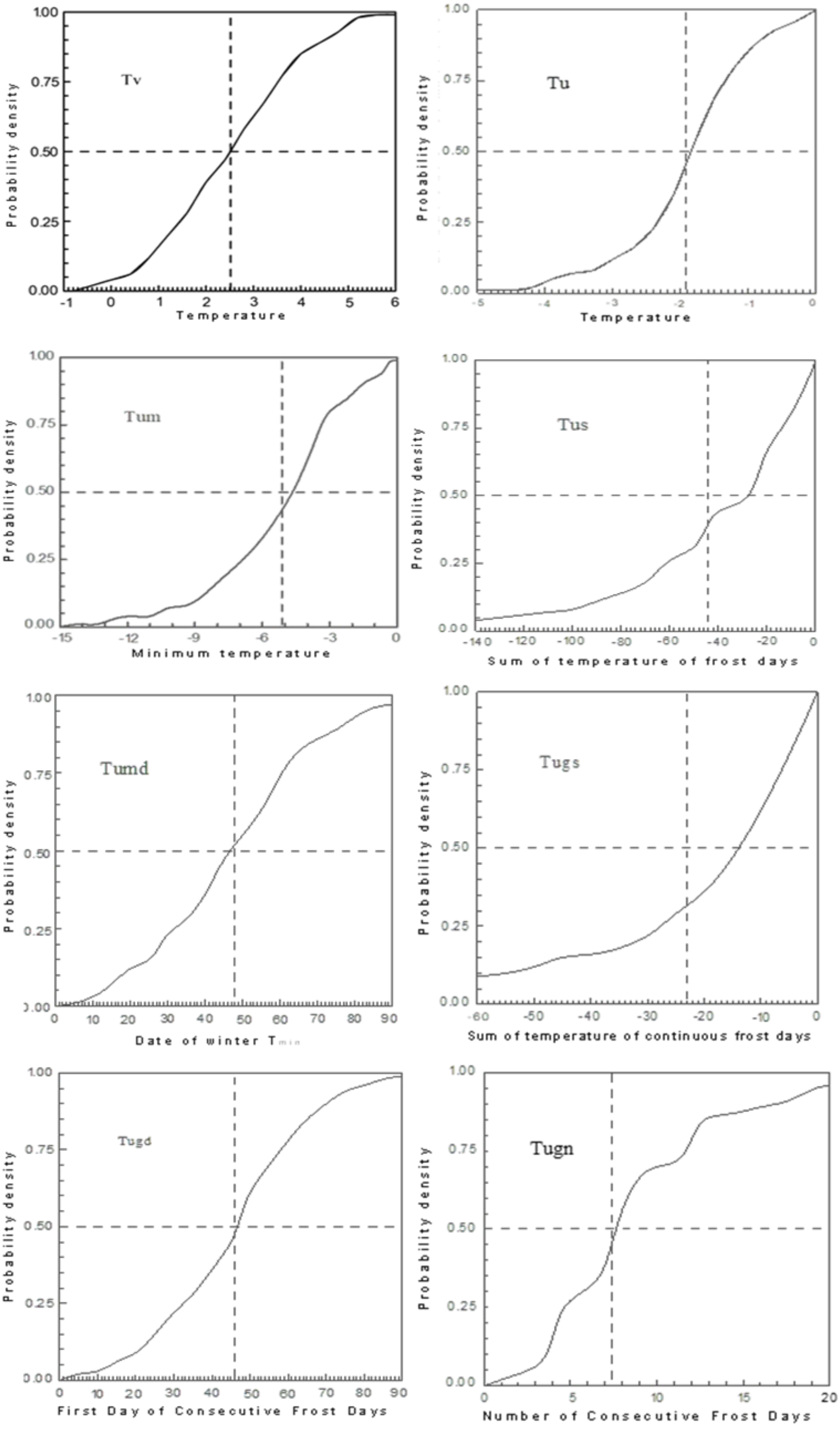


Figure 1. Probability densities of parameters characteristic of the regime structure of Tbilisi winter season

The change of parameters was determined using four methods: 1. Difference method, 2. Linear approximation, 3. Cyclic approximation and 4. Non-linear approximation.

The parameters analysed are:

1. Day-night average temperature (Tv °C)
2. The average temperature of frosty days and nights (Tu °C)
3. Number of frosty days and nights (Tun days)
4. Sum of temperatures of frosty days and nights (Tus °C)
5. Minimum temperature of frosty days (Tum °C)
6. The maximum number of frozen days (Tugn days)
7. The sum of the temperatures of consecutive frosty days (Tugs °C)
8. Date of occurrence of minimum temperature from frosty days (Tumd number, month)
9. The date of the first day of consecutive frosty days (Tugd number, month)

The accuracy of each method was evaluated by comparing the mean squared deviations relative to the arithmetic mean of each parameter over the entire period. Absolute minimum temperatures were determined using the least squares parabola method (Mazmishvili 1968) to reduce random errors.

Results

The autocorrelation matrix (Tab. 1) indicates that each parameter provides small but different information. The calculated probability density of each parameter characterizes the expected range and likelihood of values (Fig. 1). For example, the average temperature of the Tbilisi winter season during 1881–2018 covers the range from -1°C to +5°C.

Table 1. Autocorrelation matrix of winter season parameters (Tbilisi, 1881–2018)

	Tv	Tu	Tun	Tus	Tum	Tugn	Tugs	Tumd	Tugd
Tv	1	0.72	-0.91	0.83	0.77	-0.72	0.68	-0.13	0.05
Tu		1	-0.72	0.87	0.91	-0.73	0.82	0.05	-0.09
Tun			1	-0.89	-0.76	0.82	-0.72	0.05	-0.09
Tus				1	0.84	-0.85	0.90	-0.01	0.16
Tum					1	-0.68	0.77	-0.05	0.09
Tugn						1	-0.89	-0.01	-0.18
Tugs							1	0.02	0.19
Tumd								1	0.54
Tugd									1

The average temperature of frosty days, the sum of temperatures of frosty days, minimum temperatures, and total freezing-day temperatures gradually increased. The number of frosty days and the maximum number of frosty days decreased. Dates of minimum temperature and the first day of consecutive frosty days remained unchanged (Fig. 2).

The reduction of standard errors relative to the arithmetic mean is shown in Tab.2. Difference and linear approximations improve accuracy by 4–7% for most parameters. Cyclic and non-linear approximations further improve results for cumulative and extreme measures. Frost-date parameters remain largely stable.

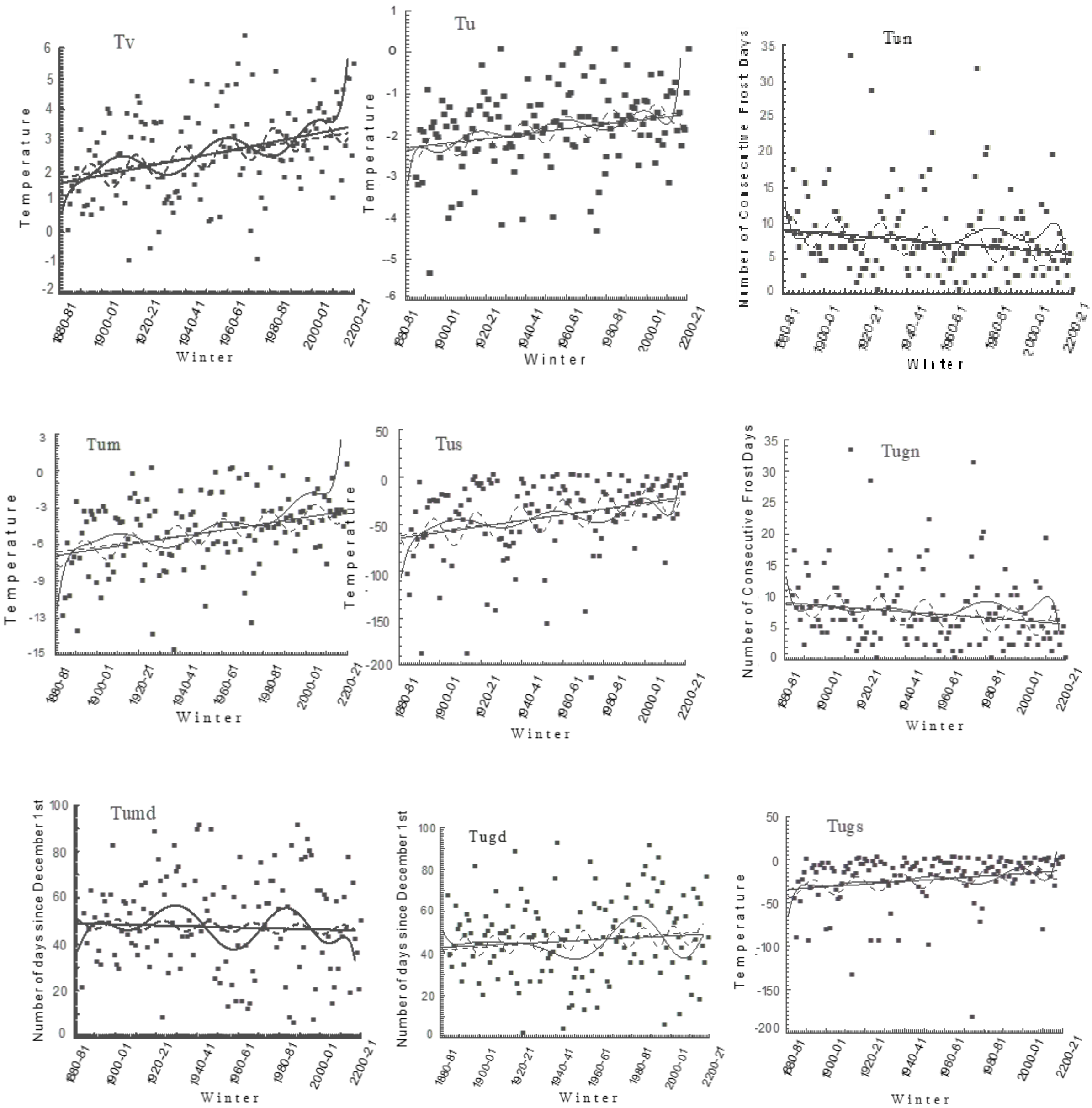
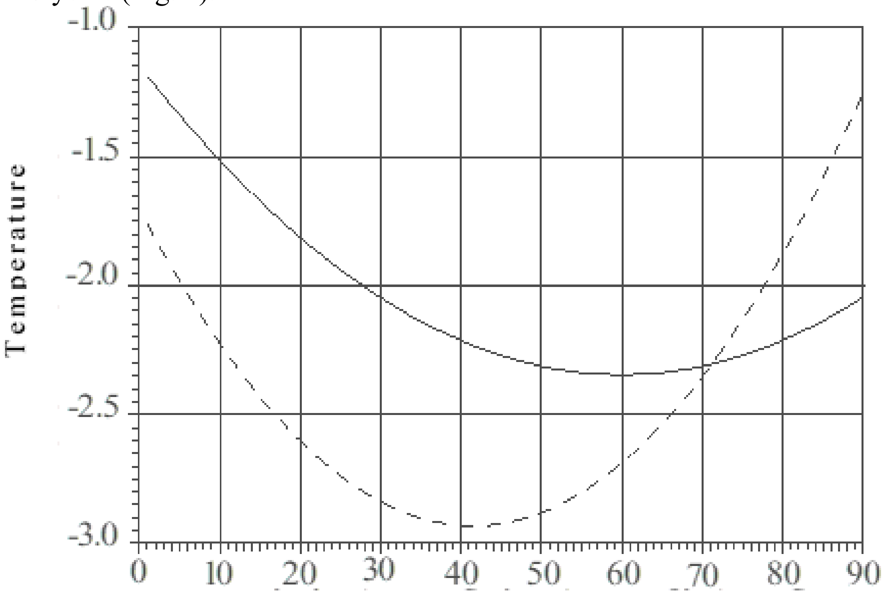


Figure 2. Changes in the characteristic parameters of the winter season of Tbilisi during the global warming period, with linear approximation (straight line), cyclical approximation (dashed curve) and non-linear approximation (continuous curve)

Table 2. Reduction of standard errors (%) compared with arithmetic mean

Winter season determining parameter	Reducing of standard error in % compared with static norm error			
	Difference	Linear approximation	Linear cyclic approximation	Nonlinear approximation
Tv	6.69	6.96	9.82	9.82
Tu	3.82	3.89	6.41	5.86
Tun	4.09	4.39	8.35	7.56
Tus	4.48	4.42	8.31	6.54
Tum	6.07	6.22	9.10	4.73
Tugn	1.34	1.40	3.97	0.27
Tugs	3.31	3.31	4.95	4.28
Tumd	0.09	0.09	0.40	3.99
Tugd	0.41	0.46	1.93	4.42

The absolute minimum temperature increased from -2.90°C in 1904 to -2.40°C in 1991, a rise of 0.50°C over 87 years (Fig. 4).



Number of Days After December 1

Figure 4. Probability density distribution of absolutely minimum temperature of the winter season size and occurrence date in Tbilisi¸ 1945-46 (dashed curve) and 1946-47 2017-18 (continuous curve) by years.

Conclusion

The defining parameters of the winter regime show that during the period of global warming, the average temperature of frosty days, the sum of temperatures of frosty days, the minimum temperature of frosty days, and the total number of freezing-day temperatures gradually increased, as expected. The number of frosty days and the maximum number of frosty days decreased. The dates of minimum temperature and first frost days do not change.

The results obtained by the difference and linear approximation are almost identical, about 4–7 percent, correcting the results obtained with Tv, Tu, Tun, Tus, and Tum. Only, the results obtained by difference are slightly less accurate than the results obtained by linear approximation. The parameters determining the interpolated frost days approach the true distribution with less precision (about 1–4%). The dates of minimum temperature remain stable.

The analysis of absolute minimum temperatures shows a modest increase of 0.50°C over 87 years, reflecting a reduction in extreme cold events. Probability density and autocorrelation analyses demonstrate that even small differences in parameters provide useful information about the winter temperature regime. Overall, the combination of multiple approximation methods provides a reliable assessment of regional climate change in Tbilisi.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

K.T. took the lead in writing the manuscript. N.B. was responsible for editing the manuscript. N.S. took responsibility for data visualization, including the preparation and drawing of all graphs and figures. All authors provided critical feedback and contributed to the research design, analysis, and final preparation of the manuscript.

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The Role of Agritourism in Rural Economy Diversification: Do Georgian Farmers Fully Leverage Its Potential?

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Abstract

Agritourism development is considered to be an effective way to raise the income of rural households and address their vulnerabilities associated with overdependence on agricultural activities by proposing additional activities on the farms. This has incentivized farmers and governments to introduce and invest in developing so-called "non-agricultural" undertakings, including under EU CAP. However, as various scholars have identified based on economic analysis, agritourism demonstrates quite varying results as regards farm size, output, experience, location and other factors. Its complex and varying nature has only been exacerbated by the non-existence of a single definition and cross-cutting nature causing confusion with rural tourism. In light of the newly adopted law of Georgia "on Tourism" and proposed tax cuts for agritourism service providers, this research aims to identify agritourism service providers in Georgia and the activities they offer to the visitors by conducting qualitative in-depth interviewing and on-site observation enabling to elaborate recommendations to better manage and address the needs of rural households in diversifying their income and making effective use of the existing agritourism potential. In addition, the research contributes to the everlasting challenge to define agritourism as it is essential prerequisite to develop adequate and needs-based policy framework for agritourism, allowing to provide tailored support to rural households in a long run. In this regard, local context should serve as the cornerstone.

Keywords: Agritourism, rural tourism, rural economy, diversification, policy framework for agritourism.

Introduction

Agritourism is an emerging segment of tourism that creates opportunities to diversify the income of farms by adding new activities, attractions, and experiences, allowing these rural households to break into new markets, attract more visitors, and reduce the risks associated with overreliance on a single activity (Wu et al., 2024). As various studies have shown, agritourism has a positive impact on farm income, and the income growth rate of farmers engaged in agritourism is higher than that of non-agritourism farms (Grillini et al., 2023), from the perspective of service providers, agritourism is a source of higher and more stable income for not only exclusively agritourism service providers but also in the broader community, on regional level, in general, as the increased number of tourists positively influences the turnover of local businesses, groceries, museums, etc. (Martinus et al., 2024).

In addition, there is a growing scholarly interest in this phenomenon. As Ndhlovu & Dube's bibliometric search and content analysis have shown, an increasing number of studies are devoted to the relationship between agrotourism and sustainable development. However, on the one hand, there are signs of the "North-South dichotomies", expressed in a quite uneven distribution of studies conducted in developed and developing countries, and, on the other hand, the studies tend to focus on economic and environmental dimensions of sustainability and to a lesser extent on socio-cultural-historical aspects of agritourism (Ndhlovu & Dube, 2024), while one of the key components of agritourism is storytelling.

At the same time, the number of tourism service providers in Georgia is increasing, who promote their services and position their destinations as agritourist destinations, accompanied by increased state engagement to regulate and support the industry. In 2023, the law of Georgia "on Tourism" was adopted, which defines agritourism (Law of Georgia "on Tourism", 2023), while the Tax Code of Georgia envisages a special tax regime for agritourism service providers (operators).

In light of the abovementioned developments, it should be noted that there is a lack of consensus among scholars regarding the definition of agritourism, as the concept fully or partially overlaps with Rural Tourism, Gastronomic Tourism, Cultural, Heritage, and Historical Tourism.

This research aims to identify and further analyse agritourism destinations in Georgia and their proposed activities, and to develop recommendations for diversifying farms and increasing income. We defined the units of observation as the agritourism destinations listed in the ELKANA and AGROGATE databases, as well as those found through personal contact. Moreover, we tried to collect observations not only from agritourism service providers and study the activities they carry out, but also, a secondary objective of our inquiry was to assess the perspectives of tourists and visitors themselves who are receiving such services.

To achieve the aim of the study, the following two research questions were defined:

What types of agritourism activities are offered to visitors/tourists in Georgia?

What is needed to utilise Georgia's agritourism resources and potential efficiently?

Methods and Materials

Given the nature of the research topic and the ambiguity in the definition of agritourism, the research was conducted in two stages. In the first stage, we conducted an in-depth analysis of relevant literature to conceptualise agritourism and articulate an appropriate conceptual definition. This was essential to avoid confusion between agritourism and rural tourism, enabling proper selection for the survey. Considering that there is no official (officially recognised) list of agritourism facilities in Georgia, which could have served as a basis for quantitative research, it was considered appropriate to conduct an in-depth qualitative study. Several non-probability sampling techniques were used to select the respondents for the survey, in particular, quota and purposive sampling (Neuman, 2014). As part of the selection, in the first stage, we selected relevant cases that, to a certain extent, aligned with the study's purpose. This sample was drawn from the ELKANA and AGROGATE databases and from personal contacts. Afterwards, quota sampling was conducted based on three criteria: gender, location, and the services/activities offered. This was important, especially for the service/activities category, as the study was mainly conducted in a wine-producing region of Georgia, and we tried to avoid surveying 'only wineries', which would have biased the study.

Finally, based on the literature review and survey results, recommendations were developed to better utilise agritourism potential in Georgia's rural areas.

Study Area

As mentioned earlier, there is still no unified list of agritourism destinations in Georgia, making it difficult to identify relevant service providers. Therefore, obtaining generalizable results at the national level is difficult. Consequently, given the research budget and other limitations, it was decided to focus the research on two regions of Georgia: Kakheti and Racha-Lechkhumi and Kvemo Svaneti. More precisely, we focused on the Zemo (Upper) Racha part of the Racha-Lechkhumi and Kvemo Svaneti region.

It is also worth noting that Kakheti, according to information obtained from ELKANA and AGROGATE databases and personal contacts, is characterised by a high concentration of agritourism destinations compared to other regions of Georgia.

Results

Conceptualizing Agritourism

One of the most obvious challenges of the relevant scientific literature on agritourism and tourism is the lack of clarity and improper definition/conceptualisation of key terms and concepts. Agritourism is one segment of rural tourism, although, for some scholars, the two terms have the same meaning. For example, Brandth and Haugen use “farm tourism” and “Agritourism “(Brandth & Haugen, 2010) interchangeably. Grillini et al. consider agritourism part of rural tourism, which involves agricultural activities and attracting visitors to the farm (Grillini et al., 2023). Considering agritourism's complex and overlapping nature, some researchers refer to it as "enigmatic" (Martinus et al., 2024), reflecting the challenges associated with its conceptualisation.

"Rural tourism" or "tourism in rural areas (activities that are carried out in rural areas)" can include various activities and types of tourism services, such as Agri, ecological, ethnographic, cultural and cognitive, medical, and some types of sports tourism.

Rural tourism development began in the 1970s in Spain, Italy, the US, France, and other countries, while in developing countries it commenced later, in the 1990s. In today's world, rural tourism is considered an alternative way to stimulate entrepreneurship and rural economic development, helping revive lagging rural areas and local economies and transferring capital and jobs from cities and developed areas to non-industrial areas (Khartishvili et al., 2019). It is also noteworthy that currently, rural tourism accounts for 15% of Europe's tourism industry (Kusters & Khartishvili, 2019).

The prerequisites for the development of rural tourism are the need of city residents for recreation in a new, ecologically clean environment and a new way of life, which is due to the growth of urbanization; low prices for recreation in rural areas; the possibility of consuming ecologically clean products; various opportunities for organizing rest; engagement in agricultural activities on the farm and familiarization with local culture, gastronomy, and customs (Aleksandrova, 2010).

Rural tourism is considered one of the priority destinations of tourism by the World Tourism Organization, and to encourage it, every year the tourist village of the year is named (in 2023, Mestia was the best tourist village in the world).

The Organization for Economic Co-operation and Development (OECD) (1994) describes rural tourism as "tourism that takes place in rural areas" and specifies that rural tourism is a complex, multifaceted activity; It is not just farm tourism. It includes farm stays, ecotourism activities, hiking, horse riding, adventure, sports and wellness tourism, hunting and fishing, educational travel, art, cultural heritage tourism, and, in some cases, ethnographic tourism (Development Committee on Tourism Secretariat, 1994).

According to another definition (Comox Valley, 2010), "rural tourism" is travel from an urban environment to rural areas for the traveler to enjoy and experience natural beauty, the tranquility of small towns, the richness of culture, and escape from the pressures of urban life to have pleasant experiences and improve the quality of life" (Khartishvili, 2020).

Rural tourism in Georgia is a relatively new type of tourism, although it has important traditions. Due to the close familial ties between the urban and rural populations of Georgia in the 20th century, it was common, especially in the summer and sometimes in the winter, to rest in rural areas with relatives or in their own homes or rented apartments, especially for families with children. "Tourists" mainly rented homes in those villages that served as resorts or resort areas and had facilities for the treatment and recovery of the population, since there were not enough accommodations in those resorts, and the distribution of trips there was carried out under conditions of a centrally planned economy. Since the 1970s, this phenomenon has been supplemented by the transfer of garden plots in the outskirts of large and medium-sized cities a very low prices to employees of enterprise institutions. This form of recreation was closer to today's concept of rural tourism, since the owners of garden plots were themselves involved in agricultural activities on their family farms, rather than the previously discussed forms of stays with relatives or in rented apartments, which involved less involvement in village life and farming. Most such settlements, especially near big cities, still serve their original functions.

Agritourism is a special form of tourism that combines organised and unorganised recreational activities for tourists in rural areas to connect with rural nature, lifestyle, and agricultural traditions. This type of tourism is distinguished by special forms of spending free time, such as taking care of cattle, working in a garden, a vegetable garden, or a vineyard, tasting local cuisine, walking, and arranging picnics in rural areas (Aleksandrova, 2010).

In the Law of Georgia "on Tourism" that was adopted in 2023, agritourism is defined as a type of tourism, the activities of which are carried out on a farm and encompasses receiving tourists, providing meals, sharing /familiarizing with a rural lifestyle, local traditions, and sights, engaging tourists in agricultural activities, providing them with locally produced agricultural products and performing other activities related to tourism and agriculture (Law of Georgia "on Tourism", 2023). As evidenced by this definition, it covers a wide range of activities, including other tourist services that are not directly related to agritourism. However, it is geographically limited because, according to the definition, agritourism is carried out only on farms.

The mentioned definition is mainly consistent with the definition provided by Martinus et al (2024), which is also shared by the authors of this article, according to which, agritourism is "economic exchange via a range of on/off-farm and authentic/staged experiences directly or indirectly related to agriculture" (Martinus et al., 2024, p. 3).

The local context should also be taken into account when conceptualising. Among agritourism facilities in Georgia, wine cellars are the most sought-after, primarily destinations for gastronomic or wine tourism rather than agritourism; however, many of these destinations offer accommodation and host tourists who often participate in harvest and wine-pressing activities.

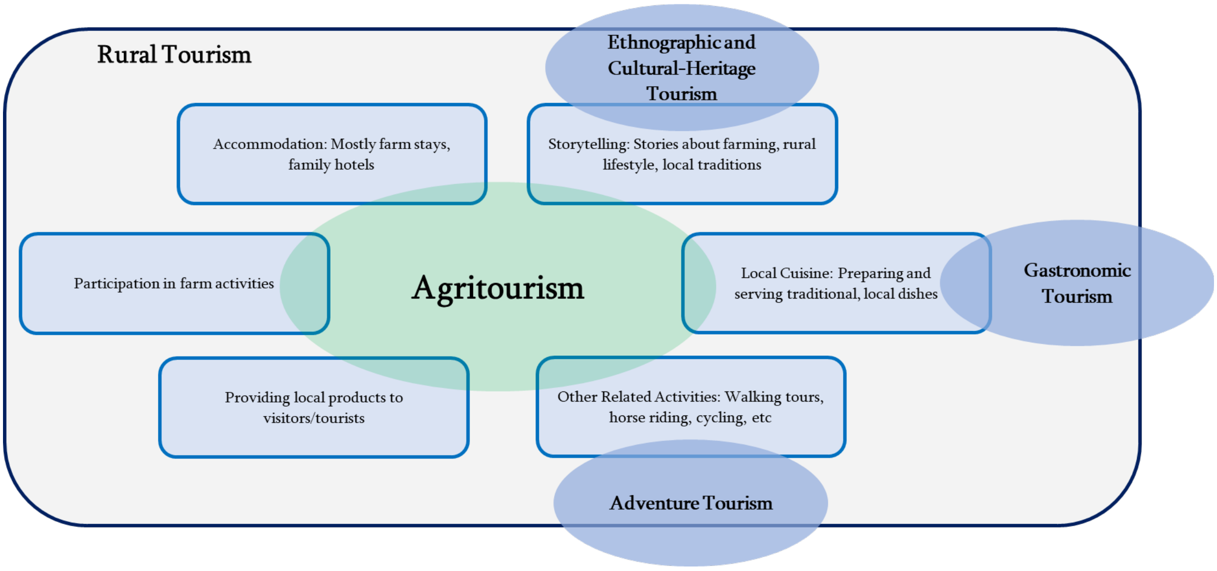

Figure 1. Defining Agritourism (based on a literature review)

The Results of the Survey

As part of the survey, 17 respondents were interviewed in two regions of Georgia, namely Kakheti and Racha-Lechkhumi and Kvemo Svaneti (in particular, Zemo (Upper) Racha–Oni Municipality) through face-to-face in-depth interviews. The geographical distribution of the respondents in terms of the municipality was as follows: Akhmeta Municipality (6 respondents), Telavi Municipality (3 respondents), Gurjaani Municipality (2 respondents), one respondent each from Sighnaghi, Kvareli and Sagarejo municipalities and three respondents from Oni Municipality (Zemo (Upper) Racha). The varying levels of agritourism activity explain such a distribution of respondents and are largely proportional to the geographical distribution of the agritourism destinations.

The Results of the Survey in Kakheti Region

Kakheti region, both from the historical perspective and at the current stage, is the centre of viticulture and winemaking in Georgia. According to the 2023 data, out of the 221.2 thousand tons of grapes processed in Georgia, 204 thousand tons of grapes were processed in the Kakheti region; at the same time, more than 81% of the income from the sale of grapes comes from Kakheti (National Wine Agency of Georgia, 2023). Therefore, one of the criteria for selecting respondents for the survey was their activity and location, so the research was not limited to the perspective of winery owners, who are quite a few in Kakheti. The question of whether the agritourism destination was located on the "Wine Route" served as a filter/contingency question. As a result, of the 14 selected respondents, only 6 own an agritourism destination located on the “Wine Route”, which enabled us to draw conclusions about the challenges facing the agritourism sector in the region and to develop relevant recommendations.

In selecting respondents, it should be noted that before the face-to-face interview, we did not ask detailed questions about their activities and limited ourselves to more general questions, for example, "Do you consider your activity as agritourism?" "Are you currently engaged in agritourism activity?" These questions allowed us to exclude from the initial list the agrotourism destinations that no longer considered their activities to be agrotourism and/or did not express a willingness to discuss their experience.

As a result, 14 respondents were interviewed face-to-face, and the general information about them is summarised in Table 1.

Gender

Male	*14%*
Female	*86%*
Age	
18 -34	*21%*
35 - 54	*36%*
55 and over	*43%*
Household Size	
1	*0%*
2 - 4	*64%*
5 and more	*36%*
Educational Level	
Graduate (at least bachelor's degree or equivalent)	*100%*

Table 1. The general information about the respondents of the Survey in the Kakheti Region

The majority of respondents (84%) have been engaged in tourism activities for at least 5 years and have been providing "agritourism" services, 8% of respondents had 3-4 years of experience in delivering agritourism services. Therefore, the interviewed agritourism service providers had significant practical experience in this area, which enabled us to ask detailed questions about their activities, existing challenges, and opportunities.

Since the public's perception and understanding of "agritourism" are not uniform or accurate, before asking detailed questions about their activities, it was important for us to understand how our respondents perceive agritourism and whether the “agritourism” services they provide align with their understanding of the phenomenon. For this purpose, during the survey, we asked the respondents to name 3-5 words or phrases that they associate with agritourism, and the results of this exercise are summarised in Figure 2.

Figure 2. Word Cloud - How do the respondents understand "agritourism"?

After this, we asked the respondents to evaluate how their activities correspond to the vision of agritourism they described, and we got the following result: 14% of the respondents believe that their activity "corresponds to some extent", 57% believe that their activity "corresponds", and 29% believe that their activity "fully corresponds". It should be noted that one of our respondents (Respondent_10) considered that her destination was closer to being ecotourism than agritourism, although she did not substantiate her answer. While describing agritourism and the activities she offers, she used words/phrases such as "family environment" and "tranquillity/quietness", and "close/direct contact with tourists", which, in our opinion, are elements of agritourism.

In terms of employment, the survey results show that tourism activities, including agritourism, are a source of income for many people living in rural areas. Most of our respondents (73%) are assisted by at least one household member in delivering agritourism activities. In addition, it is significant that each of our respondents employs at least one person (excluding household members) with varying intensity. Respondent_11 mentioned that during the summer-autumn season, in addition to household members, she employs seven people in agritourism activities. However, as already mentioned, this usually has seasonal/episodic character and largely depends on the demand and the type of service that tourists request (Respondent_12 mentioned that she periodically employs a cook when there is a demand from tourists for a master class in cooking local dishes, and Respondent_10 mentioned that she periodically employs a neighbour when there is a demand for a horse tour).

Agritourism activities require specific education/experience on which to base the business's success. As highlighted by Martinus et al. (2024), respondents engaged in agritourism service provision had „deep prior experience in agriculture“ (p. 3), which served as a basis for their subsequent activities. Therefore, an important part of our questionnaire was devoted to the experience and support (in terms of education or material-technical assistance) that our respondent agritourism service providers received in starting or expanding their businesses.

Before the start of agritourism activities, agriculture (primary production or processing) was the main activity of only 33% of the respondents. In comparison, the main activity for 67% was non-agricultural. The majority of respondents were employed in the public sector, predominantly in the field of law, and their activities did not intersect with tourism or agriculture. In addition, from an educational perspective, we can consider the education of only 29% of respondents to be in line with their current activities, namely, tourism, viticulture-winemaking, food technology, and agribusiness. The results of our research provide a different picture in this respect compared to the results of Martinus et al.'s study, which was conducted in Western Australia.

The words "spontaneously", "by chance", "personal initiative", and "own imagination" predominated in the answers of the majority of respondents to the question "What prompted you to start your agritourism business?". As a result, we can conclude that the majority of agrotourism service providers surveyed in Kakheti did not have a prior clear vision of their tourism business development when they started their activities, and according to their answers, the initiation of tourism business and the formation of relevant service types are mainly the result of random processes. All respondents indicate that they get information from different sources to expand their agritourism activities. These sources include: information available on the Internet in open access, personal or family members' travel/living abroad and services received there, and services/activities requested by tourists.

86% of the surveyed agritourism service providers in Kakheti benefited from "state or international/non-governmental organisation grant/co-financing or other assistance, and most of them benefited from various financial assistance schemes. It should be noted that the majority of respondents found it difficult to accurately recall all the assistance they received to start or expand agritourism activities, as most participated in 3 or more projects, indicating a high level of investment in this segment of economic activity.

Another block of questions was devoted to the types of provided agritourism services and the profile of visitors/tourists.

From a service point of view, it should be noted that the vast majority of respondents offer a wide range of services to visitors/tourists. The clarifying questions revealed that the majority of surveyed agritourism service providers do not offer a standard set of services to guests and use a very flexible approach. This approach involves pre-arranging the types of services in agreement with the visitor/tourist or the connecting travel company, and planning the services accordingly. For example, Respondent_08 mentioned that "tourists agree on the service in advance and the tour is planned accordingly", and Respondent_12 mentioned that "they always know exactly who is coming, when and what service they want".

The services provided by the respondents are diverse; however, it is noteworthy that when we asked whether they involved their guests in farming activities, only half (50%) offered such services, while 79% of the respondents had a farm and engaged in agricultural activities (primary production). Therefore, despite having a farm, some of the agritourism service providers preferred not to engage the guests in their farming activities, for example, Respondent_12 has several varieties of grapes planted in her vineyard, and despite the request of tourists to participate in the process of picking grapes, she says no, because “tourists may not pay attention to what kind of grapes they are picking", which will damage the quality of her wine.

According to the survey results, the most popular services are serving local dishes/drinks (93% of respondents), involving guests in the preparation of local dishes (71%), and getting to know the ethnic characteristics (71%). In addition to activities and master classes related to viticulture and winemaking, such as wine pressing, Churchkhela preparation, etc., as well as Khinkali master classes (such services are provided by more than half of the respondents), about a third of our respondents offer quite unique food/beverages to guests, such as mulberry leaf tea, Khinkali made from nettle leaves, etc. About a third of the respondents also use the harvest from their vegetable gardens/plots for cooking, and about 20% involve guests in the picking process.

In our opinion, to fully share the agritourism experience, service providers need to accommodate guests, as more extended stays facilitate sharing this experience through Storytelling. Accordingly, we inquired whether the respondents had accommodation and how much time on average they spent communicating with visitors/tourists. Based on the survey results, 64% of agritourism service providers can accommodate guests. In addition, only 36% of respondents spend more than 3 hours a day in direct contact with tourists. In terms of average visit duration, two groups of agritourism service providers were distinguished. The first group mainly focuses on short visits, and the average visit duration with these respondents is less than 6 hours. The second group offers a broader range of services to customers, including accommodation. This group of respondents (50% of respondents) named 1-4 days as the average duration of the visit.

Concerning Storytelling, only 29% of the respondents indicated that their service provision involves telling stories about local traditions and ethnic characteristics. We can consider the mentioned aspect as the main challenge of the interviewed agritourism service providers, as, in our opinion, a close connection should exist between agritourism services and Storytelling.

Regarding the profile of visitors/tourists, first, it should be noted that the absolute majority (over 90%) of the surveyed agritourism service providers received more than half of their visitors/guests from abroad (i.e., non-residents). Only one destination (Respondent_07) was predominantly visited by citizens of Georgia (up to 60% of visitors), but the pandemic significantly changed their visitor profile, with 80% of guests being foreign residents by 2020. This dynamic coincides with the tendency mentioned by another respondent (Respondent_05) that "the number of local tourists significantly increased after the pandemic (Covid-19)". Despite this trend, the general conclusion is that the surveyed agritourism destinations in the Kakheti region are less popular with the population of Georgia, as Respondent_03 noted, "I do not even remember the last time I received a guest from Georgia.

We also asked our respondents to recall the "countries from which they received the most guests" and "the farthest settlement or country from which they received a guest". The results were quite impressive as the respondents were able to recall visitors from Japan and the USA (Respondent_08), Canada (Respondent_07), South Korea (Respondent_05 and Respondent_06), New Zealand, Australia, the USA, Canada and Japan (Respondent_11). In the case of Respondent_04, the host had collected banknotes (national currency) of "all the countries of the world", most of which had been left by the visitors.

As for the most visitors, according to our respondents, tourists mostly visited from European countries, mainly Germany, Poland and France. It should be noted that, although Russian citizens predominate among international tourists in Georgia, only one of our respondents (Respondent_05) listed Russian tourists among their main guests. We did not ask the respondents to explain our observation, only during an in-depth interview with one respondent (Respondent_12), she touched on this issue and explained, "I am also surprised that I do not have Russian tourists... maybe it is the result of high prices. However, in the case of another respondent (Respondent_06), who allowed visitors to leave their initials and the name of their hometown/country on the walls, we noticed many inscriptions referring to several Russian cities, including during the last year, although the respondent did not name tourists from Russia as the main country of origin.

Another issue we touched upon during the in-depth interviews was the means of promoting agritourism destinations/services and the significance of the location of the respondent's "agritourism destination". In terms of advertising their services, the majority of respondents use a wide range of communication channels and involve almost all household members who can do so. It should also be noted that those members of the respondent's household who are fluent in English or other foreign languages (Respondents_04, _08, and _12) are particularly actively involved in communication with potential customers. In the case of Respondent_07, she used "sign language" to communicate with a French tourist who visited her tourist attraction without prior reservation.

While assessing the importance of location for the success of agritourism activities, more than 80% of respondents consider the location of their destination to be "very important or important".

Challenges and Opportunities of Agritourism in Kakheti Region - The Perspective of our Respondents

As a result of the survey, a wide range of impending circumstances was revealed, ranging from the personal/household level to current processes in the region and the world, which, according to the respondents, negatively impact their activities. When answering this question, the respondents also remembered funny stories. One female respondent mentioned that her family member told her the following when she started agritourism activities: "You harm my image/reputation by taking money for food" (Respondent_04). Apart from these relatively “funny” moments, about 20% of female respondents found "stereotypes" to be a challenge, though this was less about the female role than about ethnic aspects.

"Massive influx of non-resident guides" (Respondent_03), "non-existing tax benefits" (Respondent_05), and "political situation in the Region and the World" (Respondent_11) were named as other hindering factors.

Most of the respondents named "access to finance" as an obstacle; however, at the same time, they mentioned the help they received through various state, international, and other aid instruments. As mentioned in the survey, almost 90% of respondents have benefited from various financial assistance mechanisms, and the majority have participated in more than one support scheme.

Regarding the contributing factors, the most frequent answers were: "location", "support from the family", "knowledge of languages", "tradition of hospitality", and "authenticity".

Speaking about prospects, the majority of respondents mentioned the need for greater financial support for business expansion and for government regulation of the agritourism sector.

The Results of the Survey in Zemo (Upper)Racha Region

Zemo (Upper) Racha region was chosen as the study area to assess the trends, challenges, and opportunities of agritourism development in Georgia from a “non-traditional” agritourism region perspective. Zemo (Upper) Racha is currently characterised by quite severe socio-economic conditions, with growing depopulation accompanied by complex natural processes that hinder tourism development in the region. As mentioned, Kakheti is the centre of winemaking and viticulture in Georgia; at the same time, it has a higher concentration of farms than Zemo (Upper) Racha, and its proximity to the capital should be considered a contributing factor to the development of the agritourism industry in Kakheti.

Despite the different geographical and socio-economic characteristics, the research conducted in Zemo (Upper) Racha region revealed largely similar, and in some respects identical, results.

Out of the 3 agritourism service providers whom we interviewed, 2 respondents have more than 5 years of experience, and one has been delivering agritourism services for about a year. Therefore, they have significant practical experience in agritourism. However, similar to the results in Kakheti, before starting the agritourism business, 2/3 of respondents in the Zemo (Upper) Racha region had no prior experience in agriculture or agritourism (or related fields); in particular, they were employed in a public institution (i.e., public servants).

From the service types perspective, it is worth noting that, as in Kakheti, the interviewed agritourism operators in Zemo (Upper) Racha offer tourists a wide range of services. However, they do not offer guests a standard set of activities that adequately reflect the true identity of their agrotourism destination. As Respondent_16 pointed out, a tourist's request for specific services is crucial. As a result, in our opinion, the identity of the agritourism destination is to a certain extent compromised.

The questions asked about the profile of visitors/tourists also showed us similar results, in particular, international tourists accounted for the most significant part of the income of 2 out of 3 respondents, while in the case of one respondent (Respondent_16), the distribution was essentially equal. In the case of Zemo (Upper) Racha, the agritourism destinations mainly were visited by guests from European countries (similar to the results from Kakheti), and the respondents used various means of communication to contact international tourists. In the case of Respondent_17, whose agritourism destination was mainly visited by Polish tourists, a member of the household of Polish origin played a crucial role in communication with international visitors.

The level of investment and access to financial resources should be considered as the main differentiating circumstances revealed as a result of the survey conducted in the two target areas. In particular, only one of the three interviewed respondents (Respondent_15) had used a grant/co-financing from the state or an international/local organization or other financial instruments to start or expand his or her agritourism business. In contrast, 86% of the surveyed agritourism service providers in Kakheti have benefited from such assistance and most of them have participated in at least 3 different support schemes.

Discussions

Questions about the motivation for starting agritourism activities revealed that respondents' decision was not driven by the decline in agricultural activities, consistent with a study by Wu et al. in Taiwan. This study found that farm diversification was driven more by the desire to generate additional income and use existing resources more efficiently than by reducing "traditional" farming activities (Wu et al., 2024).

The survey conducted in both Kakheti and Zemo (Upper) Racha clearly showed that the surveyed agritourism destinations depend to a significant extent on income from international tourism, thereby increasing the vulnerability of these service providers to global political, economic, or social processes, especially crises. The economic analysis conducted by Bacsi and Szálteleki (2022) shows that agritourism is characterized by similar trends in farm output and income during the financial crisis (such as a 2008 financial crisis), however, in the case of the Covid-19 crisis in 2020, farm incomes from agricultural production have been largely stable, while agritourism incomes have declined by 35% in 2019-2020 (Bacsi & Szálteleki, 2022), indicating the acute sensitivity of agritourism to mobility-related constraints.

Concerning the income of surveyed agritourism destinations in Kakheti and Zemo (Upper) Racha regions, according to the results of the survey, a visitor spends on average less than 1000 GEL per visit in the surveyed agritourism destinations; a more detailed distribution is presented in Figure 3.

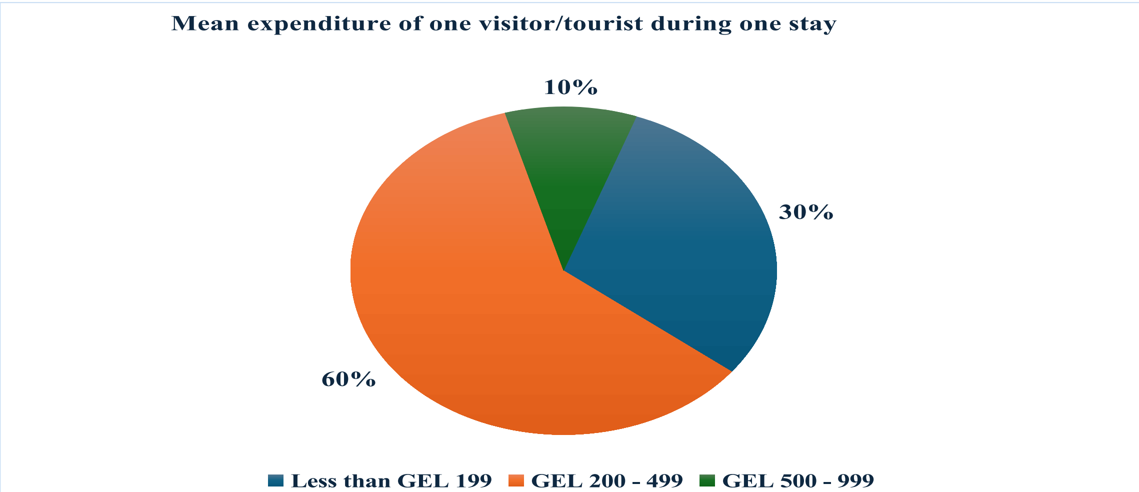

Figure 3. On average, how much a visitor/tourist spends per visit (service providers' perspective)

The success of agritourism as a business activity is significantly influenced by "farm identity" (Brandth & Haugen, 2010), which encompasses not only the farm's location and proximity to natural and cultural attractions but also the farmers themselves. As one of the respondents of Brandth and Haugen's (2010) research pointed out, they become part of the tourism product willingly or unwillingly (Brandth & Haugen, 2010). However, location remains one of the most important factors shaping a visitor's experience (Martinus et al., 2024). This opinion is confirmed by our research results, as mentioned, more than 80% of respondents in Kakheti consider the location of their destination "very important or important".

The popularity of the agritourism product and the willingness to repeat the visit are also significantly influenced by "engagement", which is manifested in the host's ability to create a pleasant and friendly environment for the visitor, to ensure their involvement in farming activities and to share the rural lifestyle and experience (Martinus et al., 2024). The role of the host involves Storytelling, telling a unique story related to a village or a farm to the visitors, preparing dishes based on local recipes or engaging guests in their preparation, as well as carrying out farming activities in a traditional way, not through modern technologies (Brandth & Haugen, 2010). Storytelling is considered one of the key elements in the context of the visitor experience, enhancing the sense of authenticity and belonging/connection to the place, which in turn ensures repeat visits to the farm; however, this requires „a holistic and coordinated approach" (Martinus et al., 2024). Despite the recognised role and importance of storytelling in agritourism, our survey revealed that less than a third of our respondents employ storytelling techniques as part of their agritourism experience.

Both internal and external factors influence farm diversification. The results of the study by Wu et al. (2024) highlighted the importance of external factors in this process, in particular, the attractiveness of agritourism service (demand for this type of service in the tourist market), improvement of transport infrastructure and technological progress in the field of communication were named as determining factors (Wu et al., 2024, p. 8), which brings these destinations closer to consumers and increases the motivation to invest. The survey conducted as part of our study showed that the majority of agritourism service providers actively use various communication channels, which may increase tourists' interest, including international tourists'. It is also important to note that most respondents have used various available financial assistance schemes to improve/expand their agritourism businesses.

When discussing the importance and promotion of agritourism, its economic and social aspects should be adequately considered. A study by Grillini et al. (2023) in the Austrian-Italian border region, examining the intersection of agritourism (ATFs) and non-agritourism (non-ATFs) farms with sustainability, revealed differences in sustainability outcomes. In particular, the results differed across the three indicators of sustainability (economic, social, and environmental). From an economic perspective, the income of agritourism farms has been increasing, but their agricultural output has been decreasing, which may ultimately negatively impact food security. From a social perspective, relationships between people within the farm are strengthened. However, communication among community residents is reduced, and, from an environmental perspective, agritourism farms rely more on agri-environmental-climatic practices, thereby making their production more sustainable in this regard (Grillini et al., 2023). Based on Bacsi and Száteleki's (2022) study, the relationship between agritourism income and farm output/performance was not straightforward. However, medium-sized farms in the EU were more involved in agritourism service provision and therefore received more income from these activities (Bacsi & Szálteleki, 2022).

As for the state's support of agrotourism, it is important to analyse both its positive and negative aspects. Grillini et al (2023) consider that when planning to support agritourism, support should be limited to farms with limited potential for agricultural development, for example, smallholders, areas with an unfavorable climate, or other hindering factors that have little effect on agricultural production (Grillini et al., 2023).

Martinus et. al. (2024) consider the lack of visitors' and users' perceptions/impressions as a limitation of their research and a promising direction for further research (Martinus et al., 2024) because it could reveal different tendencies and factors, rather than studying the issue from the perspective of tourism service providers.

The present study sought to fill this gap in the literature, although in most of the agritourism destinations we visited, tourists were absent. In those agritourism destinations where services were provided to tourists, the service was either not agritourism in nature or, in other cases, our intervention could have hindered agritourism service delivery to consumers.

Conclusion

Agritourism, first of all, means diversifying the agricultural activities of farms in rural areas by adding non-agricultural activities. This is aimed at reducing the overdependence of farms and farmers on primary agricultural production and the risks associated with it. Agritourism creates additional income and employment opportunities in rural areas and reduces the risks associated with seasonality, which was confirmed by our research.

As mentioned, agritourism intersects with various types of tourism, including gastronomic, cultural heritage, and adventure tourism. In our opinion, the starting point for agritourism services should be raising tourists' awareness of farming practices through demonstrations and/or storytelling, and increasing the country's population's interest in the countryside in general. On the other hand, the experience of the agritourism service provider is important. Our survey showed that the majority of people involved in agritourism lack a clear vision for developing their agritourism business.

More than half of the respondents also offer accommodation to guests, facilitating direct contact with tourists, although only a third employ storytelling strategies, a key element of agritourism.

According to our survey results, the main challenge for agritourism destinations is the risk of authenticity and excessive dependence on international tourism. Research conducted in Kakheti and Zemo Racha highlighted the sector's excessive reliance on income from international visitors, leaving agritourism operators vulnerable to international political developments.

In addition, the mix of different tourist services, in our opinion, reduces the likelihood of an authentic agritourism experience. At the same time, as various studies indicate, the farm's identity is essential for repeat visits to agritourism destinations. In our opinion, this challenge can be addressed by offering a niche agritourism product/service.

The fact that the agritourism destinations included in this study are not attractive to local tourists suggests a lack of authenticity in the surveyed destinations. In other words, the agritourism destinations participating in the research and their products/services are authentic with respect to Georgia, that is, they express the national identity, and are a visiting card of Georgia, but are not authentic on the farm/destination level. To increase Georgian tourists' involvement, it is necessary to understand better the state of play and study agritourists' perceptions and impressions.

The respondents of the survey consider that the factors contributing to the development of their agritourism destination include a good location, family support, language proficiency, the tradition of Georgian hospitality, and the authenticity of the tourist attraction. Certain stereotypes, the absence of economic benefits, and the global and regional political situations were identified as obstacles. By generalising these factors, we think that, in parallel with the development of agriculture in Georgia and through financial and other incentives provided by the state, further successful development of agritourism is possible.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

A.S. conceived of the presented idea. Both authors contributed to the design and implementation of the research and the writing of the manuscript. Both authors provided critical feedback and helped shape the research, analysis, and manuscript.

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Svaneti at a Crossroads: Socio-Economic Challenges and Opportunities for Regional Development

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Abstract

Svaneti, the most mountainous historical-geographical region of Georgia, is characterized by its exceptional natural conditions and culturally rich anthropogenic landscape. The region encompasses the municipalities of Mestia and Lentekhi, whose distinct physical environments, historical heritage, and socio-cultural traditions shape divergent trajectories of socio-economic development. In the summers of 2023–2024, a sociological survey was conducted within the framework of the Vakhushti Bagrationi Institute of Geography's field expedition to evaluate contemporary socio-economic dynamics in the region through active engagement with local residents. A total of 35 respondents participated, enabling a comparative assessment between Mestia and Lentekhi and facilitating the identification of key development constraints and emerging opportunities. The survey was complemented by cartographic materials, statistical diagrams, and photographic documentation. The results reveal severe challenges related to depopulation, limited employment opportunities, and pronounced out-migration—issues particularly acute in Lentekhi, where sustained emigration has resulted in the closure of kindergartens and schools in several villages. Although livestock breeding continues to represent a traditional economic activity, tourism has become an increasingly important sector, with a majority of respondents expressing interest in acquiring the skills necessary to participate more effectively in tourism-related services. Nevertheless, infrastructure remains unevenly developed: while major transportation corridors have been improved, rural road networks require substantial reconstruction, and deficiencies persist in telecommunications, healthcare provision, and commercial services. Tourism infrastructure, including accommodation facilities and visitor information centres, also remains insufficient and requires systematic, state-supported development. The analysis further indicates that migration pressures are more pronounced in Lentekhi than in Mestia, driven by a complex interplay of economic, infrastructural, and demographic factors. Addressing these challenges will require integrated regional policies aimed at strengthening population retention, diversifying employment, and balancing tourism-driven growth with the needs of agriculture and traditional livelihoods. Given the limited availability of arable land and other natural constraints, sustainable development in Svaneti cannot rely solely on agriculture; instead, it must be underpinned by targeted job creation, improved infrastructure, and enhanced state involvement across multiple sectors.

Keywords: highland developments, socio-economic vulnerability, Mountainous Region, Svaneti, Agriculture, Migration, Tourism.

Introduction

Mountain regions occupy approximately 27% of the Earth's terrestrial surface and support more than 1.1 billion people, while providing vital ecosystem services—such as freshwater resources, biodiversity protection, and cultural landscapes—to billions more living in adjacent lowlands (FAO, 2015). Extending from the Alps and Himalayas to the Andes and the Caucasus, these regions are marked by highly diverse geographies, distinctive cultural systems, and rich biocultural heritage. Despite their global ecological and strategic significance, mountain territories remain among the most vulnerable and socio-economically marginalized environments worldwide (Jodha, 2005; Price, 2013; Messerli & Ives, 1997). In Europe alone, mountains cover approximately 36% of the continent and host 16% of its population, reflecting the considerable demographic and territorial importance of upland regions across the continent (Moretti et al., 2023). Yet chronic environmental fragility, geographic isolation, infrastructure deficits, and the accelerating impacts of climate change continue to undermine pathways toward sustainable development (Beniston, 2003; UNEP, 2012). Understanding the future of mountain communities requires context-sensitive, place-based strategies that acknowledge local socio-ecological systems, settlement histories, and cultural identities.

The socio-economic challenges facing mountain regions are rooted in both physical constraints and long-standing structural marginalization. Rugged terrain and seasonal climatic barriers hinder mobility, complicating access to education, healthcare, and national markets. Many highland regions—including those in Nepal, Kyrgyzstan, and Georgia—continue to experience seasonal isolation, with roads closed for months during winter, reinforcing patterns of social exclusion and limiting engagement in broader political and economic processes (Price, 2013; Debarbieux & Rudaz, 2015). Mountain communities also frequently contain ethnic and linguistic minorities whose representation remains limited within centralized governance frameworks. Outmigration, particularly among younger cohorts, is widespread and contributes to demographic ageing, cultural erosion, and the weakening of traditional knowledge systems essential for sustainable land management.

Economically, mountain regions face multiple structural disadvantages, including limited agricultural potential, ecological fragility, and underdeveloped infrastructure. Steep slopes, shallow soils, and short growing seasons constrain agricultural productivity and render mechanization difficult or economically unviable (UNECE, 2019). Consequently, subsistence farming, pastoralism, seasonal labour migration, and remittances remain central livelihood strategies in many upland communities. Persistent deficits in transport, telecommunications, education, and healthcare infrastructure further entrench marginalization and restrict access to markets and services (Jodha, 2005). Tourism has emerged as a significant economic alternative in numerous mountain destinations such as the Alps, the Andes, and parts of the Caucasus; however, its benefits are often unevenly distributed, weakly regulated, and vulnerable to seasonality and external shocks. Moreover, unplanned tourism development may intensify environmental pressures and cultural commodification if not embedded within integrated regional planning (Khartishvili et al., 2019).

Georgia and the wider Caucasus region exemplify many of these challenges and dynamics. Svaneti—one of Georgia's most mountainous, remote, and culturally distinct regions—offers a compelling case for examining the interaction between natural-geographical conditions, demographic processes, and socio-economic development. Situated along the northwestern flank of the Greater Caucasus, Svaneti consists of two municipalities, Mestia (Upper Svaneti) and Lentekhi (Lower Svaneti), each shaped by contrasting topographies, altitudinal gradients, and economic specializations. While Mestia is dominated by high alpine landscapes, with over 96% of its territory situated above 1,000 meters and nearly two-thirds above 2,000 meters, Lentekhi features more moderately elevated terrain that supports a more diverse range of agricultural activities, including fruit cultivation and viticulture. These differences significantly influence settlement patterns, agricultural potential, and diversified livelihood strategies.

The region's development prospects are further influenced by its peripheral location and limited transport connectivity. Svaneti is accessed primarily through the Enguri and Tskhenistskali river valleys, with additional routes constrained by natural barriers. Scarcity of arable land, steep slopes, and challenging soil–climatic conditions limit agricultural productivity and mechanization, while extensive natural hayfields, pastures, and forests dominate the regional land fund. Demographic decline, persistent emigration, and the underutilization of local labour resources exacerbate socio-economic pressures, especially in Lentekhi, where depopulation is more acute and widespread.

Nonetheless, Svaneti possesses considerable potential for sustainable tourism development. Its unique combination of high mountain landscapes, UNESCO-recognized cultural heritage, and distinctive ethnographic traditions has increasingly positioned the region as a key destination for adventure and cultural tourism. Mestia has emerged as a regional tourism hub, benefiting from recent infrastructural investments, while Lentekhi is beginning to promote its natural attractions—including the Kheledura and Mananauri gorges and the Ailama peak and glacier. Ongoing projects, such as road reconstruction and resort rehabilitation, illustrate expanding state and private-sector interest in the region. However, socio-economic surveys reveal significant remaining challenges, including limited employment opportunities, insufficient healthcare access, uneven tourism development, and the need for more sustainable land-use planning.

This study examines the socio-economic processes shaping contemporary development trajectories in Svaneti, with particular emphasis on the interrelations between physical geography, demographic trends, and local livelihood strategies. Through a comparative analysis of Mestia and Lentekhi municipalities, the research identifies convergent and divergent patterns in economic activity, population dynamics, infrastructure, and development priorities. Drawing on sociological field surveys conducted in 2023–2024 by the Vakhushti Bagrationi Institute of Geography, the study integrates local perspectives to assess both the opportunities and the structural constraints shaping sustainable development in the region. By situating the findings within broader debates on mountain development, the research contributes to a deeper understanding of the pathways and policy mechanisms necessary to support resilient, inclusive, and sustainable futures for highland regions of the Caucasus.

Study area

Svaneti is located on the southern slope of the Central Caucasus in the upper part of the Enguri and Tskhenistskali basins. It occupies 4388.9 sq. km (6.2% of the country's territory). The most characteristic feature of Svaneti's location is its isolation. It is bordered on all sides by high ridges: to the north rises the Main Caucasus Range, which reaches the highest hypsometric level in the territory of Svaneti. Here is located the highest peak of Svaneti and at the same time Georgia, Shkhara - 5203 m. To the west, Svaneti is bordered by the Kodori (highest peak Moguashirkha 3847 m) and Akibi (lowest peak Akibi 2811 m) ranges, to the south by the Egrisi range (lowest peak Tsekuri 3486 m), to the southeast and east by the Lechkhumi range (lowest peak Samertskhle 3584 m).

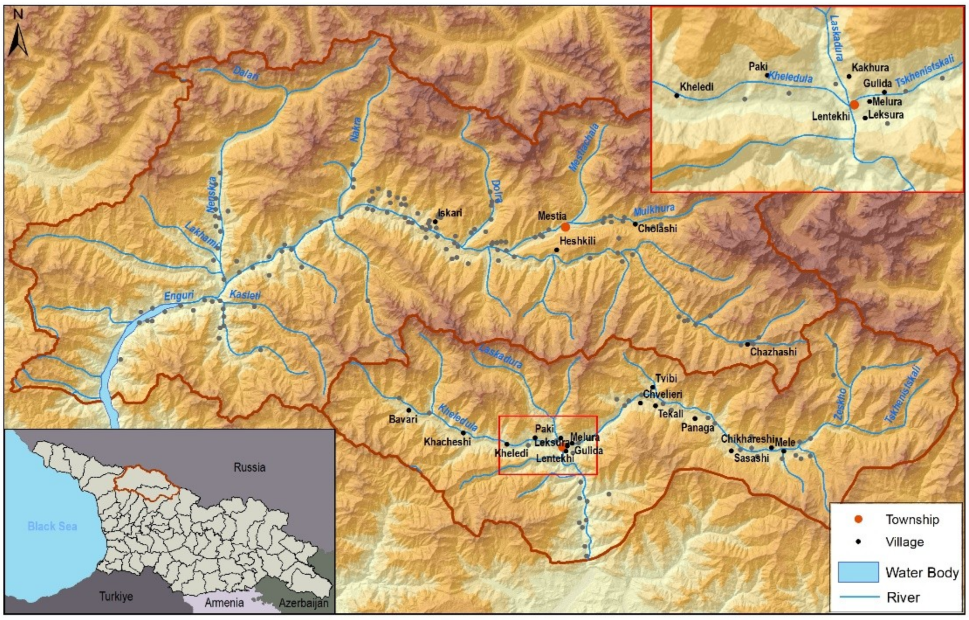

Figure 2. Study area (created by authors)

The geographical feature of Svaneti lies in its division into two parts: Lower Svaneti (Lentekhi Municipality) (fig. 2) and Upper (Mestia Municipality) (fig. 3) Svaneti. They are separated by the Svaneti range (lowest peak Lahili or Laila, 4008 m). Which is a watershed between the Enguri River (Upper Svaneti) and the Tskhenistskali River (Lower Svaneti). The Svaneti ridge is difficult to cross and represents a kind of barrier between the two parts of Svaneti, there are passes on it, through which Upper and Lower Svaneti are connected to each other. In the Svaneti section, all the passes of the Caucasus are located above 3000 meters (Khazaradze &. Salukvadze, 2024).

Upper Svaneti has difficult natural conditions, is very remote from other regions of Georgia and is connected by the only, difficult transport route, which follows the Enguri River valley through the Jvari Kldekari.

Lower Svaneti is somewhat better located. It is hypsometrically lower, due to which its natural conditions are less severe, secondly, the distance from the plain regions is not so great, but the fragmentation of the relief here is almost the same as in Upper Svaneti, due to which the scarcity of land resources is sharply expressed. In Svaneti, agricultural lands occupy 31% of the entire territory, with a large abundance of natural forage. Cultivated lands occupy only 1% (Salukvadze & Chaladze, 2025).

Figure 3. Lentekhi (Photo: M.Tsitsagi)

Figure 4. Mestia (Photo: M. Tsitsagi)

Methods and Materials

This study was conducted in the mountainous region of Svaneti, focusing on the municipalities of Mestia and Lentekhi and their respective settlements, including Tekali, Khacheshi, Melura, Leksura, Paki, Bavari, Kakhura, Gulida, Panaga, Chikhareshi, Chvelieri, Tvibi, Kveda Chvelieri, Sasashi, Mele, Kheledi, Chazhashi, Heshkili, Iskari, and Cholashi. These localities were selected through purposive sampling to ensure representation of both Upper and Lower Svaneti and to capture the geographical, socio-economic, and cultural variability across the region's highland landscapes. The selection strategy aimed to reflect differences in altitude, accessibility, demographic dynamics, and livelihood structures.

A qualitative research design was employed to achieve a comprehensive and reliable understanding of socio-economic conditions in Svaneti. Following Creswell (2014) and Bryman (2016), the integration of qualitative and quantitative components allowed for methodological triangulation, enhancing validity and reducing bias. The primary instrument of data collection was structured personal interviewing, supported by standardized questionnaires commonly used in sociological and human-geographical field research (Bernard, 2017). In total, 35 respondents participated in the survey, representing diverse age groups, occupations, and settlement types across the region.

Fieldwork included systematic photographic and video documentation to support qualitative interpretation and to generate a visual archive of settlement morphology, infrastructure, and landscape features. These materials provided contextual depth and aided the verification of observational data. All collected information was organized in a digital database to facilitate subsequent coding, categorization, and comparison.

Geospatial analysis constituted a central component of the methodology. The study utilized Geographic Information Systems (GIS) to produce thematic maps illustrating settlement patterns, infrastructure distribution, accessibility, and land-use characteristics. Mapping procedures followed established cartographic and geospatial analysis standards (Longley et al., 2015). The integration of social survey data with spatial datasets aligns with contemporary approaches in socio-environmental research, which emphasize the value of GIS for linking human perceptions, demographic indicators, and environmental conditions (Pfeffer et al., 2005).

Quantitative results were visualized through statistical diagrams, while qualitative findings were analysed thematically. The convergence of multiple data sources—including interviews, questionnaires, visual documentation, and geospatial mapping—strengthened the robustness of the findings and allowed for a nuanced interpretation of regional socio-economic processes. This methodological framework ensured a realistic depiction of the conditions shaping development in Svaneti and supported the formulation of context-specific recommendations for enhancing regional sustainability.

Results

The sociological survey conducted in the municipalities of Mestia and Lentekhi provides insights into the demographic, economic, and infrastructural conditions shaping contemporary socio-economic development in Svaneti. A total of 35 respondents participated in the study, allowing for an indicative, community-level assessment of trends characteristic of Upper and Lower Svaneti.

Demographic Structure and Migration Trends

The age composition of respondents reveals pronounced demographic ageing (fig. 4). Elderly residents (65+) constitute 35% of respondents, nearly equalling the middle-aged working population (32%). In contrast, young adults (18–29) represent only 3% of the sample, reflecting significant youth outmigration. This pattern aligns with broader demographic trends in mountain regions globally, where young people frequently migrate to urban centres in search of education and employment, resulting in aging rural communities (Ives & Messerli, 1989; MacDonald et al., 2000).

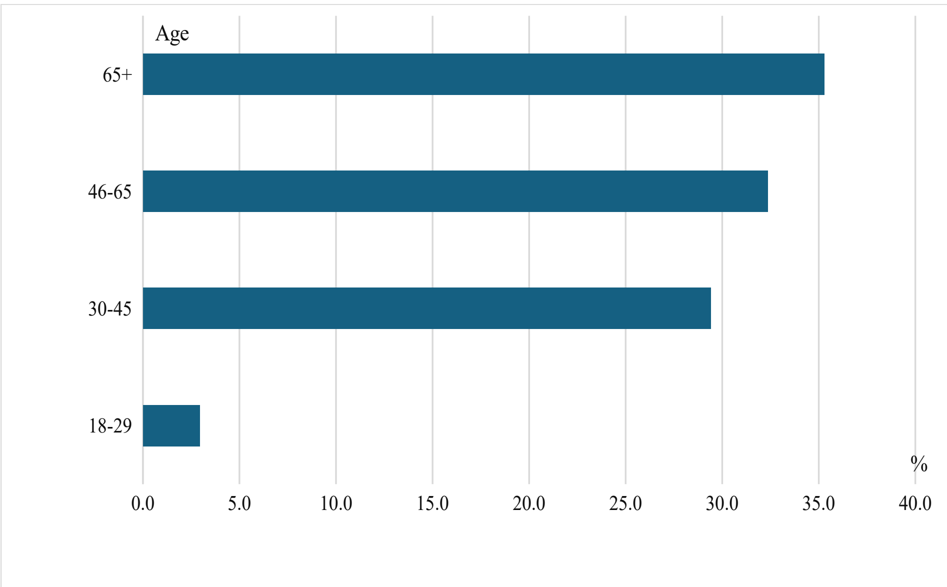

Figure 4. Percentage distribution of respondents by age

Gender composition shows a strong predominance of women (77%) over men (23%) (fig. 5). This imbalance is consistent with established migration dynamics in the Caucasus and other mountainous areas, where men migrate seasonally or permanently for work, leaving women and elderly residents as the primary population remaining in rural settlements (UNEP, 2012; Debarbieux & Rudaz, 2015). Daytime data collection likely also contributed to the overrepresentation of women, as men were more likely to be engaged in agricultural, construction, or tourism-related activities.

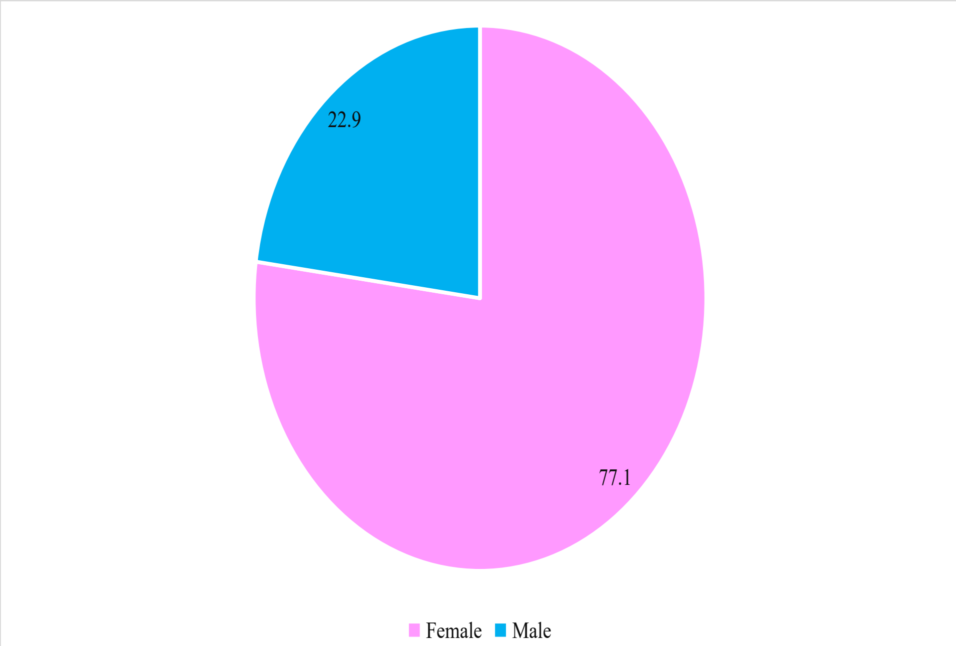

Figure 5. Percentage distribution of respondents by gender

Permanent residents constitute 66% of the sample, while 34% are seasonal residents (Appendix A) who spend most of the year in urban centres or abroad. Temporal means that They spend most of the year in Tbilisi or Kutaisi, working or studying there, and only return in the summer. This category also includes eco-migrants who live in other regions of Georgia but return to Svaneti in the summer.

Migration remains a major socio-economic issue: 26% of respondents (Appendix A) reported having at least one family member living abroad, with Spain representing the most common destination. These findings reflect the broader Georgian context, where labour migration plays a major role in household income strategies, particularly in peripheral mountainous regions (Salukvadze, 2022).

Comparative evidence from other mountain regions shows that youth departure is not universal: in parts of the European Alps and Carpathians, young people express greater willingness to remain in highland communities when local economic prospects improve (Ivasciuc & Ispas, 2023). This contrast underscores the importance of targeted policies for youth retention in Svaneti.

Similar studies have been conducted in several mountainous regions. A study conducted across Europe has shown promising results, in particular the surveys covered Italy, France, Norway, Poland, Romania, and Spain revealed that young people want to stay in the mountains because they enjoy both the quality of life and the natural environment. Young generation respondents also mentioned that they want to be entrepreneurs and act against climate change. In Romania, the mountain area is particularly attractive to young people (Ivasciuc & Ispas, 2023).

Educational Attainment and Human Capital

In our study area, most respondents (61%) have higher education, which clearly reflects the positive attitude of the region's population towards education; this fact indicates that there is a significant intellectual resource for the development of the region. The educated population plays an important role both in the process of rural development and in the introduction of innovations and improving decision-making. Their involvement is especially important, as higher education helps them to consciously direct their efforts towards the social, economic and cultural development of the region. In addition, the educated population can effectively engage in initiatives aimed at identifying and solving the problems of rural settlements. Accordingly, this group is an important asset for the further development of the region. However, the second question is how much educated people want to return to their usual environment and realise themselves where they see no prospects. As illustrated by fig. 6, respondents with secondary education (33%) are a large group. Their involvement in the activities of the region, through continuing education or retraining programmes, will potentially increase their work capacity. Persons with incomplete secondary and basic education make up 6% of the surveyed population. This group is relatively small, although their presence may be associated with barriers to access to education in the past. For most respondents (61%), having higher education and a significant number of persons with secondary education (33%) indicate the educational potential of the region's population.

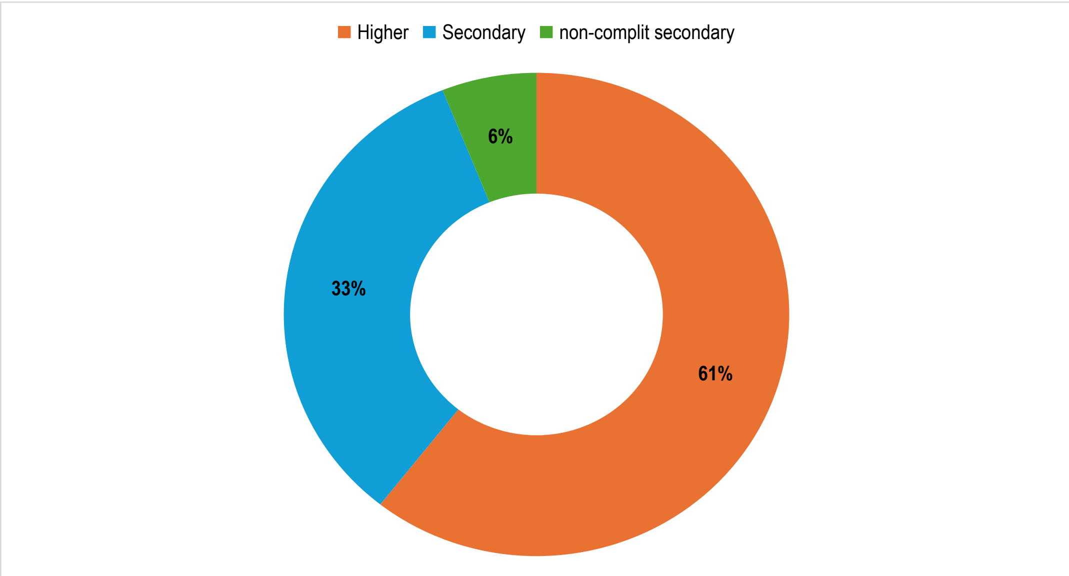

Figure 6. Education level among respondents (percentage distribution)

Data in Appendix B suggest Foreign-language knowledge also reflects the region's socio-economic history and emerging needs. Russian remains the most widely spoken foreign language (46%), reflecting Soviet-era educational legacies. Meanwhile, knowledge of English (24%) and German (10%) is rising, likely due to increased tourism and international exposure. However, 20% of respondents do not speak any foreign language, highlighting a need for targeted language training to support tourism development and strengthen economic diversification.

Employment Patterns and Land Ownership

As we can see in Appendix C, a significant part of the respondents (39%) is employed in the private sector, and 25% in the public sector. The low rate of leaving their place of residence for employment (3%) indicates the desire for stability among the local population, despite the existing difficulties.

More than 88% of property is privatized as detailed in Table 1. The fact that 88% of respondents have privatised their land indicates stable land ownership, which is a good basis for long-term investments and development. However, the unpayment of land tax by 67% may indicate a certain financial burden for the population and require a review by local governments. As a result of land privatization after the collapse of the Soviet Union, landowners do not pay taxes on agricultural land. Given that (especially) in Lower Svaneti, there is less resale of agricultural land, it is logical that the number of lands taxpayers is also lower. Similar patterns of smallholder land ownership but limited commercial use are found across the Caucasus (UNECE, 2019).

Table 2. Percentage of privatized property and population paying taxes

	Housing has been privatized (%)	Pays land tax (%)
Yes	88.6	33.3
No	5.7	66.7
Do not know	5.7	-

At the same time the high rate of negative attitude towards the alienation of land to foreigners (88%) indicates the sensitivity of the local population to this issue and the importance of land as a cultural and economic resource (Appendix D). The negative attitude of the Svaneti population (88%) towards the alienation of land to foreigners is due to several deep-rooted factors. Their attitude is likely based on historical, cultural and economic considerations. In Svaneti, as in the mountainous regions of Georgia, land is not simply an economic resource. It is the heritage of ancestors, a spiritual and cultural value that is closely linked to the identity of the family, clan and region. Its alienation is perceived as a betrayal of cultural heritage and roots; due to the mountainous terrain of Svaneti, the area of land for agricultural purposes is limited (as in mountainous regions in general). The loss of this limited resource poses a direct threat to the economic future and existence of the local population; there is a fear that the land transferred to the ownership of foreigners will lead to a change or loss of the traditional appearance, architecture and way of life of the region. Svan towers and unique villages are part of their cultural identity; the local population, often dependent on agriculture and tourism, fears that foreign investment and large landowners will reduce their competitiveness and ultimately take away their livelihoods; increased demand for land by foreigners may lead to a disproportionate increase in land prices, making it completely unaffordable for local youth and the population. This, in turn, will contribute to increased migration from Svaneti. In addition, it is doubtful that foreign owners will use the land effectively and rationally, considering local interests. Also, land, especially in border regions, is often perceived as an integral part of the country's sovereignty and security. The transfer of a large part of it into foreign hands may be considered a threat to national interests. It is important that the development of the area and the management of resources remain under the control of local government and the community, and not external actors.

Tourism: Perceptions, Participation, and Uneven Development

The priority given to future tourism development (Table 2) by most respondents (60%) demonstrates the potential of this sector in the region. This may be related to the opportunities for increasing income, creating new jobs and promoting the region. The response received confirms the situation not only in Svaneti but also in the mountainous regions of Georgia. In recent years, tourism has become one of the main sources of transformation of the population's economic activities, and the strongest competitor to agriculture in the mountainous regions of Georgia (Salukvadze, 2022). In a pre-pandemic survey, respondents generally had positive attitudes towards the impacts of tourism development. Regarding economic impacts 96.8% believed that tourism development would provide more jobs for local people, 85.5% noted that the tourism industry would play a major economic role in the community. The pandemic has reduced these numbers and locals have clearly seen the need for economic diversification.

Table 3. Percentage of the respondents according to the priority sectors and future training

	Priority sectors for the future	Would like training in
Livestock	27.5 %	5.6 %
Horticulture	5 %	-
Industry	5 %	-
Tourism	60 %	55.6 %
Greenhouse farming		19.4 %
All the above	2.5 %	-
None of the above		19.4 %

The high percentage of those willing to undergo training in the field of tourism (56%) once again emphasises the great interest in the development of this sector. The presence of those interested in greenhouse farming (19%) and livestock farming (6%) also indicates the potential for development of various branches of agriculture. The presence of respondents (19%) who do not believe that they need training in any field may be related to their existing knowledge and experience.

Some of the studies carried out (studies conducted by the NDI organization) show that examples of successful cooperation between citizens and municipalities are very rare. The main reason for the passivity of the population, along with the lack of information, is the feeling of community members that they cannot influence decisions, and, as a result, citizens are indifferent to cooperation (Public Attitudes…) (Gogorishvili & Zarandia, 2021).

Agriculture: Scale, Practices, and Constraints

Table 3 reveals that, 80% of respondents do not use fertilizers in agriculture, 14% do, and 6% refrained from answering. The high rate of use of machinery in agriculture (60%) indicates a certain modernisation of this sector, although the high rate of non-use of fertilisers (80%) may be related to financial difficulties or traditional approaches.

Table 4. Use of machinery and fertilizers in the study area

	Use of machinery in agriculture (%)	Use of fertilizers in agriculture (%)
Yes	60.0	14.3
No	37.1	80.0
Seldom	2.9	
No answer		5.7

Table 4 summarises that, 61% do not sell products grown on site. They use them themselves. The main sales markets are Kutisi (17%), Mestia (8%), Lentekhi (5%), and Tskaltubo (3%). The low rate of sales of local products indicates a problem with the market, or the harvest is so small that the population refrains from selling it, consuming it themselves. Respondents use trade facilities in different cities. Among them: Lentekhi (37%), Kutaisi (30%), Mestia (24%), and Tsageri (9%). The geography of use of trade facilities indicates the importance of regional centres (Lentekhi, Mestia) and larger cities (Kutaisi) for the local population.

Table 5. Main marketplaces for the respondents

	Buy Goods (%)	Sell Goods (%)
Kutaisi	30.3	16.7
Lentekhi	36.4	5.6
Mestia	24.2	8.3
Tsageri	9.1	
Tskaltubo		2.8
Do not Sell		61.1
other		5.6

According to the given statistics, the difficulties of the agricultural sector of Svaneti were identified: the fact that 61% of the respondents do not sell their products and only consume them for their own consumption indicates that the agricultural sector of Svaneti has problems with scale and effective access to the market; The low sales rate of local products may be due either to the small harvest, which does not allow for the creation of sales stocks, or to the infrastructural and logistical difficulties of the sales market; For the sale of products, the population of Svaneti is forced to rely on relatively distant markets, such as Kutaisi (17%) and Tskaltubo (3%), which increases transportation costs and logistical challenges, which is especially difficult for a mountainous region; Respondents mainly use shopping facilities in Lentekhi (37%), Kutaisi (30%), and Mestia (24%), which emphasizes the vital importance of these regional centers for the local population, but at the same time indicates internal economic weakness in the area (village).

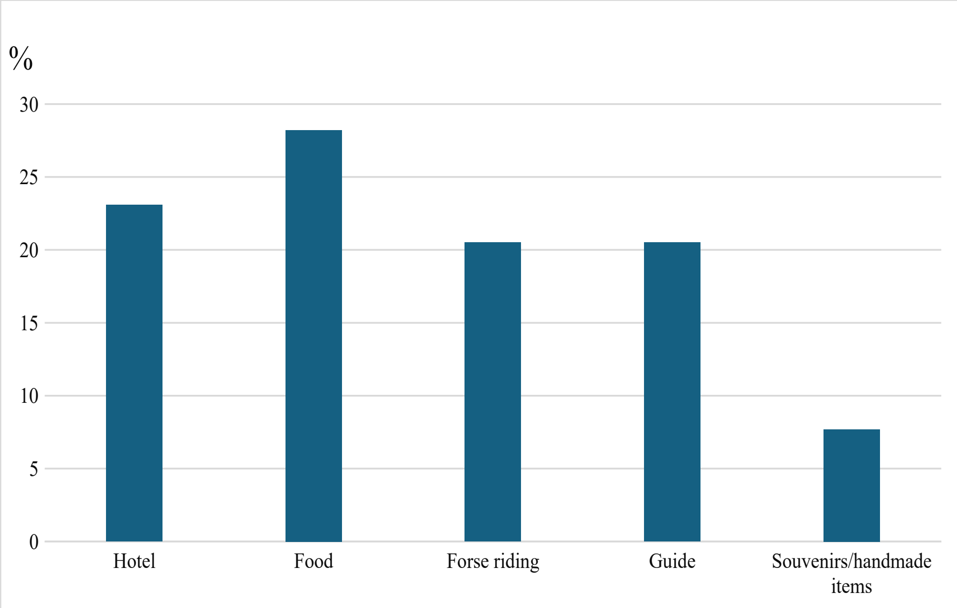

Figure 7. Offer for tourists

Appendix E displays that, 86% of respondents express a positive attitude towards the development of tourism in the region. 8% express a negative attitude, while 6% do not know whether it is good or bad. 8% of respondents are precisely those people who, during the pandemic, clearly saw the negative consequences of switching completely to tourism, when A boom in tourism resulted in abandoned agricultural lands and reduced products (Sharia, 2019). 31% do not benefit from tourism, while 69% do. The high rate of positive attitude towards tourism development (86%) indicates the great potential for the development of this sector and the willingness of the local population to engage in this process. However, a significant number of people who do not benefit from tourism (31%) indicate that the benefits are not distributed equally and more inclusive approaches are needed. The diversity of tourist services (fig. 7) offered by the local population (hotel, meals, horse riding, guides, souvenirs) reflects the diversity of the region's tourist potential. When it comes to the benefits derived from tourism, it is imperative to highlight the stark difference between the two municipalities in this regard. It is no secret that Mestia Municipality (Lower Svaneti) far exceeds Lentekhi Municipality (Lower Svaneti) in terms of the number of tourists and the corresponding services. Appendix F shows that 4 hotels operate in this municipality, while in Mestia Municipality this number is 178.

This is mainly due to the greater development and popularity of Mestia as a tourist center. Mestia is the administrative center of Upper Svaneti and has been developing intensively over the years as a major hub for mountain-skiing and adventure tourism (e.g. Hatsvali, Tetnuldi, museums). This has led to significant investments in tourism infrastructure (hotels, family houses, catering facilities) and a sharp increase in their number, due to the large influx of tourists. Lentekhi (Lower Svaneti) is less developed on the tourist map and, accordingly, the number of hotels and accommodation facilities is much smaller at present.

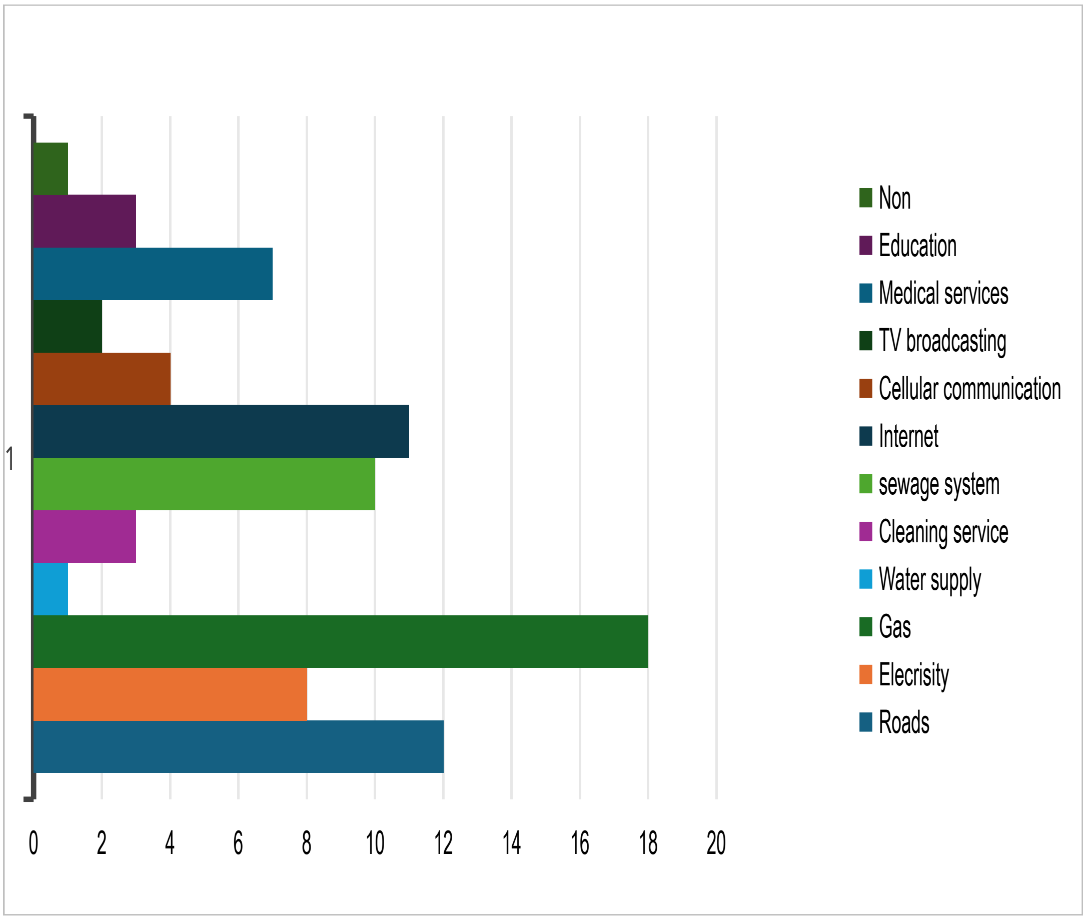

Figure 8. Socio-economic challenges

Infrastructure, Services, and Quality of Life

As listed in fig. 8, mountainous regions are characterised by many socio-economic problems. The surveyed population is concerned about the lack of roads (15%), lack of electricity (10%), lack of gas (22%), lack of water (1%), lack of cleaning services (4%), unregulated sewage system (12%), lack of internet (14%), lack of telephone connection (5%), lack of satellite dishes (3%), inadequate medical services (9%), and lack of access to education (4%). Surprisingly, 1% stated that they are not concerned about any of the above socio-economic problems. The list of socio-economic problems identified by the respondents (no roads, no electricity, no gas, no water, no cleaning service, unregulated sewage system, no internet, problems with telephone connection, access to medical services, access to education) clearly reflects the infrastructural and service problems in the region.

As mentioned above, the population of the study area is elderly, and therefore their medical needs are diverse. It is logical that the respondents 94% use medical services, while 6% do not use these services. They mainly use them in Lentekhi (44%), Kutaisi (2%), Mestia (32%), and the local medical station (16%). From table 5 43 per cent of the respondents consider the number of medical stations and doctors sufficient. The high rate of use of medical services (94%) and access mainly to regional centres and local stations indicate the challenges in this area.

Table 6. Use and satisfactory rate of medical services

	Use medical services	Are there enough medical facilities and doctors?
Yes	94.3	43.2
No	5.7	56.8

Most respondents (80%) consider the number of schools and kindergartens sufficient to be a positive factor; against the backdrop of acute migration and depopulation, schools and kindergartens are indeed sufficient. However, the dissatisfaction of 20% requires study. In this case, we can assume that these respondents are not permanent residents and did not fully understand the question asked.

Energy Perceptions and Environmental Concerns

Rational use of natural resources is important in mountainous regions. Our respondents noted that the construction of hydroelectric power plants in the region is important, although dangerous; therefore, they consider the construction of hydroelectric power plants wrong (54%). However, 54% believe that it is necessary. Some (20%) do not know and cannot understand this issue. It would be good to raise awareness among the local population in this direction. 83% of respondents support the use of renewable energy, while 17% do not.

Table 7. Percentage distribution of population by use of new hydropower plants and renewable energies

	Build new HPPs in the region (%)	Is the use of renewable energy acceptable? (%)
Yes	28.6	82.9
No	51.4	17.1
Do not know	20.0	

The mixed attitude towards the construction of hydroelectric power plants (54% in favour, 54% against) and the lack of awareness of 20% of the population on this issue indicate the need to improve communication with the public. Support for the use of renewable energy (83%) creates a perspective for the ecological sustainability of the region. The local population considers the natural conditions and resources (nature, fresh water, mineral springs, forests, wood), ecologically clean environment and products, historical past and cultural heritage to be the region's strengths. According to the local population, the following factors hinder development: harsh geographical environment, poorly maintained internal rural roads, low population, employment problems, unresolved social problems, no gasification, no Internet, unregulated sewage system, and lack of sports fields. In their opinion, for the development of tourism, it is necessary to arrange ski slopes and cottages and improve winter resorts. It is necessary to improve the resort of Muashi (fig. 9) with an entertainment area for children and swings. Creation of a rafting infrastructure on the river. Improvement of public gathering places, promotion of education, promotion of a healthy lifestyle, construction of a ritual hall. Development of farming, gardening, greenhouse farming, production of wild fruits, and potato growing. Factors identified by the local population as the strengths of the region (historical past and cultural heritage, ecologically clean environment, water resources, and potential for tourism development) create a solid foundation for the sustainable development of the region. The identified negative factors (unmaintained roads, harsh winters, low population, employment problems, social problems, lack of internet) require a systematic and consistent solution. Initiatives considered as development prospects (creation of ski slopes, improvement of resorts, development of farming, improvement of tourism infrastructure, arrangement of public spaces, promotion of education) reflect the local population's vision of the future of the region.

Figure 9. Resort Muashi (Photo: M. Tsitsagi)

Local Perceptions of Strengths, Weaknesses, and Development Priorities

Residents identify the following as the region's key strengths:

- pristine natural landscapes and clean environment
- abundant water and forest resources
- cultural heritage, including Svan towers and unique architecture
- untapped tourism potential

This mirror widely recognized attributes of mountain cultural landscapes (Debarbieux & Rudaz, 2015; Price, 2013).

Key constraints include:

- poor internal roads and winter isolation
- depopulation and outmigration
- limited employment opportunities
- insufficient social and public services
- lack of gasification and inadequate internet
- underdeveloped tourism infrastructure in Lentekhi
- Residents prioritize several development directions, including:
- improved tourism infrastructure (ski slopes, resorts, cottages)
- rehabilitation of Muashi resort
- development of rafting and other adventure activities
- enhancement of education and public spaces
- expansion of farming, gardening, greenhouse production

Such locally grounded priorities align closely with contemporary concepts of place-based rural development, which emphasize integrating local knowledge, cultural identity, and environmental sustainability (Ray, 1998; OECD, 2020).

Conclusion

The findings of this study demonstrate that Svaneti is undergoing significant demographic transformations, characterized by population ageing, youth outmigration, and a gender imbalance driven largely by male-dominated labor migration. These trends pose substantial risks to the region's long-term demographic sustainability and social cohesion. Seasonal mobility and the fragmentation of family structures reflect broader socio-economic vulnerabilities that are typical of peripheral mountain regions.

Despite these challenges, Svaneti retains considerable human capital. The high proportion of residents with higher education indicates an important resource for future development, although the mismatch between educational attainment and local employment opportunities continues to contribute to outmigration. Foreign language proficiency—particularly in English—remains insufficient for the effective expansion of the tourism sector, underscoring the need for targeted capacity-building programs.

Tourism is widely viewed by the local population as the primary avenue for economic development, and its growth has already reshaped livelihood strategies in parts of the region. However, the benefits of tourism remain unevenly distributed, especially between Mestia and Lentekhi, and more inclusive development models are required to avoid deepening intra-regional disparities. Agriculture is undergoing gradual modernization, yet structural constraints—including limited market access, small-scale production, and infrastructural shortcomings—continue to limit its economic potential. Enhancing market linkages for local products could play a significant role in improving household incomes.

The land question emerged as a particularly sensitive issue, reflecting the cultural, historical, and economic significance of land ownership in Svaneti. Strong opposition to land alienation to foreigners highlights concern regarding cultural preservation, long-term security, and equitable development. Similarly, attitudes toward hydropower projects reveal ambivalence and a need for improved communication, transparency, and community engagement. In contrast, strong support for renewable energy indicates an opportunity to advance environmentally sustainable development pathways.

Svaneti's unique natural landscapes, cultural heritage, and traditional knowledge systems constitute major assets for its future development. However, realizing this potential requires addressing persistent infrastructural deficits—such as inadequate roads, limited telecommunication networks, and insufficient healthcare services—that constrain mobility, economic diversification, and quality of life. A comprehensive regional development strategy should therefore integrate local perspectives, support community-driven initiatives, and ensure that development interventions align with the needs, values, and aspirations of the population.

Overall, the study underscores the critical importance of place-based, participatory, and multi-sectoral approaches for promoting sustainable development in Svaneti. Strengthening human capital, improving infrastructure, diversifying economic opportunities, and ensuring equitable distribution of tourism benefits will be essential for fostering resilience and enhancing the socio-economic well-being of this distinctive mountain region.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

All authors provided critical feedback and helped shape the research, analysis, and manuscript.

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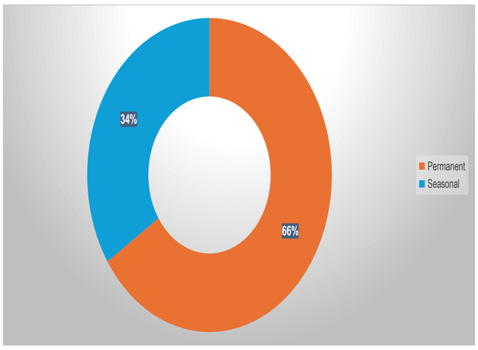
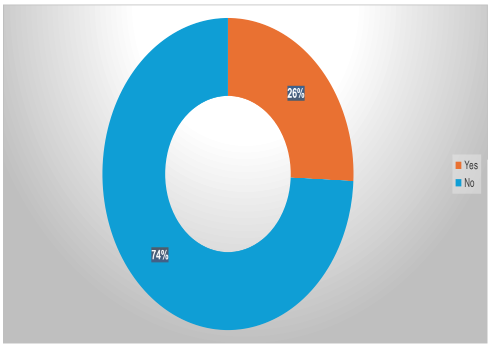
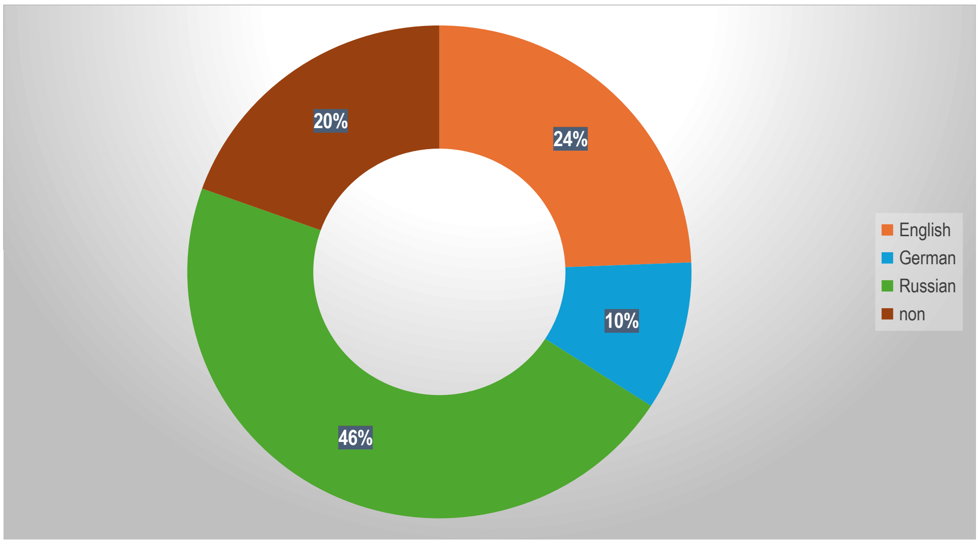
Appendix A: Residential status (left), Percentage distribution of respondents who have a family member in emigration (right)

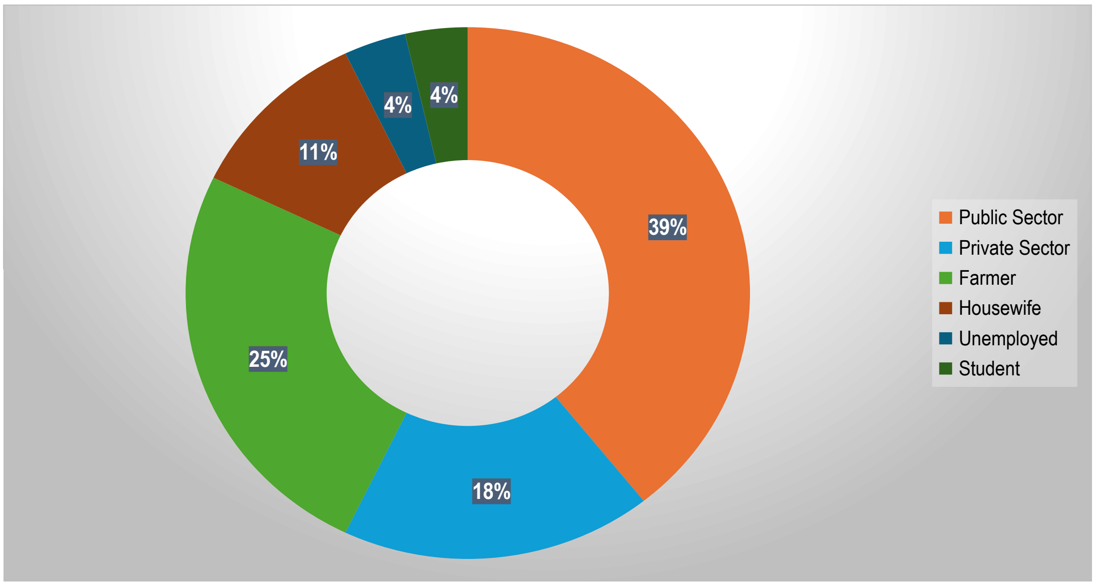




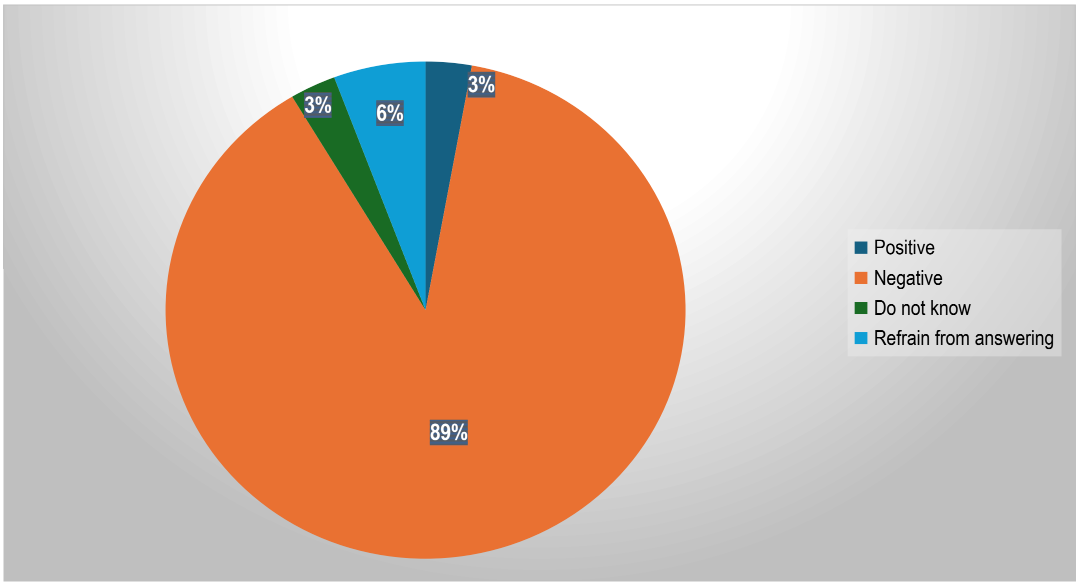
Appendix B: Knowledge of foreign language



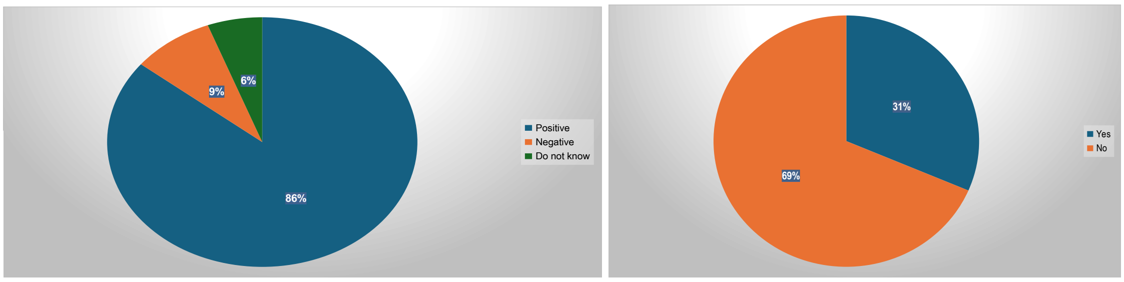
Appendix C: Employment



Appendix D: Privatized residential area



Appendix E: Attitude towards tourism development in the region (left); Benefits from the tourist (right)



Appendix F: Number of hotels

Municipality	Number of hotels
Lentekhi	4
Mestia	178
sum	182

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Protected Areas Policy and Geopolitics in Georgia: Convergence of Ecological Governance and Spatial Strategy

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Abstract

The history of the protection of natural areas in Georgia dates back centuries. As early as the 12th century, Queen Tamar issued royal decrees aimed at safeguarding specific natural territories. Five hundred years later, Vakhtang VI's "Collection of Laws" identified the Korugi territory as a protected area, where logging and unregulated access were prohibited and the site was guarded. In mountainous regions, so-called "Khati forests" functioned as strictly protected sacred reserves. The first official state reserve was established in 1912 in Kakheti with the foundation of the Lagodekhi Reserve. During the 20th century, the network of reserves and protected areas gradually expanded throughout the territory of Georgia (BUDE, Protected Areas of Georgia, 2007). Following the restoration of independence, the policy of protected areas acquired new significance, shifting toward sustainable development, tourism, local community involvement, and alignment with international standards. The geopolitical dimension of this process is particularly important. Protected areas are no longer perceived solely as instruments of environmental protection; they have become mechanisms of spatial management and determinants of state interests. Georgia's geographical location at the crossroads of Eurasia, where ecological, economic, and political boundaries intersect, makes nature conservation closely linked to territorial strategy. The interplay between ecological governance and geopolitics has become especially evident in recent years, as the state has introduced new formats, including geoparks, into the framework of protected area policy. As an international instrument, geoparks integrate the conservation of natural and cultural heritage with education, sustainable tourism, and geopolitical identity. In this way, ecological governance in Georgia is gradually transforming into a spatial strategy that intertwines environmental, economic, and diplomatic interests. Analyzing these processes provides insight into how protected area policy has evolved into a key aspect of geopolitical thinking, demonstrating how environmental protection goals intersect with state representation and regional dynamics. This paper examines the theoretical foundations of this convergence and its impact on contemporary nature protection policy in Georgia.

Keywords: Protected Areas, Geoparks, Ecological Governance, Spatial Strategy, Geopolitics, Biodiversity Conservation, Sustainable Development.

Introduction

Georgia, with its unique geographical location and rich natural resources, is an important region where nature conservation policies and geopolitical strategies are closely linked. The system of protected areas, which includes national parks and reserves, aims to preserve biodiversity, protect ecosystems, and promote sustainable development (Paichadze, 2014).

Geoparks, as a new concept, are a tool for protecting geoheritage and developing geotourism. In addition, they contribute to the economic development of local communities and the strengthening of geopolitical identity (Zhuang A., 2024).

The integration of ecological governance and spatial strategy is an important aspect of modern nature conservation policy. This approach involves not only protecting natural resources, but also ensuring their sustainable use, which includes the creation of ecological corridors, the assessment of ecosystem services, and the consideration of natural factors in spatial planning processes (Elizbarashvili, 2019).

The development of a network of protected areas in Georgia requires consideration of not only ecological, but also social and economic factors. It is important to involve local communities, take into account their needs and interests, so that protected areas do not become just a tool for nature protection, but also a platform for sustainable development (Elizbarashvili, 2019).

The development of geoparks in Georgia is an important part of this process. Geoparks are not only a tool for protecting geoheritage, but also contribute to the promotion of local cultural and natural heritage, which has a positive impact on the development of tourism and the strengthening of the local economy (Elizbarashvili, 2021).

It is important to note, however, that the policy of protected areas and geoparks should not be isolated. There should be close coordination and cooperation between them to ensure the effective management and sustainable use of natural resources. An important role in this process is assigned to state institutions, international organizations and local communities.

This article will discuss the interdependence of the policy of protected areas and the development of geoparks in Georgia. Special attention will be paid to the processes of integration of ecological governance and spatial strategy, their impact on nature conservation policy and sustainable development prospects.

Georgia's Context and Political Evolution

Protected areas policy in Georgia has gradually evolved since the restoration of independence, addressing the legacy of Soviet centralized governance while adapting to new environmental challenges. The Law on the System of Protected Territories (Parliament of Georgia, 1996) established the legal basis for the creation and functioning of protected areas, integrating the principles of sustainable development and the protection of both natural and cultural heritage. The subsequent Law on the Status of Protected Areas (Kakabadze, 2012) and complementary legal acts refined definitions, zoning, and management procedures.

In recent years, the Georgian government has worked to strengthen governance mechanisms, develop long-term management plans, and enhance local community involvement. The first management plans in Georgia were developed for the Borjomi-Kharagauli, Lagodekhi, and Vashlovani Protected Areas, establishing the foundation for integrated conservation planning. In 2022, updated management plans were approved for the Borjomi-Kharagauli Protected Areas, Ktsia-Tabatskuri Managed Reserve, and Goderdzi Phosphorized Forest Natural Monument, integrating natural and cultural values, ecotourism potential, traditional livelihoods, and ecosystem services (Georgian Government, 2022).

International Commitments and Global Framework:

Georgia's protected areas policy is closely aligned with international environmental frameworks. The country is a signatory to the Convention on Biological Diversity (CBD), which calls for the expansion of protected area networks and the implementation of ecosystem-based management principles (MEPA, 2018) Georgia is also a party to the Ramsar Convention, which defines the mechanisms for the protection of wetlands of international importance (Ramsar Secretariat, 2018),

Furthermore, Georgia participates in the UNESCO World Heritage and Emerald Network programs, which integrate the country into European biogeographical conservation systems (Council of Europe, 1979; Council of Europe, 2019; UNESCO, 2023). These frameworks support not only nature conservation but also the protection of cultural landscapes and the strengthening of mutual trust in regional cooperation (Council of Europe, 2019; UNESCO, 2023).

The Growing Role of Geoparks and Spatial Strategy

Geoparks have recently become a vital extension of Georgia's protected areas policy - serving as platforms for the convergence of ecological, cultural, and geopolitical objectives. Research indicates that Georgia has multiple potential geopark areas that could serve simultaneously as environmental, educational, and economic assets (Gamkrelidze, 2021).

Potential locations for conservation and geotourism initiatives include the Racha region, Samegrelo (Tsalenjikha, village Mukhuri), Kakheti, Javakheti, Kvemo Kartli, and Kazbegi. Significant natural features such as the Vashlovani Protected Areas with the "Areuli" erosion complex, paleontological objects of elephants and mollusks, Takhti-Tepa volcano, and the Lagodekhi Protected Areas with two large waterfalls, a high mountain lake, and gorges have been documented in previous conservation reports (Council of Europe, 2020). In addition, the Dariali Glacier Complex National Geopark represents both national natural heritage and opportunities for transboundary cooperation. Geopark initiatives are particularly promising in Samtskhe-Javakheti, Kvemo Kartli, and Kakheti—regions where natural and cultural heritage are closely intertwined with border geopolitics.

Challenges and Development Pathways: The convergence between protected areas policy and geopolitics in Georgia is accompanied by a complex set of systemic, institutional, and spatial challenges that directly determine the effectiveness of the country's ecological governance.

The first and perhaps most critical issue concerns the deficit in protection effectiveness. Although the total area of protected territories in Georgia has expanded considerably in recent years, internal management remains largely formalistic. Many areas of high endemic and ecological value are still outside the official protected areas network or receive only nominal protection - the so-called "paper parks." Research demonstrates that a significant portion of high conservation value (HCV) areas remains vulnerable to the combined pressures of climate change, unsustainable land use, and the spread of invasive species (Slodowicz, 2018). Simultaneously, intensive natural resource exploitation - including logging, mining, and hydropower development - often conflicts with the principles of ecological sustainability. This highlights the urgent need for comprehensive spatial planning and the full application of Environmental Impact Assessments (EIA) across all development sectors. And the boundaries and information of geoparks need to be included in the strategic development documents of the regions and the management plans of the administrations of protected areas and the strategic plans for the development of protected areas of Georgia.

The second challenge lies in legal and institutional inconsistencies. Despite the existence of a comprehensive legal framework, management structures in Georgia still suffer from fragmentation. The Ministry of Environmental Protection and Agriculture, the Forestry Agency, and the Agency of Protected Areas maintain overlapping mandates, complicating the implementation of unified policies. Land tenure and delineation remain legally ambiguous - particularly in emerging initiatives such as the Erusheti National Park, where community property rights continue to lack clear legal definition (MEPA, 2023). Furthermore, the limited involvement of local populations in decision-making processes generates a deficit of trust and slows the democratization of environmental governance.

A third difficulty involves financial and technical constraints. Funding for protected area management continues to rely heavily on international donor assistance, which undermines long-term sustainability. The lack of basic infrastructure - including access roads, monitoring stations, and educational centers - hampers the development of sustainable tourism and environmental education. Under these circumstances, the establishment of a national and transboundary geopark network emerges as a key opportunity for economic diversification, linking nature conservation, tourism, and cultural heritage within an integrated management framework.

The fourth and increasingly relevant dimension pertains to geopolitical and transboundary complexities. Georgia's geographic position within the South Caucasus - a region marked by political sensitivities and competing interests - creates both opportunities and constraints for cross-border environmental cooperation. The establishment of transboundary geoparks, such as David Gareja–Gobustan (Georgia–Azerbaijan) and Javakheti-Arpi (Georgia–Armenia) (Ten years ago, the country began working with Azerbaijan to create the Lagodekhi-Zakatala transboundary protected area). requires mutual trust, functional coordination mechanisms, and clear legal agreements. Yet, ongoing border delimitation issues with Azerbaijan and differing legal regimes with Armenia pose tangible challenges to implementation. Meanwhile, participation in the UNESCO Global Geoparks Network demands adherence to international standards that integrate geological heritage protection, education, and community-based development (Eder, 2019).

A fifth emerging challenge involves the intensifying impacts of climate change. Rising temperatures, altered precipitation patterns, and the increased frequency of extreme weather events have created new environmental threats, particularly in mountainous and semi-arid regions. Existing management plans often lack climate adaptation and risk assessment components, limiting their resilience and long-term effectiveness (IUCN, 2020). However, it is noteworthy that over the past 3 years, the management plans of 7 protected area administrations have included information and planned activities on climate change, adaptation, and mitigation measures.

From a development perspective, Georgia must transition toward an integrated governance model that unites nature conservation, geopolitical stability, and socio-economic sustainability. Key strategic priorities include:

1. **Implementation of Geographic Information Systems (GIS)** to improve monitoring and spatial decision-making;
2. **Enhanced community engagement** in the management of national parks and geoparks;
3. **Institutionalization of transboundary cooperation**, especially in southern and eastern regions;
4. **Expansion of educational and research programs** to strengthen national expertise and capacity.

Ultimately, the path forward for Georgia's protected areas policy and geopolitics depends on the country's ability to transform its management paradigm from one of "regulatory protection" toward a model of "shared socio-ecological stewardship." In this model, conservation goals are embedded within spatial strategies and cross-border cooperation, turning natural heritage into both an environmental and geopolitical asset.

1. Policy and Governance Dimensions

The evolution of Georgia's protected areas system reflects a gradual transition from a conservation model rooted in post-Soviet environmental management to a modern governance framework that integrates sustainability, participation, and spatial equity. While early institutional efforts were focused primarily on biodiversity preservation, recent reforms have expanded the political and social role of protected areas as instruments of regional development and environmental diplomacy (Dudley, 2018; IUCN, 2020).

The establishment of large-scale management plans, the inclusion of cultural landscapes, and the increased attention to ecosystem services all mark a shift toward more adaptive and inclusive management paradigms. However, despite these improvements, governance effectiveness remains limited by overlapping administrative mandates, fragmented coordination between agencies, and inconsistent implementation of international obligations (MEPA, 2023).

2. The Geopolitical Perspective

The geopolitical dimension of protected areas in Georgia extends beyond ecological management. It encompasses the strategic use of territory in maintaining sovereignty, facilitating cross-border relations, and stabilizing frontier regions. In this regard, Georgia's location between the Black and Caspian seas and along the South Caucasus corridor creates a unique interface between conservation, national identity, and regional security (Eder F, 2019). Protected areas situated near borders - such as Vashlovani, Lagodekhi, and Javakheti - serve as both ecological buffers and symbolic representations of state presence. The management of these territories must, therefore, balance environmental priorities with geopolitical sensitivities. In regions adjacent to disputed or sensitive borders, protected areas often function as instruments of "soft diplomacy," fostering cooperation through ecological science, cultural exchange, and shared management frameworks (Council of Europe, 2019).

Yet, the potential for cross-border collabora.tion is uneven. Relations with Armenia are relatively stable and institutionally supported, making transboundary cooperation - particularly within the Javakheti-Arpi ecological complex - more feasible. Conversely, the Georgian-Azerbaijani frontier remains politically sensitive, constraining the development of the David Gareja-Gobustan Geopark concept, despite its exceptional cultural and geomorphological potential.

3. The Role of Geoparks in Policy and Spatial Strategy

Geoparks in the contemporary world represent a significant instrument that integrates environmental governance, regional development, and cultural diplomacy. They create a bridge between nature conservation, education, and sustainable tourism, while in border regions they often facilitate political cooperation.

In Georgia, several areas are identified as important for geopark planning, with the Racha region being one of the most significant. Located in the northwestern part of Georgia on the southern slopes of the Great Caucasus, Racha represents a prospective segment for geopark development. The region has undergone geomorphological zoning and comprehensive relief studies, with the central part featuring

Cambrian and Paleozoic crystalline substrates (gneisses, migmatites, crystalline schists) and granitoid intrusions of varying ages. The Great Caucasus and higher massifs are composed of granitoid, gneissic, and metamorphic schists, the oldest rocks (600 million years) are observed in the highest peaks. Due to hypsometric effects, the age of rocks decreases in the lower areas (70–30 million years) (Chichinadze, 2022).

The geological structure of Racha shapes karstic, erosional-denudational, volcanic, and periglacial reliefs, including caves, valleys, canyons, glacial and rocky lakes, waterfalls, deep gorges, and mineral springs. This diversity has significantly influenced the formation of ancient settlements and cultural development in the region, particularly near the sources of the Rioni River, where natural deposits of iron, gold, and copper supported early human societies.

A particularly important component of the geopark planning is the microzone of viticulture and winemaking, where traditional vineyards and wine production practices have maintained economic and cultural significance from the past to the present. In addition, the Upper Racha archaeological sites - Oni, Brili, Tevresho, and Ghebi - contribute additional cultural value and provide opportunities for integrated cultural tourism within the geopark (Chichinadze, 2021).

Regarding cross-border regional cooperation, the Kakheti-Shaki-Zagatala region stands out for its high biodiversity and rich cultural heritage. Existing protected areas (Lagodekhi Protected Area, Zagatala State Reserve) and territorial stability provide a solid foundation for the creation of a joint geopark, promoting sustainable tourism, scientific collaboration, and strengthening cross-border trust.

The Javakheti and Arpi Plateau represents a potential cross-border geopark aimed at conserving volcanic and lake ecosystems within the framework of Georgia-Armenia cooperation.

All of these initiatives integrate ecological, social, and political objectives, supporting tourism, local community engagement, education, and sustainable development strategies. International experience confirms the effectiveness of such approaches: in Europe, the Teruel–Aliagas Geopark (Spain) and the Hațeg Geopark (Romania) combine nature conservation, multi-sectoral governance, and active local community participation.

Georgia's geopolitical realities, particularly border restrictions with Azerbaijan, require an adapted governance model. The optimal approach may involve a hybrid structure that simultaneously integrates national coordination and bilateral technical committees. This model creates a realistic basis for the development of transboundary geoparks and facilitates a safe, sustainable, and cooperation-based spatial strategy.

5. Toward a Georgian Model of Geopark Governance

Based on comparative European experiences and Georgia’s own institutional context, an optimal national model for geopark governance would combine the following principles:

1. **Polycentric management** — a framework where local, regional, and national authorities share decision-making responsibilities;
2. **Participatory governance** — ensuring meaningful engagement of communities, universities, and NGOs in management processes;
3. **Scientific integration** — involving research institutions in geological mapping, monitoring, and risk assessment;
4. **Cross-border coordination mechanisms** — bilateral working groups or joint commissions for data sharing and heritage protection;
5. **Economic diversification** — aligning geopark strategies with regional development and eco-tourism planning.

Such a model would enable Georgia to strengthen its environmental diplomacy and position itself as a regional leader in sustainable landscape governance. The geopark initiative, if effectively institutionalized, could become a symbol of cooperation across political boundaries and a new dimension of “green geopolitics” in the South Caucasus.

Conclusion

In conclusion, the history of protected areas in Georgia spans more than a century. The evolution of the policy reflects a shift from post-Soviet conservation practices to an adaptive model that integrates ecological protection, sustainable development, and geopolitical awareness. Protected areas now encompass a diverse range of natural and geological features, many of which have the status of natural monuments.

In addition to their primary functions of protection and management, these areas support scientific research, environmental education, public engagement, and institutional collaboration. Such activities highlight the growing convergence between traditional protected area management and geopark initiatives, highlighting their common principles, complementary goals, and potential for integrated conservation and sustainable development.

Overall, Georgia's protected areas continue to serve not only as reserves of biodiversity and geodiversity, but also as strategic spaces where ecological, cultural, and diplomatic interests intersect. This combination of natural and geological heritage creates a solid foundation for future geopark programs, while maintaining conservation mandates and strengthening the country's role in regional cooperation and environmental governance.

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

Both authors provided critical feedback and helped shape the research, analysis, and manuscript.

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Political Geography of Sachkhere Municipality

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Abstract

Political geography, as a branch of historical geography, examines the political and geographical characteristics of a given territory through their integrated and holistic synthesis. It provides a clear representation of a country's administrative structure and the principal trends in its historical development, which have significantly influenced the political affiliation and spatial organisation of individual regions over time. The study of political geography also allows for the identification of long-term processes that shape territorial boundaries and governance systems. This article aims to present a comprehensive description of the political geography of the largest municipality in Upper Imereti—the Sachkhere region—from ancient times to the 19th century, highlighting key stages in its administrative evolution and territorial transformation within the broader historical and geographical context of the region.

Keywords: history, geography, politics, Argveti, nobility

Introduction

In developing this research topic, the aim was to examine the political geography of Sachkhere Municipality to the extent permitted by available documentary sources and scholarly literature. The chronological framework of the study primarily covers the period from the 5th to the 19th centuries. The article begins with an examination of the Argveti principality (სამთავრო, samtavro). This administrative unit occupied a strategically important geographical position, as it encompassed the Likhi Range, which divides eastern and western Georgia, as well as the historical passes that connected western Georgia with the eastern regions of the country. Based on an analysis of the available scholarly literature, an attempt is made to delineate the boundaries of the Argveti principality (სამთავრო, samtavro) and to clarify its territorial affiliation. The article also addresses the territorial scope and variability of historical geographical names, including Upper Imereti, as well as related macrotoponyms.

Following the definition of the boundaries and political affiliation of the Argveti principality (სამთავრო, samtavro), the study proceeds to examine the political geography of the Chihi principality (სამთავრო, samtavro), focusing on its territory and political affiliation.

In the 15th century, the unified Georgian Kingdom disintegrated. Whereas the earlier administrative system had been based on eristavis, this structure underwent a radical transformation. The eristavis were replaced by new, smaller political and administrative units known as principalities. Under this system, feudal families inherited their estates and enjoyed a higher degree of internal autonomy in governance than under the previous administrative arrangements.

After the collapse of the unified Georgian Kingdom, the territory of Sachkhere Municipality, together with the rest of Upper Imereti, became part of the Kingdom of Imereti. However, due to political circumstances and the region's geographical position, there were periods during which this territory was incorporated into the Kingdom of Kartli. Within the territory of the present-day Sachkhere Municipality, two principalities were formed: Satseretlo and Saabashidze.

For a certain period, the Palavandishvili family also held estates in the area; however, these lands were eventually confiscated by the two aforementioned noble families, leading to the expulsion of the Palavandishvilis from the municipality. Of the two dominant families, the Tseretelis were the most influential, owning approximately 80% of the municipal territory. Over time, the landholdings of the Abashidze family were significantly reduced by the Tseretelis, resulting in their territory being divided into two non-contiguous parts. The Abashidzes who remained in Sachkhere retained control only over the villages of the present-day Chali community, including villages that are now occupied.

In addition to the noble families, the King of Imereti himself possessed estates within the territory of Sachkhere. These lands, known as royal domains, were administered by officials directly appointed by the king. Such estates included, for example, Khodabunebi (interpreted by Sulkhan-Saba Orbeliani as meaning “royal field”) and Yaurebi. These domains were among the most fertile lands in the river valleys and were supplied with irrigation canals. The article also presents, as a separate issue, the territorial distribution of the historical region of Khefinihevi.

Methods and Materials

In conducting this research, ancient Georgian historical sources contained in The Life of Kartli were utilised, with particularly extensive material drawn from the works of Leonti Mroveli and Juansher. Significant contributions to the understanding of the topic were also provided by the scholarly works of Vakhushti Bagrationi, Koba Kharadze, Niko Berdzenishvili, Jurkha Nadiradze, Olga Soselia, and Valery Silogava.

In addition to the analysis of existing historical and scientific literature, all villages and settlements within Sachkhere Municipality were visited and documented during a scientific expedition carried out by the Institute of Geography of Ivane Javakhishvili Tbilisi State University in 2017. The present article is therefore based on a combination of primary historical sources, secondary scholarly literature, and original field research conducted by the authors.

Results

Argveti principality („სამთავრო“ - samtavro). Historically, the territory of Sachkhere Municipality was part of Zemo Mkhari or Upper Imereti, although this term has been used not since ancient times, but since the late feudal period. Before Zemo Mkhari, the territory of Sachkhere, like all of Eastern Imereti up to Persat-Rioni, was called Argveti, the same as Margveti, which represented a principality („სამთავრო“ - samtavro) or political-administrative division. Leonti Mroveli, the author of one of the chronicles of Kartli, defines the borders of the Argveti principality as follows: to the Likhi Range in the east, to the Rioni River in the west, to the Racha Mountains in the north (thus, Racha-Lechkhumi remained within its borders), and to the Persati Mountains in the south. According to the historian and geographer K. Kharadze, this region also included the Khanistskali River gorge and, possibly, the "land of Vani" of the Hellenistic period (Kharadze; 2003: 226). As we can see, the Argveti principality („სამთავრო“ - samtavro). previously included Okriba, but it later separated from Argveti and formed a separate geographic and political region (the geographic term Okriba was first mentioned in the 11th century), along with Zemo Khari, Vake, and Samokalako. According to historical tradition, in the 5th century, during the reign of Vakhtang Gorgasali, Racha-Lechkhumi (Takveri) was also part of Argveti, but later separated from Argveti and became an independent state. Racha was governed by its own eristavi, and he separated from Argveti. This development ultimately limited the borders of Argveti to only "Zemo Khari," that is, Upper Imereti (Life of Kartli. 1955: 24).

As we have already mentioned, Argveti extended to the eastern part of modern Imereti, including the territory of Sachkhere, while the term "Samokalako" has been used to designate the western part since at least the time of David the Builder. Let us cite a historical source: "Currently, Asisforni and Klarjeti are located within the sea pyramid of Ivanobis, Shavsheti, Adjara, Samtskhe, Kartli, Argveti, Samokalako, and Chkondidi are occupied by the Turks" (Life of Kartli. 1955: 319).

The 8th-century author Juansher proposes a completely different division of Western Georgia, while Leonti Mroveli lists the ethnographic regions of Western Georgia as Egrisi, Suaneti, Takueri, Argveti, and Guria (Life of Kartli. 1955: 241). As we can see, Imereti is also not mentioned here. Thus, new ethnographic terms emerged, while the upper region with Sachkhere remained part of Argveti. The term Imereti has been applied to Western Georgia only since the 11th century (the reign of David the Builder).

As already mentioned, the territory of Sachkhere Municipality has been administratively part of the Argveti principality(„სამთავრო“ - samtavro) since the time of Parnavazi, a fact recognized by all scholars studying ancient Georgian history. Historical atlases indicate the municipality's modern territory as part of the Argveti principality („სამთავრო“ - samtavro). This is also confirmed by ancient Georgian authors such as Leonti Mroveli, Juansher, and Vakhushti Bagrationi.

In his historical collection, The Life of Kartli, Leonti Mroveli attributes the creation of the Argvetic chiefdom to King Parnavaz: “He sent one leader, Margvi, and gave him a small mountain, which is Likhi, beyond the border (of Egris), above Rioni, and on this mountain Parnavaz built two fortresses, Shorapani and Dimna” (Life of Kartli. 1955:24).

Leonti Mroveli's historical conception partially echoes that of Juansher, who places this administrative unit in the same geographic region as Leonti Mroveli but, unlike him, presents it as a larger administrative district. According to Juansher, Bakuri, founded by Vakhtang Gorgasali as the principal of this region, simultaneously owned both Argveti and Takveri (Life of Kartli. 1955:185).

Vakhushti Bagrationi describes the borders of Argveti as follows: "And to the south of Racha, beyond the mountain, lies Argveti or Margveti, which was named for the fertility of the land and the roundness of the land for its labor—the roundness of the land. And the borders of Argveti are: to the east—the border of Kartli, the western side of Mount Likhi; to the south—Persati, Merme, Kharageuli, the Dzirula River; and to the east—the Kvirila River as far as Tskaltsiteli" (Bagrationi; 1997: 744).

After the death of Parnavazi, this territory became part of the Kingdom of Colkhi, which emerged in western Georgia. In the first half of the 2nd century, it again appeared as part of the Kingdom of Kartli.

Historical sources on the reign of King Parnavazi and Georgia at the time are extremely scarce. We are particularly concerned by the paucity of materials, especially regarding the locations of ancient cities, architectural monuments, and so on. Archaeology can greatly help us fill this historical gap. We will examine in detail the archaeological geography of Sachkhere and the significance of archaeology for history in the relevant chapter.

Archaeological discoveries in Upper Imereti confirm that by the mid-1st millennium CE, society of that period was at a fairly advanced level of development. This is evidenced by the late antique tombs of Modinakhe, Sairkhi, Itskisi, and Chikhi, which contain numerous brilliant examples of jewelry and weapons, clearly demonstrating the considerable economic resources of their owners.

The Early Middle Ages, the 5th and especially the 6th centuries, represent an eventful period in the history of both Kartli and Egrisi. This is the era of the outstanding kings Vakhtang Gorgasali, Gubaz I, and Gubaz II. The 6th century marks the abolition and restoration of statehood in Kartli, while in Egrisi, the "Great War" raged during the same period. Unfortunately, neither Georgian nor foreign sources provide any concrete information about Argveti during this period.

In the 650s, the Arabs invaded Georgia. The Samar, Jieti, and Itskis burial grounds date back to the aforementioned events, and we have reason to believe that the community that created these monuments played an active role in the historical events of that period.

In the 780s, the Abkhazian eristavi Leon united all of western Georgia, naming it the Kingdom of Abkhazia, and Argveti also became part of this political entity.

Chikha Principality. In the late Middle Ages, Upper Imereti was indeed part of one of the important Georgian fiefdoms, the Argveti Principality, and the residence of Eristavi was also located there. The Chikha Principality is mentioned in the "Chronicle of Kartlis." In this historical source, the Argveti Principality of Leonti Mroveli and Juansheri is no longer mentioned, but rather "Chikhinsky Eristavi." Clearly, "Prince of Chikha" is undoubtedly a principality. The mention of this principality is associated with the Kartla of the Abkhazian kings: "At that time, George, king of the Abkhazians, brother of Theodosius and Demetrius, son of Leonidas, set out. He conquered Kartla and left the principality to Demetrius, son of Chikha. When George, the king of the Abkhazians, died, he left a son, Dmitry the Younger, whose name was Bagrat, and who was known to his acquaintances. The wife of King George killed her son Dmitry, the principality of Chikhi" (Life of Kartli. 1955: 258). As can be seen from the above quote, the "principality of Chikhi" is mentioned only twice in Georgian historiography. N. Berdzenishvili doubted that in this case the "Chikhinsky Eristavi" meant the Eristavi of Kartli (Berdzenishvili; 1975: 354). If Chikha was the eristavi of Kartli, then it is clear that Upper Imereti of this period was also included within the borders of Kartli.

From an archaeological point of view, the village of Chikha remains virtually unexplored, and it was only in the 1970s that J. Nadiradze conducted some exploratory work here. To the south of the village church, at the Gobinari settlement, extremely scant remains of layers containing material culture from the early antique and Hellenistic periods were confirmed. Small fragments of red-painted and red-toned ceramics were discovered (Nadiradze; 1990: 135-136). N. Berdzenishvili believed that Chikha was the successor of Sachkhere in a later period (Berdzenishvili; 1966: 31). According to this opinion, Chikha and Sachkhere could have been one and the same geographical location. This assumption should be supported by the data from the Modinakhe burial ground, since this is the only archaeological monument from the medieval period discovered in the area of Sachkhere and Chikha to date.

J. Nadiradze pointed to the Modinakhe necropolis and noted that, from the beginning of the late antique period, the center of Argveti principality („სამთავრო" - samtavro) was supposed to be located on the right bank of the Kvirili River, while the residence of the rulers of this country, as well as the necropolis, were supposed to be located on the territory of Sachkhere. Based on the norms of the Old Georgian language, the researcher did not rule out the possibility of a connection between the comparatively late toponym Sachkhere and Chikha (Nadiradze; 1975: 76). If this opinion is correct, then it becomes clear that the Modinakhe necropolis laid the foundations of the medieval Chikha (Sachkhere) principality („სამთავრო" - samtavro). Sachkhere has a much more favorable strategic location than Chikha. Vital roads converged near Sachkhere, which always carried heavy traffic and played an important role in the political and economic life of the country.

As J. Nadiradze's archaeological research has shown, the 6th–7th centuries represented the settlement's heyday. Almost the entire hill was inhabited, and the cultural layers reach a thickness of 2 meters. Based on this fact, archaeological literature suggests that the Itskhi Fortress of this era may have been the main fortification in the upper reaches of the Kviri River, controlling the roads leading to the mountains and plains of Shida Kartli (Makharadze; 2005: 40).

In studying the ancient history of Sachkhere, along with Modinakh and Chikha, the Itskhisi Fortress of this period is of great importance. The architectural monuments surrounding the Itskhisi Fortress demonstrate the particular significance of the area, among which the Church of St. George in Savani stands out for its historical significance. The church's façades are richly decorated and represent an interesting example of 11th-century architecture. Several historical inscriptions have been preserved on the walls of the church, among which the inscription on the tympanum of the southern gate is particularly significant, revealing that the church was built by George Eristavteristavi in 1046, during the reign of King Bagrat IV. The names of Eristavteristavi's deceased parents, Gulzviad and Mariam, and Goliath's brother and son, are also inscribed here (Silogava; 1980: 59). Queen Mariam and her children, Giorgi and Khursi, are also mentioned in a 1,000-year-old inscription of the Koret Church's Divine Liturgy, studied and published by G. Gaprindashvili (Gaprindashvili; 1970: 54-61). He also correctly linked the founders of the Savani and Koret churches and believed that the name of Giorgi Eristavi's brother, the Eristavi from the Savani Church inscription, was Khursi.

Thus, the builder of the church in Savani was Giorgi Eristavteristavi. He was a member of a powerful feudal house, and there is no doubt that this family, in addition to large estates, owned roads leading to Kartli and was engaged in extensive construction activities. The existence of the Itskhi Fortress and the Church of St. George in Savani is consistent, and it is possible that the Itskhi Fortress was the residence of this powerful feudal house.

In the 10th century, the unified Georgian Kingdom was established, and Argveti, of course, was politically part of it.

In 1329, King George the Magnificent united the country devastated by the Mongols and reclaimed Western Georgia, including the Argveti principality („სამთავრო" - samtavro).

In the 15th century, a unified Georgia finally disintegrated, and Georgian kingdoms and principalities arose on its ruins (Kharadze; 2005: 227). Part of Sachkhere's territory at this time remained part of Kartli, while the rest became part of the Kingdom of Imereti. Two noble estates, Satseretlo and Saabashidze, were established on the territory of today's Sachkhere Municipality. Both royal and princely estates, as well as church villages, were located here. We will discuss this in more detail below, when discussing the nobility and the royal estate.

Nobility. The Imereti principality („სამთავრო" - samtavro). system began to take shape during the reign of Parnavazi (Argveti principality). After the collapse of unity, the territory was largely divided into separate noble houses. The system underwent significant changes until its end (the second half of the 19th century). The Imereti nobility was almost completely formed in the 15th century; at this time, the unified Georgia collapsed, and the country was divided into several kingdoms and principalities. It was from this time that the nobility in Imereti began to grow significantly.

From the 15th to the 19th centuries, a feudal noble system existed within the territory of the municipality within the Kingdom of Imereti. Two noble houses, Satseretlo and Saabashidze, were present within the boundaries of the modern municipality; their approximate locations are also shown on the map. A significant change to these borders occurred only in the first half of the 18th century, when the growing Tsereteli family seized the villages of Lichi, Makhatauri, Savane, Koreti, and Godora from the feudal house of Saabashidze. The border line is shown on the accompanying map as it existed in the 18th and 19th centuries.

While mapping the principalities' borders, we encountered a minor confusion: should the territories of the modern villages of Perevi, Jria, Kardzmani, Tedeleti, Jalabeti, Khakhieti, and Choisi be included in the Saabashidze estate, whose estates these territories directly adjoin? None of these villages are indicated on Vakhushti Bagrationi's map, suggesting that they did not exist at the time. The historical sources we found also provide no clue as to the ownership of this territory. It's noteworthy that we decided to include this territory in the Saabashidze estate because these villages and territories are not mentioned as part of the Shida Kartli-Samachablo principality, which borders it to the east. Geographically, this area belongs more to the Sachkhere Municipality and is sharply separated by mountains from the villages of the Java region: Sirkhlabirti, Alkhashenti, Ribisi, Biliurta, Kardanakhumi, and Rustavi. These villages are geographically directly adjacent to the territory of the Sachkhere Municipality (formerly Saabashidzeo).

Based on the above sources and personal observations, we have compiled a retrospective cartography of the nobles who lived in the territory of today's Sachkhere Municipality in the 15th–19th centuries.

In 1810, the Russian Empire conquered and abolished the Kingdom of Imereti, and the old form of noble rule ceased to exist along with the kingdom (Soseliya; vol. II, 1981: 203).

Satseretlo. One of the largest and most powerful nobles was Satseretlo, which was formed around the 16th century. The Tseretelebi nobles lived in Upper Imereti. This included primarily the territories of today's Sachkhere and Chiatura municipalities, as well as small parts of the Terjola (Dzevri), Oni, Ambrolauri, Kareli, and Khashuri municipalities. The borders and the area of settlement of the nobles in Sachkhere are shown on the map.

The Tseretelis also owned serf estates: Chikha, Didtsipela, Opcha, Darkveti, Sakurze, Katskhi, Tsinsopeli, and others. The Tseretelis owned Mount Khikhata, "Hunter's Mountain," and part of the village of Rokiti.

Satseretlo's borders were: the Racha Principality to the north, the Dzirula River to the south, the Likhi Range to the east, and the Chiatura Waters to the west.

Among the Georgian nobility of the 15th–19th centuries, nothing has been studied as thoroughly as the history of the feudal house of Tsereteli. The historian Olga Soselia made the first contribution to this.

The Tseretelis were not native to Imereti; this opinion is unanimous among scholars studying the history of the nobility. Etymologically, there are numerous place names in Saingilo and Kartli containing the surname Tsereteli, allowing researchers to conclude that the Tseretelis migrated from Saingilo to Kartli, and from there to Imereti. The Tseretelis likely migrated from Kartli to Imereti after the invasions of Temur-Leng.

"Satseretelo" as a designation for an estate belonging to the Tsereteli family has been found in the territory of modern-day Sachkhere since the 16th century.

The Tseretelis were a border noble family of the Kingdom of Kartli. In the late 16th century, during the campaign of King Simon of Kartli into Imereti, they fought on his side. During the reign of Vakhtang V Shahnavazi (1658–1675), Satseretelo was apparently a vassal of the king of Kartli, not Imereti.

The Tseretelis were hostile to Giorgi Saakadze during his vassal rule. Vakhushti Bagrationi writes: "The Mouravis threatened the Tseretelis of Kveli. The Mouravis were forced to burn his estate; the Tseretelis of Kveli attacked the Mouravis, and they fought each other. But Mouravi shot three arrows into his chest, and "Kveli and Mouravi were victorious" (Bagrationi; 1913: 67).

The Tseretelis became especially powerful in the second half of the 18th century and became the most powerful noble family in Imereti (Soseliya; 1947: 252–254).

Saabashidzeo. Saabashidzeo was formed in the 15th century and primarily included villages in the modern-day Zestafoni, Kharagauli, Tskaltubo, Terjola, and Chiatura municipalities. Geographically, Saabashidzeo was divided into two parts, the second part being located in Sachkhere, the borders of which are clearly marked on the map. Saabashidzeo's borders are: Racha principality („სამთავრო“ - samtavro) to the north, the Dzirula River to the south, the Likhi Range to the east, and the Argveta-Chkhara to the west. The Abashidzes owned the fortresses of Shorapani, Shroshi, Chalatki, and Tsutskhvati.

Beginning in the 15th century, the Abashidze-Saabashidzeo feudal clan, with its center in the village of Chala, emerged on the territory of today's Sachkhere municipality. The Abashidzes owned a palace, a fortress, a court church, and a crypt in Chalashiya.

Until the 18th century, the Abashidzes owned extensive estates in Sachkhere, controlling almost 60% of the territory. Beginning in the 16th century, after the Tsereteli family settled nearby, they gradually lost their holdings and became relatively weak.

Since the 18th century, the Abashidzes have controlled only the northeastern territory of Sachkhere. Their fiefdom was bordered to the north by the Racha Range and the following mountains: Sabvi, Phoni, Pepeleti, Dagverila, Sirkhlabirti, Ribisi, and Alkhashenda; to the east by Obolisi, Kardanakhumi, and Rustavi; to the south by Mount Peranga, Lokhoni, and Shakharadeti; and to the west by Didgora, Didi Tskhepari, Patara Tskhepari, and Tsiplari. Between these orthographic divisions lay the Sachkhere section of the Saabashidzeo patrimony, centered in the village of Chala. It included the following villages: Drbo, Gona, Orguli, Tkemalauri, Batskiuri, Panisuri, Khlebi, Perevi, Zaskhleti, Tskheprisdziri, Davaeti, Khakhieti, Tedeleti, Sinaguri, Jalabeti, Patkudjina, Khafalgomi, Dzirischala, Kheldakheuli, Sadarno, Tbeti, Kartsmani, Tsoysi, Lokhoysa, Sarbeti, Darka, Sakohia, D. Itskisi, Velebi, Churnali, Jriya, Chabukmta.

There are several versions of the Abashidze family's origins. According to one, they hail from the village of Chala in the Sachkhere municipality, where their surname originates. Another says they hail from the village of Sargveshita in the Kharagauli municipality.

In ancient times, the Abashidze's origins in Chala were apparently considered more credible. This is supported by a legend about the Abaiidze clan, which tells of the migration of Murvan the Deaf to Abkhazia and his battle with King Archil. It mentions Abash in Murvan the Deaf's army: "Among these people, a boy was born from the lineage of a certain bek, whom King Archil honored and raised alongside himself. Later, during a hunt, a wolf attacked King Archil's son, John, to warn him, and then Abash drew his sword and killed the wolf." Ganarina became the king's son, and as a reward, the king ennobled Archil, gave him the surname Abashi, and granted him estates in Chala and Zosiat-Khevi. He also accepted the other Abashids who were with him as nobles and settled them in Chala, who are called "Chalel Abashidze" (Akhuashvili; 2010: 128). The information provided contains numerous anachronisms and inconsistencies, but we consider this source pure legend and will focus solely on the fact that the village of Chala is listed as the Abashidzes' original residence, which is certainly no coincidence and must stem from historical information that the Abashidzes originated from Chala. It is also worth noting the second toponym mentioned here—Zosiat Khevi—a similar name is found north of Chala. The similarity with the ridge near Lake Ertso-Zostsveri is obvious. In our opinion, Abashidze's place of origin should be Chala. This is also supported by ancient sources mentioned in epigraphic materials in the Sachkhere municipality.

Vakhushti Bagrationi, in his "Tavarta Guartatvi," writes about Imereti: "The Abashidzes, Palavandishvili, and Amirejibi, in this union, owned estates in Imereti and Kartli, and after the division of the kingdom, one brother was placed there and the other here, as their estates and deeds show" (Life of Kartli. vol. IV, 1973: 35). Vakhushti's quote echoes the ancient historical reality, when the eastern part of Imereti was under the rule of Palavandishvili and Abashidze, and the Amirejibi bordered them on the Kartli side.

The Estates of the Kings of Imereti. In the 15th century, Georgia was divided into kingdoms and principalities. Within the Kingdom of Imereti, a new feudal property system—the nobility—emerged in place of the old principalities. The nobles had various hereditary families, and some nobles were granted complete independence from the king in internal affairs, which generally meant complete exemption from taxes. For example, the Satseretlo estate in Zemo Mkhare was precisely such a noble estate. Although noble estates often encompassed a single geographic area, the kings of Imereti had their own estates within these noble estates. Ownership of these estates often extended to an entire village, or a specific part of the village belonged directly to the king. In these scattered villages, the king had his own nobles, or simply the king's peasants, who paid various taxes to the king. It should also be noted that often in Imereti the same village simultaneously included: royal, princely, noble and monastic lands.

In the Sachkhere domains (Satseretlo, Saabashidzeo), the royal holdings were very small; the king owned only a few villages and estates. The king often donated his estates to nobles, churches, and monasteries. The king often returned the donated estates for various reasons.

During the reign of Solomon I, the royal holdings consisted entirely of the villages of Shalauri, Lichi, and Godora, which belonged to nobles living in Sachkhere. Ownership of the aforementioned villages later frequently passed from the king to nobles.

As mentioned above, the king owned estates located in various villages. On the territory of Sachkhere, the king had estates in the village of Koreti and the city of Sachkhere itself, where the king owned a large part of Khodabune (the lord's field) (Abesadze; 1973: 11, 12, 36).

As is evident from historical documents of the Imeretian Kingdom published by Sh. Burjanadze, Lichi and Godora (historical Khepinishkevi) were royal possessions until the second half of the 17th century, after which the king granted these villages to the Abashidze family, within whose borders they were located (Burdzhanadze; 1958: 14, 32). As is evident from documents cited in acts published by the Caucasian Archaeological Commission, the king again took the villages from the Abashidzes, as established by the tskhro given in the book of tribute granted by Solomon II to Zurab and Papuna Tsereteli in 1805 (Acts, vol. VI: 825).

As we see, in the 19th century, the Tseretelis occupied most of the royal holdings in Sachkhere.

Khepinikhevi. Khepinikhevi, as we already mentioned, united the villages of the upper Dziruli Gorge valley in the Sachkhere region; its location is marked on the map we plotted during fieldwork. In the "Collection of Georgian Historical Documents of the 9th-13th Centuries" (1984), we discovered a charter issued by King David Narin in 1266. The king exempted Khepinikhevi and Tsakveli from all taxes and granted them immunity: "...We made them inviolable and removed them from all interference: from the state, the principality („სამთავრო" - samtavro), and the memisupaloi" (p. 167).

After the 13th century, Khepinikhevi is mentioned in the 18th century as a royal possession of King Erekle II, which he gave to Abashidze, thus incorporating Khepinikhevi into the Kingdom of Imereti.

Conclusion

In exploring the topic of this study, we attempted to conduct a systematic study of the political geography of Sachkhere Municipality. By reviewing relevant literature, historical sources, and archival materials, we introduced a number of innovations to the region's political geography through on-site fieldwork. Using historical documents, this article examines the formation of the first historical province located here—the Argveti Principality—and the changes in its geographic boundaries over time. Following the political geography of the Argveti Principality, the article examines the nature of the Chikhi Principality, its formation, and its geographic location. This topic is directly linked to the historical processes that have occurred since the disappearance of the Argveti Principality.

In the 15th century, the unified Georgia disintegrated, which had a significant impact on administrative matters. The old traditional territorial division was completely overturned and replaced by separate noble classes. Two noble classes emerged in Sachkhere – Tseretelibi and Abashidze. This work examines in detail the formation of both classes, the changing borders, and the ownership of individual territories.

Along with the Tseretelibi and Abashidze classes, Sachkhere Municipality also included estates directly owned by the king. Revenues from these estates were channeled directly to the king, rather than following the traditional "peasant-chieftain-king" chain. The work also provides the territorial boundaries of one of Georgia's largest gorges, Khefinihevi, and its location within Sachkhere Municipality. This work will be useful to researchers interested in the historical geography of Imereti.

Competing interests

The authors declare that they have no competing interests.

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