Chapter 14
Landslide and Mudflow Hazard Assessment in Georgia

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Abstract Geological hazard posed by landslides, debris flows, rock avalanches and mudflows has always been and still represents a major threat for communities all over the world, causing extensive damage and often times the destruction of infrastructures and facilities. Over the last decades, the protection of the population from geohazards and the safe operation of infrastructures have become a significant priority for most countries in the world. Geological-related, adverse phenomena are more frequent in mountainous countries with high rainfall amounts and complicated geological settings. The above-mentioned geological hazards can also be favoured by climate change, earthquakes, as well as by pervasive human activities. Georgia belongs to one of the most complicated regions among the world's mountainous countries: thousands of settlements, buildings, roads, oil and gas pipelines, high-voltage power lines are prone to geohazards, that can trigger disasters and lead to widespread losses of life and property. Consequently, geohazard assessment is an important step towards the management and mitigation of adverse, natural events. In the present work, we introduce a set of new hazard maps for geological hazard assessment, compiled by employing methods applied at the national level, with a particular focus on landslides and mudflows.

Keywords Georgia · Geohazard · Landslide · Debris flow · Caucasus

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14.1 Rationale

Georgia is one of the most mountainous countries on Earth, bordered by the Greater Caucasus to the North and the Lesser Caucasus to the South (Fig. 14.1). It is worth pointing out that the country is also remarkable in terms of the development of different types of geological hazards, including landslides (Tibaldi et al. 2019) and earthquakes (Tibaldi et al. 2017a,b; Varazanashvili et al. 2018), with the exception of historic volcanic eruptions, though volcanoes with Holocene activity are present in the Lesser Caucasus (Pasquarè et al. 2011). Georgia hosts a great variety of morphological and climate conditions - from the humid, subtropical coastlines to highland-alpine-nival areas; whenever natural disasters strike the country, this usually leads to a great number of casualties, also due to very populated human settlements all across Georgia (Tsereteli et al. 2012; Tsereteli et al. 2014; Gaprindashvili et al. 2014; Gaprindashvili and Westen 2016; Gaprindashvili et al. 2018). A few examples of recent landslides, rock avalanches and debris flows are shown in Fig. 14.2; their location is highlighted in Fig. 14.1, which testifies to the large aerial distribution of such natural phenomena, from the Greater to the Lesser Caucasus.

Considering that geological disasters, as well as their adverse effects, have been on the rise in Georgia since the last century, based on the available data, the national government adopted a special decree (No. 967) in the 1960s, requiring the State Geology Department to develop a methodology for carrying out engineering

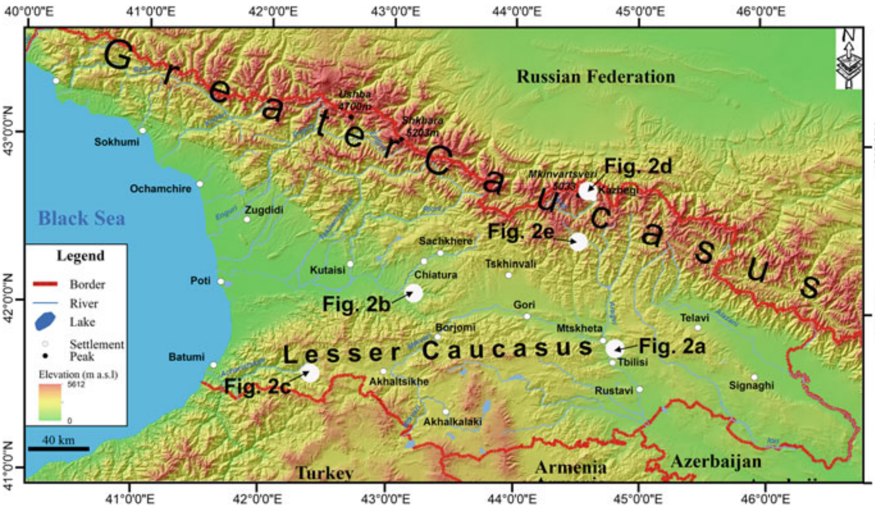

Fig. 14.1 Elevation map of the study area (Georgia), with indication of major mountain peaks and settlements, country borders, rivers and lakes (redrawn after Gaprindashvili and Westen 2016). The location of the events reported in Fig. 14.2 is also provided. Elevation data are from Aster GDEM v. 2 (Meyer 2011; Tachikawa et al. 2011); reference system: WGS84/geographic coordinates

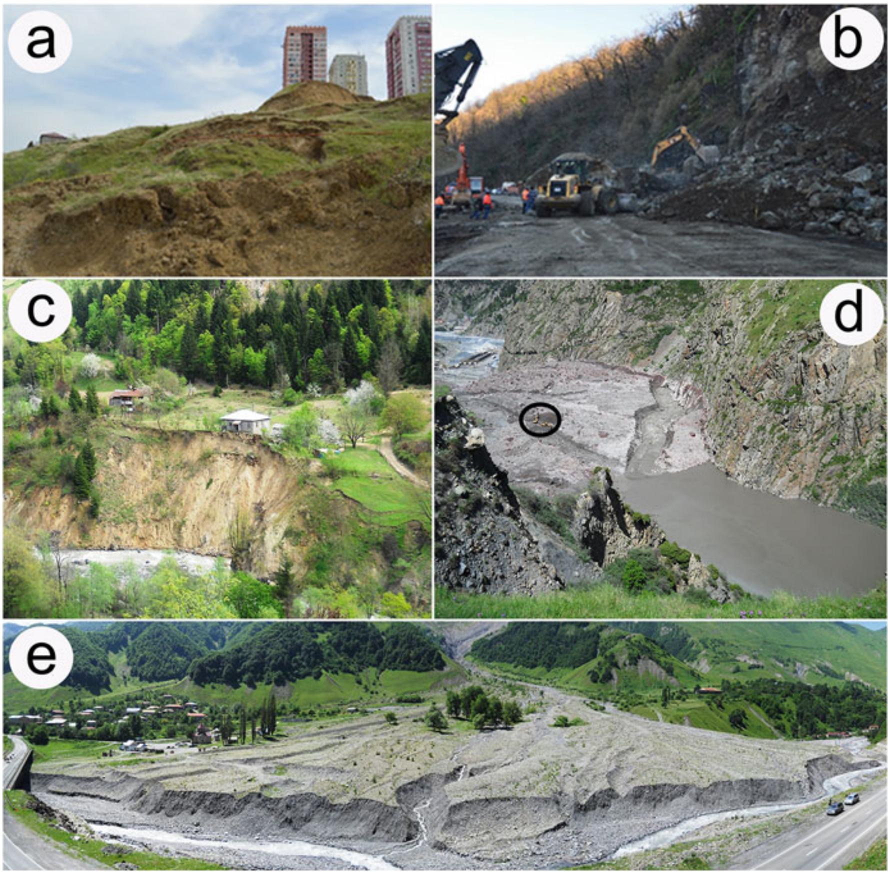

Fig. 14.2 (**a**) A major landslide occurred in Tbilisi in 2016 (Sheshelidze str.), buildings for scale; (**b**) a rock avalanche took place in 2011 at Rikoti pass (scraper for scale); (**c**) a landslide hit the Khulo municipality in 2013 (house for scale); (**d**) the Amali-Devdoraki rock avalanche and debris flow, 2014 (Kazbegi) (scraper for scale); (**e**) the Mleta debris flow in the Dusheti municipality, 2014 (cars for scale)

geodynamic studies. These comprised field geological surveys, the collection of all historical data and stationary observations; the coordination and monitoring of these activities were managed by the Ministry of Environmental Protection and Natural Resources.

By the end of the XX century in Georgia, scientists had performed geological surveys at the 1: 200,000 and 1: 50,000 scales across the whole country, and at the 1: 25,000 at 1: 10,000 scales across 45% of the territory, resulting in the production of several maps aimed at geohazard assessment.

These studies revealed that more than 70% of the Country's total area, including relevant settlements and major facilities, are prone to different geohazards. In this regard, the most critical areas are those in mountainous regions, also because these are the most affected by social and political instability. These regions are crucial from the geopolitical and economic point of views, as: *i)* several Eurasian transport facilities run through Georgian mountain passes; *ii)* they are internationally recognized landscapes with a unique historical and cultural heritage; *iii)* they offer great opportunities for mining and tourism, including trekking, skiing and climbing activities.

In Georgia, from 1967 to 2019 A.D., a total of about 3000 settlements (63% of the total) have been classified as located in areas potentially affected by natural disasters; as a consequence of this, about 60,000 families have been displaced as eco-migrants. Presently, as a result of the exposure to geological hazards, thousands of residents may have to be relocated to safer settlements, thus making them eco-migrants and causing them stress and resentment.

It is worth noting that, under the General Scheme of Anti-Erosion Measures (General Scheme of Anti-Erosion Measures 1988), geological disaster management funds were set at 1.3 billion GEL. It also needs to be underscored that, based on our data, the consequences to the population and the damage produced to infrastructures and facilities, as well as the number of human casualties, are three times greater than in the Southern Caucasus countries. As of today, the total number of landslide-gravity events exceeds 50,000, whereas those that directly affected the population and facilities/infrastructures are almost 3000. In the past, due to the more limited number of studies focused on landslide assessment, fewer events were recognized and mapped. The clearest confirmation of this was provided by the National Environmental Agency of the Ministry of Environment Protection and Agriculture of Georgia: engineering surveys conducted in Tbilisi area in 2016–2019 resulted in the identification of more than 500 landslides (Gaprindashvili et al. 2019), whereas only 60 landslides had been included in the Bulletin of Hazardous Geological Processes of the State Department of Geology in 2000. This is also confirmed by the analysis of the results of the geo-monitoring and disaster survey of the National Environment Agency in 2009–2018 (Table 14.1), which are aligned with those of the dynamic activity of landslide-gravitational and mudflow events (Fig. 14.3).

The spatial distribution of landslide and mudflow events over the territory encompasses both the seaside and the highlands. Out of the 70 municipalities regarded as affected by landslide hazards, 29 are included in the average-hazard zone (41%) and 35 (50%) in the high-hazard zone. According to recent data (2011–2018) from 8229 families (Source: Department of Geology of Georgia 2019), as a result of this monitoring activity, 1545 families were given the recommendation to relocate to safer houses/settlements (Department of Geology 2019). In view of the above, we hereunder introduce a set of new landslide and debris/mudflow hazard maps, compiled through the application of a national-scale approach.

Table 14.1 Number of landslides and mudflows with associated casualties and economic losses in Georgia (2009–2018)

Year	Landslide			Debris/Mudflow			Total casualties	Total economic loss ($ mln)	Affected objects	
	Re-activated and new	Human casualties	Approx. economic loss ($ mln)	Re-activated and new	Human casualties	Approx. economic loss ($ mln)			Settlements	Houses
2009	323	1	27.6	193	3	7.2	4	34.8	285	2696
2010	250	3	8.7	81	2	2.2	5	10.9	295	822
2011	94	3	5.6	37	8	3.9	11	9.5	309	463
2012	325	1	11.8	88	5	21.7	6	33.5	350	845
2013	336	0	19.5	93	0	20.3	0	39.8	472	1269
2014	727	0	26.7	141	10	65.2	10	91.9	845	962
2015	936	4	29.8	167	19	108.7	23	138.5	931	1014
2016	780	0	17.6	208	0	8.9	0	26.5	934	1084
2017	845	0	21.3	165	0	10.6	0	31.9	1042	1353
2018	702	1	19.6	122	0	16.8	1	36.4	1057	1245
Total	**5318**	**13**	**188.2**	**1295**	**47**	**265.5**	**60**	**453.7**		**11,753**

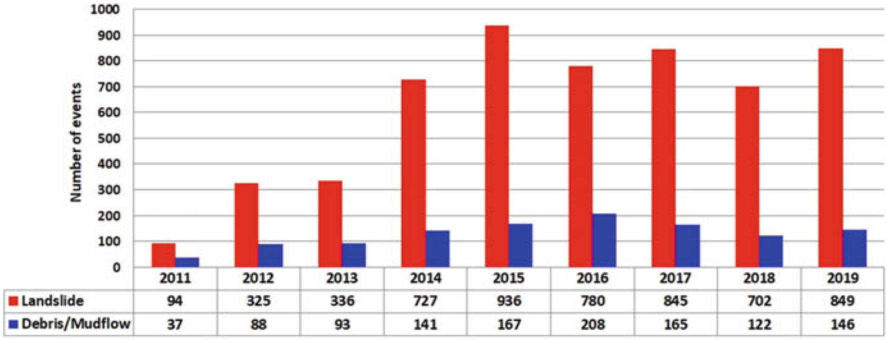

Fig. 14.3 Number of landslides and debris/mudflows that occurred in Georgia (2009–2019). (Source: Department of Geology of Georgia)

14.2 Morphological Aspects of the Territory

The magnitude of landslide-gravitational and mudflow processes and events and the associated hazards depend on factors such as rock and terrain energy potential, together with external environmental factors such as meteorological events, earthquakes and anthropogenic contributions.

Studies focused on the development and triggering causes of landslides and mudflows carried out in Georgia in the last tens of years, have been considered of relevant importance by UNEP- UNESCO, and were summarized in the monograph "Landslides and Debrisflow" (Tsereteli 1984). Based on this experience, the landslide and mudflow hazard has been assessed, providing new hazard maps and recognizing the geological units and characteristics that are more prone to potentially develop landslides and mudflows. Among the major constituent elements of the geological environment are rocks and soils, which represent not only the foundation on which human-engineering structures and facilities are built, but are also crucial in terms of the activation of geological processes, primarily landslides and mudflows. The role of such components is particularly relevant, if the Alpine-Himalayan-type geological environment of the Georgian central segment of the Caucasus is considered. In Georgia, regional studies analysing the exogenous conditions that led to the development of gravitational events, have identified the categories of terrains and slopes that are more prone to this type of geohazard (Gaprindashvili 2016; Gaprindashvili et al. 2016a, b, 2019).

The first aspect we need to consider is the relation between the terrain slope and exogenous processes, here referred to as the "energy potential of the terrain"; this is provided considering the following classes of terrain slope: up to 3°; 3–8°; 8–15°; 15–25°; 25–35°; 35–45°; 45–65°; 65–90° (Fig. 14.4).

For each class of "terrain energy potential", that corresponds to specific areas in the Georgian territory (see Fig. 14.4), all the types of dominant exogenous processes have been identified and reported in Fig. 14.5. In addition, four different

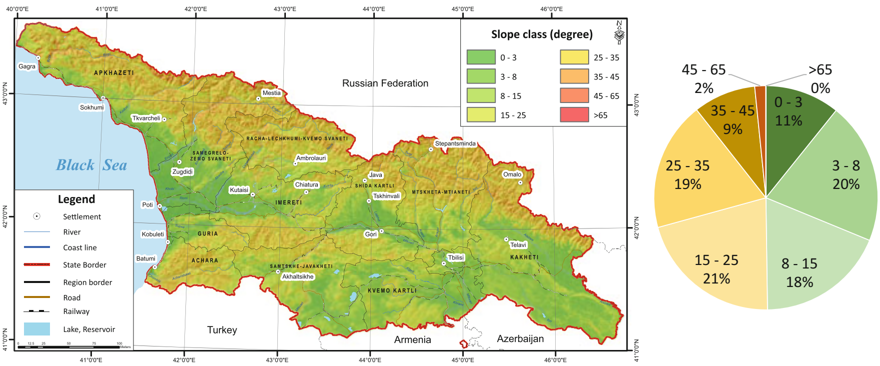

Fig. 14.4 Terrain slope map of Georgia calculated on Aster GDEM V.2 (pixel size is approximately 30 meters; Meyer 2011; Tachikawa et al. 2011); reference system: WGS84/geographic coordinates. Terrain slope classes are reported in percentage of frequency

Terrain slope (°)	Geological processes and related hazards
>65	Rocky terrains, with deep erosion and gravitational processes in the form of rock avalanches and accumulation of thick colluvium in debris/mudflow source areas.
45-65	Major gravitational processes, such as rock avalanches, rockfalls, rockslide-type landslides, debris/mudlflows, river bank erosional phenomena.
35-45	Rockfalls and rock avalanche-type landslides, river erosion and debris/mudflow occurrence.
25-35	Tectonically active, highly-weathered areas; denudation-gravitational events, with sediment accumulation and debris/mudflows as well as landslides; development of erosional processes in gullies.
15-25	Erosional processes in gullies, accompanied by debris/mudflows and landslides.
8-15	Active processes of rainfall-induced denudation and accumulation of deluvial sediments. High “moisture effects” and development of plastic-flow landslides; active processes of suffosion and erosion in gullies with subsequent mudflows; climatogenic landslides.
3-8	Suffosion processes over plain areas; weathering in mountain pediment areas and rainfall-induced denudation, with formation of deluvial sediments; gully erosion and development of shallow climatogenic landslides.
0-3	Mostly resistant to geological processes; swamping due to rising groundwater, suffosion.

Fig. 14.5 Possible geological processes and related hazards for the different classes of terrain slope reported in Fig. 14.4

areas, defined as “morphological zones” have also been defined, based on different altitudes above the sea level, and have been mapped in Fig. 14.6 and classified by percentage value. Such classes are: *inter-mountain areas* (less than 600 m a.s.l.); *lowland areas* (600–1000 m a.s.l.); *mid-altitude areas* (1001–2000 m a.s.l.); *highlands* (above 2000 m a.s.l.). The “morphological zones” have been considered for geohazard assessment together with those representing the terrain energy potential”.

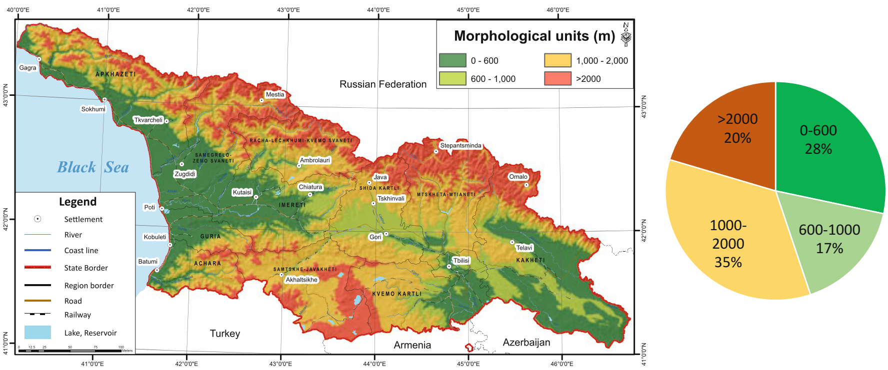

Fig. 14.6 Morphological zones in Georgia; their classification is based on Aster GDEM V.2 (pixel size is approximately 30 meters; Meyer 2011; Tachikawa et al. 2011); reference system: WGS84/geographic coordinates. Morphological zones distribution in Georgia, classified by percentage values

14.3 The Influence of Climate and Weather

Regarding the contribution of climate, the long-term weather regime for a given geographical environment should be considered as a main background for some geological processes (landslides, debris flows), whereas meteorological factors (temperature, precipitation, humidity) are the main determinants for landslide and mudflow events. Consequently, landslides and mudflows may be linked to atmospheric precipitation deviations from the average, in terms of the hereunder provided conditions:

1. **Low background activation** - when annual rates of atmospheric precipitation and “moisture effect” are below the threshold of the annual multiannual standard, and landslides are “stable”;
2. **Background (medium) activation -** when the amount of atmospheric precipitation during the year and the “moisture effect” of the deforming horizon fall within the limits of the multi-annual norm; in this case, landslide processes occur at the background level;
3. **Stressful -** when atmospheric precipitation during the year exceeds the average perennial up to 200 mm. In this case, slopes with rocks characterized by optimal receptor properties tend to activate landslide processes;
4. **Extreme -** when landslide activation begins in events of precipitation above 400 mm above the average perennial norm. In this case, almost all landslide bodies are reactivated, and new landslides processes are triggered;
5. **Paroxysmal -** Regardless of what kind of circulatory regime is present in the atmosphere, when rainfall is above (up to 400–600 mm) the perennial average, the “humidity effect” will be increased to the limit, and all new landslides in stable conditions will be activated.

Thus, in terms of regional development of landslides in Georgia and their dynamic regime, there are three main stages:

1. Maximum reactivation of landslide processes, caused by paroxysmal extremes in atmospheric precipitation (400–600 mm or more);
2. Periods of average activation of landslide processes, mainly involving the intervals between periods of intensified activation of landslide events;
3. Baseline period of landslide processes. Landslides in this kind of dynamics precede the two previous stages.

If the internal annual deviations of atmospheric precipitations and the “moisture effect” play a key role in the dynamic mode of landslide processes, the main determinants of debris/mudflow events are the amount and intensity of daytime rainfall and precipitation (that in Georgia is the warmest period of the year - months April to October).

For the mountainous territory of Georgia, we have established that the background activation of mudflow processes begins with daily precipitation ranging 30–40 mm. Extreme mudflows with high energy and volumes start in the range of 50–80 mm. In the event of precipitation of 80–100 mm or more, there will be catastrophic debris/mudflows (Gaprindashvili et al. 2016a, b; Tsereteli et al. 2019). The classic site for these phenomena is the central part of the Greater Caucasus, with the tributaries of Aragvi, Tergi, Rioni, Tskhenistskali, Enguri, Kodori and almost all the rivers on the southern slope of the Kakheti Caucasus.

As regards the complications due to human activity in Georgia, in terms of reactivation of exogenous processes and events, two categories of adverse human impacts on the geological environment can be clearly identified:

1. Natural-anthropogenic, in which the development of geo-environmental changes and exogenous processes are related to human-engineering activities, but the natural development dominates over the human effects.
2. Anthropo-technogenic adverse effects on the geological environment, when exogenous processes are strongly enhanced by human activities.

14.4 Classification of Landslide Types in the Territory of Georgia

Due to the complexity of landslide processes and events, their geological nature, multifactorial features, morphogenetic features, depth deformation, volumes, slope and many other features are so diverse that the number of classification characteristics exceeds the hundreds (Cruden and Varnes 1996; Hungr et al. 2014; Varnes 1978). All, to varying degrees, reflect the essence of landslide processes and the peculiarities of events. It is recommended that existing landslide bodies and their possible emergence areas should be assessed in terms of the characteristics of the deformable slopes, their structure, movement mechanisms, and the nature of recurring processes characterizing these types of geohazards. According to the above, two landslide classes can be established:

Class A - Landslides in lithified, although tectonically strongly disrupted rocky and semi-rocky substrate rocks. As a rule, rocks of this class are characterized by maximum deformation capacity, and a more or less uniform structure and movement mechanisms;

Class B - Landslides bound lithic rocks and quaternary slope sediments and active zones of weathering. Landslides developed in these sediments are characterized by a great heterogeneity in origin, movement mechanisms, kinematics, morphology and other features.

As far as the landslide hazard factors in the territory of Georgia are concerned, the following groups of landslides can be individuated:

- **Coastal landslides -** the origin of which is associated with erosion of riverbanks, abrasive transformation of seabeds and associated reservoirs, rising water levels, and hydrostatic and hydrodynamic regime fluctuations;
- **Climate-related landslides -** mainly occurring in slope sediments made of weak clay rocks. Associated with quantitative indices of atmospheric precipitation on an annual basis;
- **Tecto-seismogenic landslide-gravitational events -** characterized by possible earthquake triggering and localized in zones affected by tectonic dislocations;
- **Karst landslides -** quite specific in the Caucasus region, and scientific data on them is scarce;
- **Landslides influenced by anthropogenic processes -** they occupy an important place in Georgia, with little attention paid to the study of problems related to them in the recent past;
- **Cryogenic landslides -** characteristic of highland alpine-nival zone terrains in the Caucasus region.

14.5 New Hazard Maps Calculation

After relevant studies were carried out nationwide and the major factors behind the occurrence of landslide-gravitational and mudflow processes and events were identified, the next stage was to identify threats, vulnerabilities, and risks to both territorial and individual municipalities. In this regard, landslide and mudflow events were zoned according to the level of vulnerability of the potentially affected areas, recurrence intervals, and characteristics of the infrastructures. Accordingly, we have come up with different categories of hazard, which could be re-arranged in a different amount of hazard classes, depending on need. In this work, we have provided landslide and debris/mudflow hazard zoning maps grouped into 7 classes for landslide events (Fig. 14.7) and 9 classes for debris/mudflow events (Fig. 14.8).

Fig. 14.7 Landslide hazard zoning map of Georgia; reference system: WGS84 / geographic coordinates

Fig. 14.8 Debris/mudflow hazard zoning map of Georgia; reference system: WGS84 / geographic coordinates

A simplified classification can consider four classes: high, moderate, low and not dangerous; this will be applied in the future using the same methodology.

Specifically, for landslide-gravitational hazards, we use the notion of "landslide potential", which is expressed as process intensity (i.e. hazard severity) and activity (frequency, return period), generated in a uniform geological environment and climate, and in a "moisture effect". The estimated coefficient of these events is estimated using four indicators:

1. The extent of the area occupied by all-time landslide bodies ($F_{cond.}$/km^2) the total area of the geological environment (F_{lands}. km^2);
2. The total area sum of landslide bodies (N area km^2) relative to the total area of geological environment;
3. The homogeneous geological environment space (F_{area}.km^2), associated with newly formed landslides (Kn $_{lands}$.) and earlier landslides (K_N old lands), which allows us to determine the potential for landslide development dynamics;
4. The ratio of areas prone to landslide processes potentially in the state of homeostatism (fkm^2) to the total study area (F Geol.km^2).

As regards mudflows, the mudflow hazard ratio (Ks) has been used. These ratios are:

1. Comparison of the total number of mudflats in the given river basins with rivers in the same basin where no mudflows have been recorded (Ks = $n_1 n_2$);
2. Comparison of the mudflow areas of the relevant geological environment with the total area of the river basin (Ks = f km^2 / F km^2);
3. Comparison of the areas of active nutrient depletion with solid mineral product to the total catchment area of the given river basin (Ks = fmF) (Ks = f mudfl. Source km^2 / F geol.km^2).

In addition to the listed coefficients, the following shall be taken into account when determining the risk of mudflows:

4. Frequency of the transformation of the mudflows originating in the characteristic mudflats into the basin in time;
5. Single maximum volumes of mudflow flows in a mud-rich river basin (in thousand m^3);
6. Objects in the immediate danger area of mudflow events (Kc);
7. Mudflow events that pose a direct threat to the population and important engineering sites.

We use the coefficient of 0 to 1 to estimate the hazard by summing the indicators of landslide-gravitational and mudflow events, where 0 means no hazard and 1 means highest hazard.

14.6 Results

The final weights of the resulting maps ranged from 0 to 1. Landslide and debris/mudflow hazard zoning maps here presented were grouped into 7 classes for landslide events (Fig. 14.7) and 9 classes for debris/mudflow events (Fig. 14.8), as listed hereunder.

Regarding the landslide hazard zoning map (Fig. 14.7), we have broken down the most relevant areas in terms of the level of hazard:

- **Very high hazard zone**, including the mountainous Adjara, Imereti and Racha-Lechkhumi and Lower Svaneti regions, as well as the Black Sea coast of Apkhazeti;
- **High hazard zone**, including the Guria foothills, Mtskheta-Mtianeti region, Okriba foothill zone and the western part of Adjara;
- **Significant hazard zone**, including the northern slopes of the Trialeti ridge with the Akhaltsikhe depression, the Samegrelo region (the hills of the Kolkheti North side) and the Tbilisi-Asureti area;
- **Medium hazard zone**, encompassing the Trialeti ridge, eroded terrains of the medium and high mountain valleys of the Greater Caucasus, Upper Svaneti, the part of the Caucasus Ridge in Kakheti region, the peripheries of the Shida Kartli depression, and foothills of the Tsivi- Gombori Ridge;
- **Low hazard zone,** including Mesozoic units of the southern slope of Caucasus constructed with volcanogenic and carbonate formation, river Iori plateau, the left side of river Iori characterized with hilly terrain, the adjacent territories of Khrami and Loki massifs;
- **Very low hazard zone**, encompassing the Javakheti volcanogenic highland, the axial zone of the Caucasus, the massifs of Khrami, Loki and Kelasuri, the terraces of the river Mtkvari and Khrami rivers, in the Marneuli -Gardabani plain area;
- **No hazard zone**, including the Kolkheti lowland, Shida Kartli, Gardabani, Alazani, and Iori areas presented by low plain-terraces.

Regarding the debris/mudflow hazard zoning map (Fig. 14.8), we have shown the most relevant areas subdivided by level of hazard:

- **Very high hazard zone**, that encompasses Kakheti (Alazani-Iori basins), Racha-Lechkhum-Kvemo Svaneti, Samegrelo-Zemo Svaneti and Mtskheta-Mtianeti regions;
- **High hazard zone**, which includes the Alpine zones of the medium and high mountain areas on the northern and eastern slopes of the Central and Eastern Greater Caucasus, as well as the high mountainous part of the lesser Caucasus, in the Adjara region;
- **Significant hazard zone**, that includes the Trialeti and Meskheti ridges, medium and upper parts of the Kodori and Bzifi River basins of the Western Caucasus, and the western part of Adjara;
- **Medium hazard zone**, encompassing the Rioni, Tskhenistskali, Enguri and Kodori river basins, headwaters of the Kvirila River basin, the low mountain and middle mountain zone of the Caucasus Range in Apkhazeti, Algeti river basin, Trialeti ridge in the vicinity of Tbilisi, and the low-mountain area of Adjara;
- **Limited hazard zone** that includes the lowland zones of raised horst of the Dzirula, Khrami, and Loqi, Foothills of Guria and Imereti regions, Psou, Sandripshi, and Zhoekvara rivers in Aphkhazeti;

- **Low hazard zone** that includes areas made of carbonate rocks in the small and middle-size mountains of Racha, Askhi, Khvamli, Arabika, and the Bzipi and Kodori rivers, foothills of Guria and Adjara;
- **Very low hazard zone** that encompasses the Iori Plateau and part of the downstream of river Mtkvari;
- **Weak hazard zone** that includes the Akhalkalaki plateau and volcanogenic highland of Javakheti;
- **No hazard zone** that encompasses the Kolkheti lowland and Black Sea coast, plains of Eastern Georgia, Kartli and Alazani.

14.7 Final Remarks and Future Developments

The hazard maps of landslide-gravitational and mudflow events have been compiled based on multi-criteria assessment methods, and have been grouped into 7 classes for landslide events and 9 classes for debris/mudflow events (Figs. 14.7 and 14.8). In a future perspective, we intend to provide the related classification subdivided in four homogenous hazard levels: 1. High; 2. Moderate; 3. Low; 4. Not in danger.

The four homogenous hazard levels will be classified as follow:

1. Highly hazardous areas are those in which the components of the geological environment are likely to generate any kind of geological process and are characterized by high vulnerability coefficients (greater than 0.5) and extreme activation intensities averaging 8–11 years;
2. Moderate-hazard areas are those where geological environment is susceptible to landslide and mudflow events within the range of 0.1–0.5 and the probability of activation of extreme processes is up to 10%;
3. Areas of low hazard are those where the probability of landslide and mudflow events does not exceed 1%;
4. Non-hazardous areas are those in which additional unforeseen processes, without triggering agents, shall not occur.

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