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Generation of a national landslide hazard and risk map for the country of Georgia

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Abstract Landslide risk assessment for large areas at a country level requires a different approach and data than what is standard practice at large scales. The main goal of this research was to design a methodology for a nationwide landslide risk assessment for Georgia taking into account the limitations in data availability and detail, which do not allow the use of physically based models or statistical methods. Given these limitations, we decided to generate a qualitative landslide risk index using spatial multicriteria evaluation (SMCE). An attempt was made to compile a national landslide inventory, using old and partly destroyed archives from the Soviet period, combined with information from annual field surveys. A web-based interface for the reporting of landslide events was developed to improve the updating of the inventory in future. Relevant factor maps were prepared for the entire country, partly based on remote sensing data. As the available landslide inventory was not sufficient to use statistical methods, the factor maps were weighted using the expert-based SMCE method, and the resulting susceptibility map was validated using the available landslide inventory. The inventory was also used to make an estimation of the spatial probability of landslide occurrence within the various susceptibility classes. The resulting map was used in combination with element-at-risk maps to calculate exposure maps and to make a tentative assessment of the expected landslide losses in a 50-year time period.

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1 Introduction

Landslide susceptibility and hazard assessment at small scales, covering large areas such as individual countries or continents, is a major challenge. Landslide susceptibility maps provide a zonation of areas with different relative likelihood of landslide occurrence, whereas landslide hazard maps also provide probability information (spatial, temporal, size, and runout probability) for these zones (Corominas et al. 2014).

There are generally four different approaches for the assessment of landslide susceptibility: landslide inventory-based, heuristic, statistical, and physically based methods (Soeters and Van Westen 1996; Aleotti and Chowdhury 1999; Guzzetti et al. 1999; Corominas et al. 2014). The available data and the large size of the study area in such small-scale analyses do not allow the application of physically based methods, which require information on material characteristics (rock and soil types, soil depth, hydrological and geotechnical parameters), although some successful attempts have been made elsewhere (e.g., Alvioli et al. 2014). The application of statistical methods is only possible if a sufficiently complete landslide inventory is available (Guzzetti et al. 1999).

One of the first attempts to generate small-scale landslide susceptibility maps was reported for France by Delaunay (1981) and for the USA by Radbruch-Hall et al. (1982). At a global scale, such attempts have been made by Nadim et al. (2006), Hong et al. (2007), and Yang et al. (2015) using a heuristic approach based on expert-based weighting of globally available datasets, such as slope, elevation, lithology, land cover, soil moisture, active fault line density, and seismicity. Farahmand and AghaKouchak (2013) used support vector machines (SVMs) for the prediction of possible landslide locations based on satellite rainfall data, global topographic and land-cover data, and a global database of landslide occurrences (Kirschbaum et al. 2010). Based on global landslide records and TRMM data, Hong et al. (2006) established a global rainfall threshold for the initiation of landslides. The resolution of these global maps is generally too coarse to use them for national-scale landslide susceptibility and hazard assessment. When the global susceptibility maps are displayed for a specific country, there may be large discrepancies with the actual situation. This may also be the case for the global landslide inventories (e.g., Kirschbaum et al. 2010; Petley 2012), as landslide data are often very limited for individual countries such as Georgia. The global disaster databases, such as EM-DAT (Guha-Sapir et al. 2015), generally have a large underrepresentation of landslide events, due to their inclusion criteria, whereas local disaster databases, such as DesInventar (2015), are only available for a limited number of countries.

At continental level also, attempts have been carried out to generate landslide susceptibility and hazard maps. Liu et al. (2013) collected landslide data of 1200 landslide events for the past 60 years in China and used an artificial neural network model with nine variables related to lithological, topographical, soil and land-cover factors. At the European level, an attempt has been made to develop a synoptic pan-European landslide susceptibility map, as a contribution to the EU Soil Thematic Strategy (Günther et al. 2013, 2014a, b; Hervás et al. 2007; Jaedicke et al. 2013). Also in this approach a heuristic method was adopted, due to the lack of a comprehensive landslide inventory, although there is an increasing number of countries where landslide inventories are made available, and a new version of this map is in the making, in which also a differentiation will be made between landslide types in the susceptibility assessment.

National-scale landslide susceptibility maps, based on (incomplete) landslide inventories, have been produced for many countries in different environments, for example

Guatemala (Coe et al. 2004), Cuba (Castellanos Abella and van Westen 2007), Romania (Balteanu et al. 2010), Indonesia (Cepeda et al. 2010), France (Malet et al. 2013), and Italy (Trigila et al. 2013). Where a sufficiently large landslide database has been developed also statistical methods have been attempted at a European scale (Van den Eeckhaut et al. 2010) and at a national scale, for example in El Salvador (Cepeda et al. 2013) and Italy (Trigila et al. 2013). However, for most countries, the landslide inventories are not sufficiently detailed to base the assessment on statistical methods only. Therefore, a heuristic approach is considered to be the best to obtain qualitative landslide susceptibility maps for large areas which lack sufficient landslide inventories. Spatial decision-support tools are available for GIS-based heuristic analysis, which allow better structuring of various components, including both objective and subjective aspects, and compare them in a logical and thorough way (Saaty 1996). Decision-support tools such as (spatial) multicriteria analysis have proven to be suitable tools for qualitative landslide susceptibility assessment in other areas (e.g., Castellanos Abella and van Westen 2007).

The assessment of landslide risk, which is defined as the probability of losses, for large areas is even more challenging than the assessment of landslide susceptibility or hazards. For large-scale landslide risk assessment, a range of methodologies have been published (Bonnard et al. 2004; Lee and Jones 2004; Glade et al. 2005), but only limited research has been done on landslide risk assessment for large areas such as entire countries (Nadim et al. 2006; Guzzetti 2000; Yoshimatsu and Abe 2006; Castellanos Abella and van Westen 2007). Most of these authors produce a landslide risk index, which makes it possible to zoom in on the high-risk areas for more detailed studies. Attempts have been made by Nadim et al. (2006), and their method has been replicated by others (e.g., Yang et al. 2015) at global level or also at a national level (e.g., Cepeda et al. 2010, 2013). They estimate the mortality risk (fatalities per year) due to precipitation-induced or seismically induced landslides as a function of the physical exposure, and a transformed and normalized value of the Human Development Index. The equation is only applicable for risk estimation at municipal level.

This research aims to generate national-scale landslide hazard and risk maps for the country of Georgia, located in the Caucasus, between Russia, Turkey, Armenia, and Azerbaijan (Fig. 1). The available landslide inventory is not complete enough to apply statistical methods, although bivariate methods can be used to analyze the relative importance of the predisposing factors. We decided to generate a qualitative landslide risk index using the spatial multicriteria evaluation (SMCE) method in a geographic information system. The landslide risk index uses indicator maps collected from a variety of national information sources. The method follows the recommendations for regional-scale landslide hazard and risk assessment as given by Soeters and Van Westen (1996) and Corominas et al. (2014). The latter publication indicates the various recommended scales ranging from national to site-specific, and the recommended methods that can be applied for each of them.

2 Study area

Georgia is a country in the Caucasus region (Fig. 1) which is bordered to the west by the Black Sea, to the north by Russia, to the southwest by Turkey, to the south by Armenia, and to the southeast by Azerbaijan. The surface area of Georgia is 69,700 km^2, and its population is almost 4.9 million.
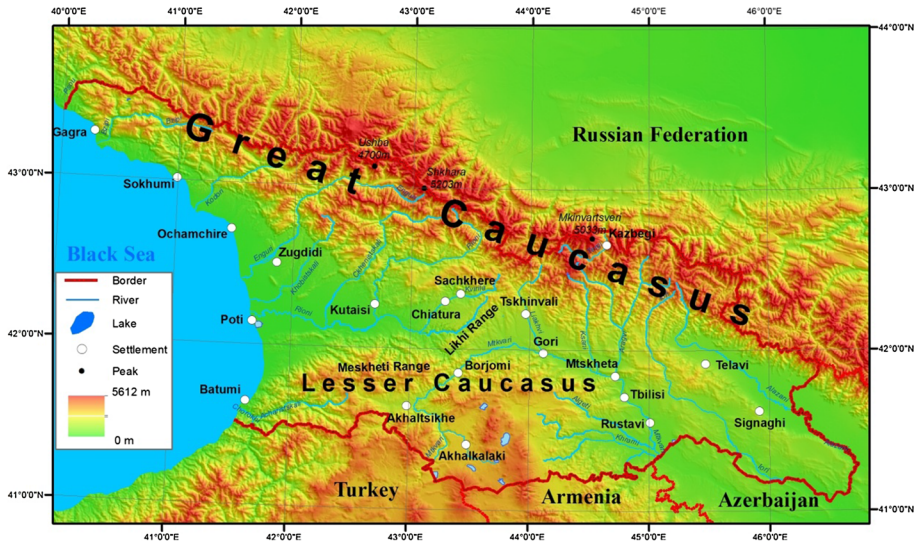
Fig. 1 Overview of Georgia

Despite its relatively small area, Georgia has a complicated topography, and its elevation ranges from sea level to the Black Sea to over 5000 m in the Caucasus Mountains. There are two mountain chains that cross the country, resulting from the collision of the Arabian and Eurasian Plates: the Lesser Caucasus Mountains in the south and the higher Greater Caucasus Mountain Range in the north. The Greater Caucasus consists of a southward-directed fold and thrust belt that has been active since the Oligocene.

The Lesser Caucasus range, which runs parallel to the Turkish and Armenian borders, and the Likhi range, which connects the Greater Caucasus and the Lesser Caucasus, create natural barriers that are partly responsible for cultural and linguistic differences among the regions. Because of their elevation and a poorly developed transportation infrastructure, many mountain villages are virtually isolated from the outside world during the winter. Georgia has a very dense drainage network, and the main rivers drain into the Black Sea to the west and through Azerbaijan to the Caspian Sea in the east. The largest river is the Mtkvari, which flows 1364 km from northeast Turkey across the plains of eastern Georgia, through the capital, Tbilisi, and into the Caspian Sea. The Rioni River, the largest river in western Georgia, originates in the Greater Caucasus and drains into the Black Sea at the port of Poti.

The climate of Georgia is extremely diverse, considering the country's small size. There are two main climatic zones, roughly separating the eastern and western parts of the country, but many smaller subdivisions. The Greater Caucasus Mountain Range plays an important role in moderating Georgia's climate and protects the country from the penetration of colder air masses from the north. The Lesser Caucasus Mountains partially protect the region from the influence of dry and hot air masses from the south as well.

Much of western Georgia lies within the northern periphery of the humid subtropical zone with annual precipitation ranging from 1000 to 4000 mm. Eastern Georgia has a transitional climate from humid subtropical to continental. The penetration of humid air masses from the Black Sea is often blocked by several mountain ranges (Likhi and

Meskheti). Annual precipitation is considerably less than that of western Georgia and ranges from 400 to 1600 mm.

Georgia belongs to one of world's most complex mountainous regions according to the scale and frequency of natural hazardous processes and damage caused to population, farm lands, and engineering facilities. Natural hazards (earthquakes, river floods, flashfloods, landslides, mudflows, rockfalls, and snow avalanches) are affecting many populated areas, agricultural fields, roads, oil and gas pipes, high-voltage electric power transmission towers, hydraulic structures, and tourist complexes. Landslides occur almost in all geomorphological zones, resulting in wide differentiation in the failure types and mechanisms and in the size–frequency distribution. Landslides destroy buildings, agricultural lands, roads, and other infrastructure. Mass movements also have a considerable effect on population, causing loss of human life (see Fig. 2). Mass movement phenomena are classified in Georgia in a slightly different way as is customary in the international literature (Varnes 1984; Cruden and Varnes 1996; WP/WLI 1993), as they are generally divided into three groups: mudflows (which includes flow-type movements according to the international classification), landslides (which includes all slide-type movements according to the international classification), and rockfalls (all fall-type movements).

Catastrophic events are triggered by earthquakes (e.g., 1991 Racha-Imereti, 1992 Pasanauri-Barisakho, 2002 Tbilisi, 2009 Oni, 2010 Vani) and extreme hydrometeorological events. The large-scale human impacts on the environment are aggravated as the society has a low level of preparedness.

Fig. 2 Examples of mass movement phenomena that have occurred in Georgia recently. **a** Debris flow in Rikoti Pass (Khashuri Municipality 2011); **b** landslide affecting a road near (Tbilisi 2013); **c** river erosion leading to landslides in Khulo Municipality 2013; **d** buildings affected by runout of landslides in Khala village (Kobuleti Municipality), 2008 (*source*: National Environmental Agency of Georgia)

Georgia is a relatively small country, which has witnessed many changes over the past decade, in relation to its independence and following civil conflicts. The extensive monitoring of natural hazard events and the dense network of rain gauges and discharge stations came to an end due to limitations in funding after independence. The National Environmental Agency, under the Ministry of Environment and Natural Resources Protection, now has the mandate to carry out landslide investigation in the country, with limited staff and resources.

The main institution active in disaster risk management (DRM), which is responsible for policy making and advising the President, is the National Security Council (NSC). According to the national legislation, at different DRM phases, different sectors of the government, individuals, and legal entities should be participating in the process. The Emergency Management Department (EMD) is responsible for the emergency management processes during natural or man-made disasters and in the post-disaster period. The functions of monitoring and forecasting, and prevention of natural disasters are allocated to the Ministry of Environment and Natural Resources Protection (which is the national focal point for the implementation of the Hyogo Framework for Action 2005–2015), different legal entities belonging to the Ministry, and to other legal entities and commissions at different levels.

In Georgia, a national digital landslide inventory covering the entire country was not available, prior to this study. Landslide information was traditionally collected by the Department of Geology of the National Environmental Agency. They have carried out field investigations for many years and have been mapping landslides during their annual field campaigns. The resulting yearbooks contain a large amount of information, but the information is mostly in an analogue format. Unfortunately, a large part of these archives have been lost or damaged. Apart from these systematic surveys, the scientific research institutes at several universities and at the Georgian Academy of Sciences have accomplished other significant studies on natural hazards for particular locations.

Up to now, a large amount of landslide research has been carried out in Georgia. However, the results are mostly presented in the local language and on paper (reports, maps, archives, etc.), and are not available in digital format. Most of these landslide studies concentrate on landslide inventory mapping for particular areas, creation of engineering geological maps for problem sites, individual landslide descriptions, and qualitative hazard assessment for small areas (Tsereteli et al.1978, 2012, 2013).

In order to improve the use of modern technologies, and the development of databases for the generation of baseline data on natural hazards and risk in Georgia, the project "Institutional Building for Natural Disaster Risk Reduction (DRR) in Georgia" was implemented by the Caucasus Environmental NGO Network (CENN) and the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, the Netherlands, between 2009 and 2012. The project was financially supported by the Social Transformation Programme for Central and Eastern Europe (MATRA) of the Netherlands Ministry of Foreign Affairs. The aim of the project was institutional capacity building in disaster risk reduction (DRR) via the introduction of modern spatial approaches and technologies and a risk communication strategy in spatial planning in Georgia. This research contributed to the above-mentioned project in terms of landslide hazard and risk assessment. The main goal of this research was to design a methodology for the assessment of nationwide landslide inventory, hazard, and risk maps for Georgia taking into account the limitations in data availability and detail. The results are presented in a national atlas of natural hazard and risk of Georgia (CENN/ITC 2014).

3 Methodology

Many environmental factors, related to geology, geomorphology, topography, and land use, determine the predisposing factors leading to landsliding (Clerici et al. 2002). In order to be able to characterize the landslide susceptibility zones, information on past landslides and the specific combinations of these factors are required. This section explains the methodology used for the generation of the national-scale landslide inventory and for preparing the factor maps for the national-scale susceptibility assessment.

3.1 Generation of a national-scale digital landslide inventory

The generation of a detailed database is a complicated and long-term process that includes not only recording past natural disasters but also standardization, re-checking, and regular updating of the existing data. It requires collaboration of many different stakeholders (e.g., local authorities, national emergency management organization, media, government organizations, NGOs, and general public) in routinely reporting landslide events, and a nodal agency to check the location of these events and recording them in a geospatial database with relevant attributes. Timely provision of these data to the population and relevant agencies is very important for disaster management in every step of the disaster cycle. The MATRA project (drm.cenn.org) was one of the first efforts to collect, sort, and systematize the databases on natural disasters recorded by various institutions in Georgia.

Historical data from past mass movement events were collected from archives, media, and existing publications. It was important to introduce a unified recording structure for each natural event when entering the information into the database (Table 1). This will make it possible to update, specify, and disseminate information with a minimal loss of time and resources in the future. Along with the collection, systematization, and updating of the database, it is also crucial to provide the information to various central and local governments, as well as the population, to enable them to take necessary action and ensure readiness and timely responses to natural events, which will reduce their consequences. Therefore, it was decided to generate a Web atlas, where the past disaster events can be queried (CENN/ITC 2014).

Risk communication is the main reason for the creation of the Internet-based platform, which was generated using open-source tools, following the OGC standards (Hall and Leahy 2008). Application of Internet technologies provides the possibility to make the database available to the public at large, raise the awareness of the population and local authorities, and improve their preparedness for dangerous/hazardous events. It also facilitates the improvement of the existing database and its regular updating. Any user, through the respective functions, can provide additional information to the web-based platform about new natural hazard events, which, after being checked by experts from the National Environmental Agency, will be used to update the database. Figure 3 shows the web-based interface where a user can indicate the event location, date, damages/losses, upload a photograph or provide a link to video and other significant supplementary information.

In addition, the Web atlas provides the possibility to query information on natural disasters by hazard types and dates on various administrative levels (regional, municipal, and community).

Table 1 Example of a section of the landslide database which was collected for Georgia

ID	Hazard type	Year	Month	Day	Location X	Location Y	Region	District	Community	Village	Information source
1	Landslide	1963	4	1	507,271	4,643,367	Mtskheta-Mtianeti	Tianeti	Sioni	Orkhevi	G. Changashvili "Sioni-Orkhevi Mudflows"
2	Landslide	1984	9	1	456,642	4,603,973	KvemoKartli	TetriTskaro	Chkhikvta	Chkhikvta	Georgian Technical University (GTU)
3	Landslide	1897	10	24	349,365	4,673,044	Imereti	Zestaponi	Boslevi	Boslevi	"Iveria" #221
4	Landslide	1969	4	1	723,962	4,777,151	Apkhazeti	Gulripshi	Ajara	Ajara	Bondirevi
5	Landslide	1975	9	1	312,835	4,741,519	Racha-Lechkhum-KvemoSvaneti	Lentekhi	Lentekhi	Laskadula	Bondirevi
6	Mudflow	1961	5	1	317,292	4,724,111	Racha-Lechkhum-KvemoSvaneti	Tsageri	Tsageri	Tsageri	L. Tsanava "Catastrophic floods, Flashfloods"
7	Mudflow	1961	5	1	315,889	4,741,533	Racha-Lechkhum-KvemoSvaneti	Lentekhi	Lentekhi	Lentekhi	L. Tsanava "Catastrophic floods, flashfloods"
8	Rockfall	1899	3	10	485,367	4,613,443	Tbilisi	Mtatsminda-Krtsanisi			"Iveria" #50
9	Rockfall	1899	3	2	365,449	4,636,194	Samtkhe-Javakheti	Borjomi	Borjomi	Borjomi	"Iveria" #50
10	Rockfall	1889	2	22	470,548	4,613,443	Mtskheta-Mtianeti	Kazbegi	Kazbegi	Kazbegi	"Iveria" #44
11	Earthquake	2009	7	9	374,246	4,633,606	Racha-Lechkhum-KvemoSvaneti	Oni	Pipileti	Pipileti	
12	Flashflood	1997	6	30	310,927	4,726,933	Samtkhe-Javakheti	Adigeni	Zanavi	Zanavi	National Environmental Agency (NEA)
13	Flood	1928	7	1	675,766	4,713,425	Apkhazeti	Gulripshi	Merkheuli	Kvemomerkheuli	"Komunisti"
14	Forest Fire	2007	1	1	452,210	4,601,813	Kvemo Kartli	TetriTskaro	TetriTskaro	Tskluleti	Forest Management Department
15	Frost	1977	4	26	317,292	4,724,111	Racha-Lechkhum-KvemoSvaneti	Tsageri	Tsageri	Tsageri	NEA

Table 1 continued

ID	Hazard type	Year	Month	Day	Location X	Location Y	Region	District	Community	Village	Information source
16	Hail	1996	1	17	447,325	4,637,582	Shida Kartli	Kaspi	Akhalkalaki	Akhalkalaki	NEA
17	Heavy rain	1929	6	14	335,244	4,690,695	Imereti	Tkibuli	Tkibuli	Tkibuli	"SakartvelosRespublika"
18	Snow avalanche	1995	1	1	461,714	4,717,824	Mtskheta-Mtianeti	Kazbegi	Khurtisi	Khurtisi	"Komunisti"
19	Windstorm	1981	1	10	527,611	4,619,798	Kakheti	Sagarejo	Sagarejo	Sagarejo	NEA
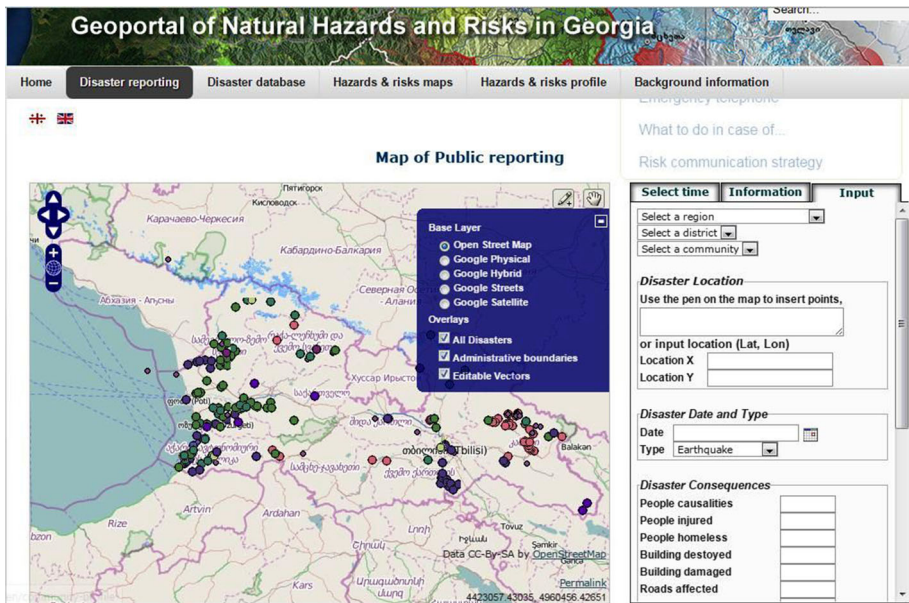
Fig. 3 User interface of the landslide reporting system (drm.cenn.org)

3.2 Generation of factor maps

In order to assess the landslide susceptibility and hazard for the country of Georgia, a number of national-scale datasets were generated related to the historical inventory, the predisposing factors (lithology, faults, altitude, slope steepness, land cover, roads, drainage network, and geomorphology), and the triggering factors (rainfall and earthquakes). Table 2 provides a summary of these data layers.

3.3 Generation of susceptibility and hazard maps

As mentioned above, in the absence of a complete historical inventory, we used spatial multicriteria evaluation (SMCE) for combining a series of spatial criteria, representing the landslide contributing factors, using expert or consensus-based weighting, with the objective to locate the areas where a set of given landslide contributing criteria apply (Castellanos Abella and Van Westen 2007). The method is based on the analytic hierarchy process (AHP), developed by Saaty (1996). This is a structured technique for dealing with quantifiable and intangible criteria that has been applied to numerous application areas, such as decision theory and conflict resolution (Vargas 1990). AHP is widely used in site selection, suitability analysis, regional planning, and landslide susceptibility analysis (Yalcin 2008). The process includes several steps: (1) breaking a complex unstructured problem down into subcomponents, and factors; (2) arrange these factors in a hierarchic order in a so-called decision tree; (3) standardize the factors and assign numerical values to subjective judgments on the relative importance of each factor; and (4) synthesize the judgments to determine the priorities to be assigned to these factors (Saaty and Vargas 2001).

Table 2 National-scale data layers used in the generation of a national-scale landslide susceptibility map

Classification	Data layers	GIS data type	Source	Scale and resolution (m)
Historical mass movements	Landslides	Points	National Environmental Agency	
	Mudflows	Points	National Environmental Agency	
	Rockfalls	Points	National Environmental Agency	
Factor maps	Lithology	Polygons	Geological map of Georgia (Gamkrelidze 2003)	1:500,000
	Faults	Lines	Geological map of Georgia (Gamkrelidze 2003)	1:500,000
	Altitude (DEM)	Raster	ASTER GDEM, resampled to a 100-m grid (http://asterweb.jpl.nasa.gov/gdem.asp)	100 by 100
	Slope steepness	Raster	Generated from the ASTER GDEM	100 by 100
	Land cover	Polygons	Geoland company, State Cadastre, CENN	1:500,000
	Road Network	Lines	National Environmental Agency	1:200,000
	Hydrography	Lines	National Environmental Agency	1:25,000
	Geomorphology	Polygons	Atlas of Georgia, Institute of Geography 1964	1:1,000,000
	Maximum daily precipitation	Raster	Atlas of natural hazards and risks of Georgia 2012	1:500,000
	Peak ground acceleration 10 % probability of exceedance in 50 years	Polygons	Ilia State University, Institute of Earth Sciences (Seismic Monitoring Centre)	1:500,000
	Physical geography	Polygons	Atlas of Georgia, Institute of Geography 1964	1: 1,000,000

In SMCE, the first step is to generate a criteria tree of factors that are considered to contribute to the susceptibility to mass movements. These factors are considered different for landslides, mudflows, and rockfalls. Therefore, three different criteria trees were generated, one for each landslide type, in which the contributing factors are organized in groups. For each of the indicators, a spatial factor (map) was selected, which either contains categorical classes (e.g., lithology) or numerical values (e.g., slope steepness). Once the criteria trees were made, the next step was to normalize the criteria, to convert the data into a range between 0 and 1 where higher values indicate a higher contribution to the susceptibility. This was done by analyzing the various factor maps and classes according to the occurrence frequency of existing mass movement events. The factor maps were overlain with the point maps of the mass movements, and the frequency ratio was calculated (for more information, see, for example, Pradhan and Lee 2010), as the fraction between the number of landslides in the factor class in relation to the total number of landslides in the whole area, and the fraction of the factor class of the total study area. If the fraction of landslides was considerably larger than the fraction of the area, the class was considered important for contributing to the susceptibility. Given the incompleteness of the mass movement inventory, which might lead to unrealistic values of the frequency ratios

when compared with expert knowledge, the actual standardization was done using expert-based weighting, taking the frequency ratio values only as guidance.

The analysis can also contain constraints, which are factors that determine where the susceptibility will be low irrespectively of the other factors used. The most important constraints used for the national landslide susceptibility assessment are flat or very gently sloping areas and water bodies. The next step consisted in the weighting of the various factors by using pairwise comparison, or rank-ordering methods. This was done first by comparing the factors within the same group and then by comparing the importance of the different groups of factors.

For implementing the model, the SMCE module of the ILWIS-GIS was used (ILWIS 2014). The output is a composite index map, which indicates the landslide susceptibility values on a scale ranging from 0 (very low) to 1 (very high). After the integration of the factor maps also two triggering factors were taken into account: earthquakes and rainfall. Peak ground acceleration was used as indicator for the earthquake trigger and maximum daily precipitation as the rainfall-related trigger (see Table 2). Three susceptibility maps were generated, for landslides mudflows and rockfall. The final score maps were classified into three classes of susceptibility (high, moderate, and low). The procedure is summarized in Fig. 4.

The next step was the conversion of the susceptibility classes into hazard classes. Hazard is defined as the probability of occurrence of a potential damaging phenomenon, with a certain magnitude, within a given period of time and within a given area (Varnes and IAEG 1984). In this national-scale landslide study, we are not able to express the hazard exactly according to this definition, as we do not have enough information on landslide magnitude and also no clear relation between magnitude and frequency. Therefore, we developed a proxy and expressed the hazard expressed as the spatial probability that a certain area (a pixel of 1 ha) is expected to be impacted by one of the

Fig. 4 Procedure for the application of spatial multicriteria evaluation for landslide susceptibility assessment
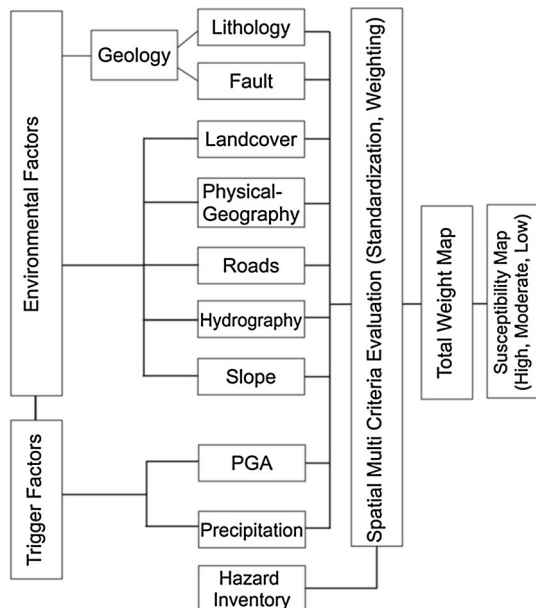
landslide types within a given reference period. In this study, we used a reference period of 50 years, as this is the period over which we were able to collect historical information. We use this to make an estimation of the occurrence of hazardous phenomena in the coming 50 years. In order to estimate the spatial probability of occurrence, we analyzed the historical catalogues of the various hazard types and extracted the number of events that have occurred in the last 50 years. We used the number of events that have occurred in the entire historic database as an estimation of the number likely to occur in the coming 50 years. This was done because the number of events in the database is probably a large underestimation of the actual number of events that have happened (due to incompleteness of the historical inventory). We assumed also that 90 % of the events occurred in the high hazard zones, and 10 % in the moderate zone, and very few events in the low hazard zones. As we did not have polygon maps for past events, we then estimated the area affected by a single mass movement event, as the average size of an individual landslide, mudflow, or rockfall phenomena. The information for this was obtained from the limited polygon-based landslide data, from expert judgement and from the literature. The average area of an individual mass movement event was estimated to be 5000 m^2 for landslides, 4500 m^2 for mudflows, and 800 m^2 for rockfall events. We multiplied the number of expected mass movements with their average size and divided this by the total area of the susceptibility classes. The resulting value expresses the spatial probability that an area within one of the susceptibility classes might be impacted by a specific landslide type in a reference period of 50 years.

## 3.4 Generation of exposure and risk maps

The next step was to estimate landslide risk in a semiquantitative manner. Whereas a lot of attention has been given in the literature to landslide susceptibility assessment, resulting a well-established methods, landslide risk assessment is still in the experimental phase, especially for medium to small scales, due to several problems, such as determining temporal probability of landslide occurrence and physical vulnerability of the elements at risk exposed (van Westen et al. 2006; Corominas et al. 2014). Risk was defined by Varnes and IAEG (1984) as "the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period." When dealing with physical losses, (specific) risk can be quantified as the product of vulnerability, cost or amount of the elements at risk, and the probability of occurrence of the event with a given magnitude/intensity (van Westen et al. 2006).

The procedure for assessing the potential losses for mass movements is part of a larger multihazard risk project in Georgia, which resulted in the production of a national atlas (CENN/ITC 2014). Figure 5 provides the general framework of the method used.

The method used is based on the generally accepted conceptual equation of risk:

$$R = H \times V \times E \tag{1}$$

in which R represents the expected losses in a period of 50 years calculated for a given administrative unit of the country. The hazard (H) expresses the spatial probability that a given basic unit of 1 ha (which is the pixel size used in this study) might be affected by a certain type of mass movement in the coming 50 years. V represents the physical vulnerability of the various types of elements at risk, which is given as a value between 0 and 1. Finally, E represents the quantification of the exposed elements at risk per hazard type, hazard class, and administrative unit.
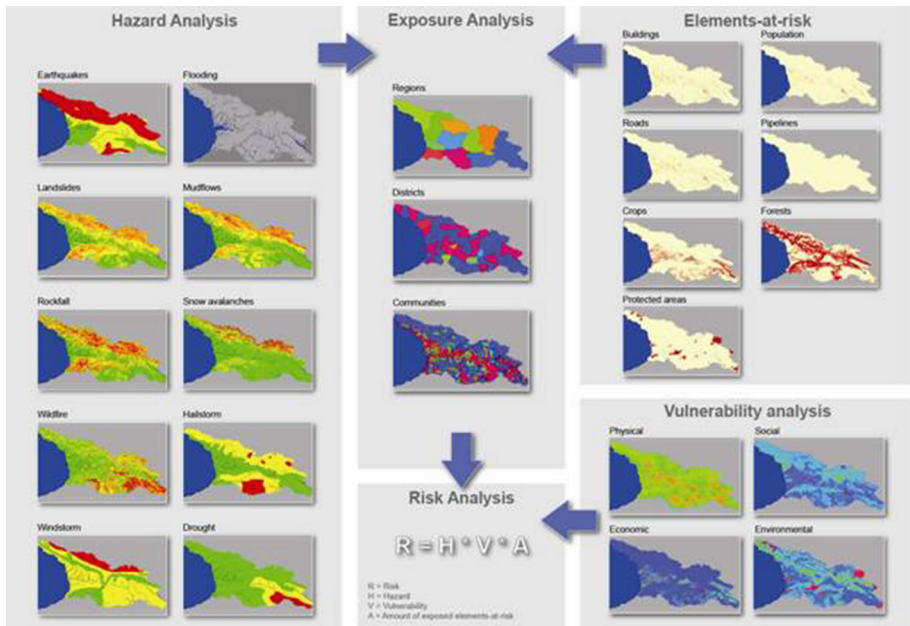
Fig. 5 Conceptual flowchart of the national multihazard risk assessment method for Georgia, of which the mass movement hazard and risk assessment was one component (CENN/ITC 2014)

First, we analyzed the exposure of different elements at risk for each of the landslide hazard types (landslides, mudflows, rockfalls). The following exposure types were used: buildings (number of buildings), population (number of people), roads (length of paved roads in kilometers), pipelines (length of oil and gas pipelines in kilometers), natural parks (area in hectares), forests (area in hectares), and crops (area in hectares).

This was done by overlaying the hazard maps for the three landslide types with the element-at-risk maps, and by administrative unit maps in a GIS and calculate the number of exposed elements per hazard class (high, moderate, and low) within each administrative unit. Three levels of administrative units were used: communities, districts, and regions. The country is subdivided into 12 regions, consisting of 73 districts (municipalities) and 1630 communities.

The next step was the estimation of the physical vulnerability of the elements at risk. Due to a lack of hazard intensity data, vulnerability cannot be described in a national-scale landslide risk analysis as a curve relating intensity with expected damage. Therefore, hazard classes were used as a proxy for intensity classes, and single values were used for each combination of landslide type, hazard class, and element-at-risk type. We estimated the degree of loss to a single element at risk, given a particular type of mass movement, and hazard class and represented these as values between 0 and 1. These values were obtained after discussions with landslide experts in Georgia from the National Environmental Agency and from the literature research (e.g., Leone et al. 1996; AGSO 2001; Glade 2003; Cascini et al. 2005; Glade and Elverfeldt 2005; Van Westen et al. 2006; Remondo et al. 2008; Fuchs et al. 2007).

Finally, the risk was calculated by multiplying the hazard (spatial probability) with the physical vulnerability and the quantification of the exposed elements at risk for each

combination of mass movement type, hazard class, element-at-risk type, and administrative unit level.

4 Results and discussion

4.1 Landslide inventory data

Historical data from past events regarding, mudflows, landslides, and rockfalls were collected from the National Environmental Agency, the Forest Management Department, and various other archives, as well as from mass media records, such as the Rustavi-2 tv-channel Web site (www.rustavi2.com), newspapers, monographs, and scientific publications. The earliest recorded dates were 1887 for landslides, 1776 for mudflows, and 1928 for rockfalls. However, data were very scarce for the period older than 30 years. Table 3 presents a summary of the landslide occurrences and associated losses from the landslide database for the period 1995–2012.

As shown in Table 3, a large number of events were recorded: 6377 landslides and 2155 mudflows. However, for most of these, no exact location was known. In order to map and digitize the landslide, mudflow, and rockfall information, a team of experts from the National Environmental Agency was able to extract information on the landslide location

Table 3 Recorded landslides and mudflows for the period between 1995 and 2012

Year	Landslides		Mudflows		Elements at risk affected	
	Number of events	Casualties	Number of events	Casualties	Damaged agricultural lands (ha)	Number of settlements
1995	670	6	250	12	179	274
1996	610	3	165	5	232.3	403
1997	871	2	335	7	336.5	458
1998	543	5	173	6	229.6	370
1999	56	1	27	–	137.8	157
2000	65	1	23	–	162.2	240
2001	75	–	26	–	127.5	191
2002	69	1	23	2	147.9	203
2003	71	3	28	–	106.5	90
2004	949	4	258	2	16,289.2	755
2005	603	–	155	4	7589.6	473
2006	356	1	63	–	3172.5	531
2007	136	–	104	–	1389.1	269
2008	311	–	126	8	1387.7	392
2009	323	1	193	3	8232.3	521
2010	250	3	81	2	1155	366
2011	94	3	37	8	652	181
2012	325	1	88	5	1255	239
Total	6377	35	2155	64	42,781.7	6113

from the analogue archives for about 900 landslide events, 350 mudflow events, and about 100 rockfall events for the period from 1995 to 2011 (see Table 1; Fig. 3). For the majority of the historical events, the archived data have been lost, in the transition period after the independence. Figure 6 presents the mass movement inventory maps by districts.

A large number of settlements, agricultural lands, roads, oil and gas pipeline routes, high-tension power transmission towers, hydropower and water treatment utilities, mining, and tourist complexes have been affected by landslides according to the landslide database. Almost all landscapes and geological zones represent some degree of landslide hazard, with the lowest values along the Black Sea and the eastern region of Kakheti and the highest values in the mountainous zones, where the extreme activity of landslides and mudflows often required evacuation of the population in certain problem zones. In the second half of the twentieth century, this resulted in the complete evacuation of tens of villages in mountainous regions and the resettlement of 60,000 households from damaged sites. In 6113 events, landslides and mudflows affected settlements, and 42,781.7 ha of land and 99 casualties have been reported since 1995 (Table 3).

Until the end of the twentieth century, the extreme activity of mass movement processes seemed to follow a certain cycle, which was repeated, on average, once every 3–5 years for minor events and once every 8–11 years for larger events. However, since the 1990s, the activity of these processes has increased, and they now take place almost every year, resulting in an increase in the losses. This increase might be related to a better landslide reporting system, although also other factors may play a role. After independence and the transition from a communist to a capitalist system, the privatization of land lead to more conflicting land uses and less governmental control on land-use practices.

4.2 Generation of factor maps

For the susceptibility analysis for landslides, mudflows, and rockfalls, a number of factor maps were prepared at the national level, using raster maps with a cell size of 1 ha. The factor maps can be differentiated in topographic, geological, and land-cover factors, and in triggering factors related to rainfall and earthquakes (Fig. 7).

4.2.1 Topographic factors

Topography is one of the most important factors in landslide susceptibility assessment (Castellanos Abella and Van Westen 2008). In the literature, slope length, slope convexity, slope direction (aspect), and slope steepness are all taken into account, while the latter is mostly used (Dai et al. 2002). For a national-scale analysis with a cell size of 1 ha, the other topographic factors are considered less relevant. Therefore, a slope steepness map was generated from the digital elevation model derived from ASTER. National-scale digital elevation models can be derived from different sources, such as from existing topographic maps and LiDAR and from worldwide DEMS such as ASTER, SRTM, and WorldDEM. We have decided to use ASTER data because this product proved to be of a better quality for Georgia than the SRTM data, whereas WorldDEM or LiDAR data were not available to us. Slope steepness calculated from such general digital elevation models
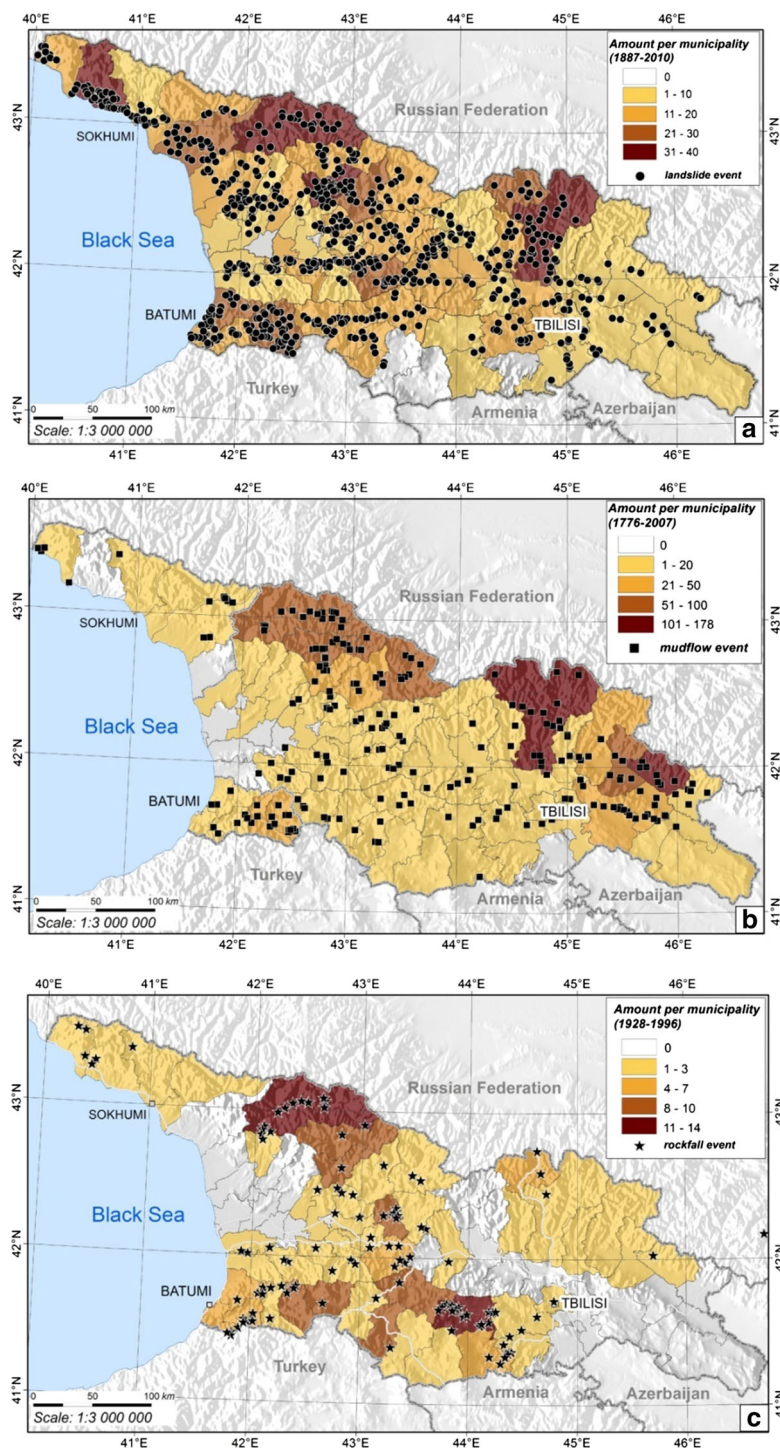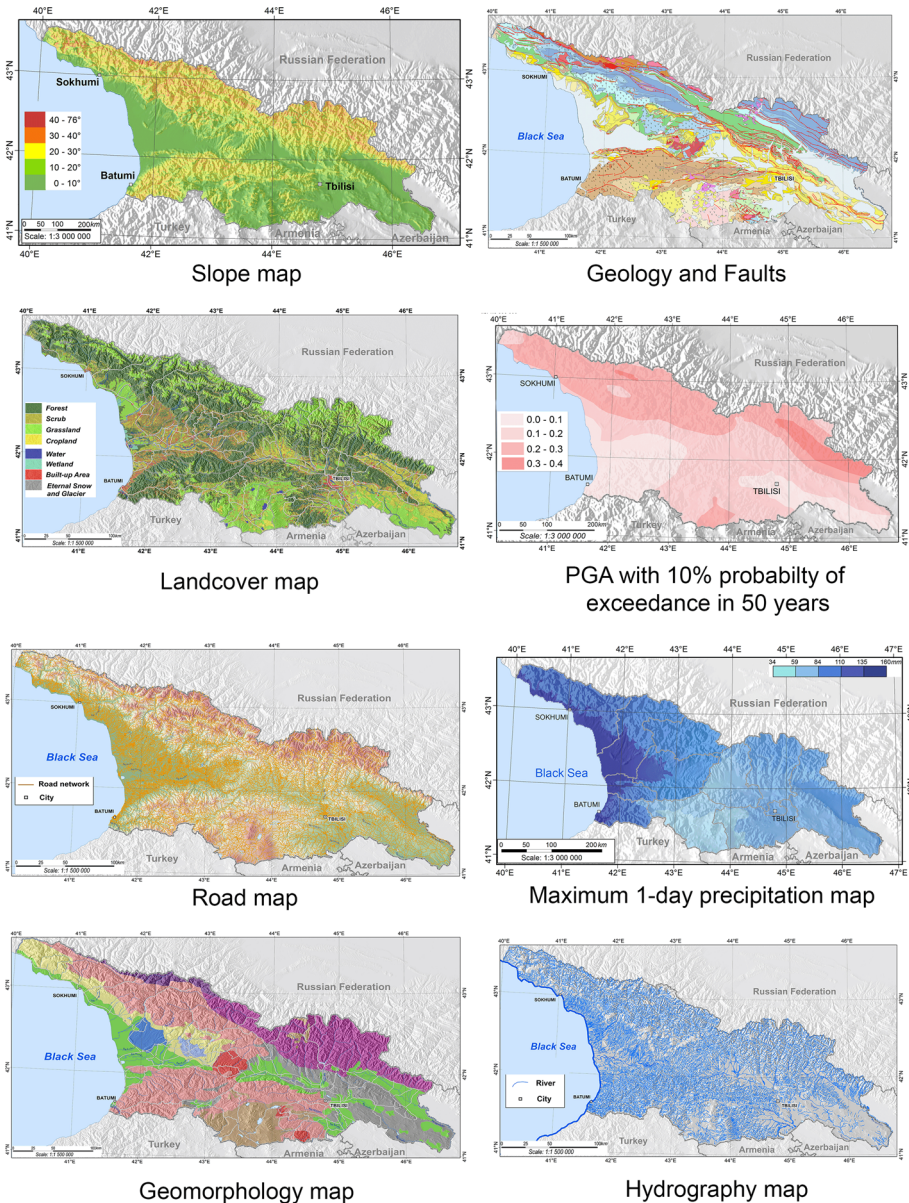
Fig. 7 Factor maps used in the landslide susceptibility assessment. For the geological and geomorphological maps, no legends can be shown as there are too many units. Higher-resolution maps with complete legends can be downloaded from: http://drm.cenn.org/paper_atlas/RA-part-2.pdf

tend to present a flattening trend, as compared to slope steepness generated from higher-resolution digital elevation models derived from interpolating digital contour lines. However, such a DEM was not available for the entire country. Besides, the relation obtained from overlaying the available landslide points with the ASTER-derived slope

steepness map, even though it may be less steep than in reality, gives an indication of the ASTER-derived slope ranges for susceptibility assessment.

The categories of steepness values for analyzing landslide susceptibility should approximate those of the slopes present in the study area. Too many classes will make it difficult to identify slopes critical to landslide occurrence and too few will be equally useless (OAS 1991).The slope map of the study area was divided into nine slope classes.

Based on the literature study (Berti et al. 2000; Catani et al. 2005; Dai et al. 2002; Thiery et al. 2007), standardized values for slope classes were selected for the slope classes in this analysis, ranging from 0 (low) to 1 (high susceptibility) (see Table 4).

4.2.2 Geological and geomorphological factors

Lithological units and soil types also have an important control on landslide occurrence frequency. The geological map of Georgia with a scale of 1:500,000 was used as the basis for the susceptibility assessment. The map contains 145 lithological units, which were each assigned a score related to their susceptibility ranging from 0 to 1.

An important factor in the triggering of landslides is seismicity. Earthquake-triggered landslides are common and may cause massive damage in the tectonically active Caucasus. The distance from major faults was also chosen as an important criterion. There are several major faults in Georgia, and we separated the active faults which are capable of producing earthquakes with a magnitude above 6, as these can cause landslides (Gorum 2013). These faults were extracted from the national Geological map (Gamkrelidze 2003), and buffers were generated ranging from 1 to 50 kilometers distance from active faults.

Another indicator map used for earthquake-triggered landslides was a map of the peak ground acceleration (PGA) with a 10 % exceedance probability in 50 years which was generated in the national earthquake hazard assessment project (Ilia State University, Institute of Earth Sciences).

The geomorphological situation is also very important for the susceptibility assessment, as landslides are common in certain denudational and denudational–structural units, and less common in others. Therefore, the available national geomorphological map which was made for the national Atlas of Georgia (1964) was reclassified into 10 zones. These zones

Table 4 Frequency ratios and standardized values used for landslides, mudlfows, and rockfalls	Slope gradient classes	Landslides		Mudflows		Rockfalls	
		FR	SV	FR	SV	FR	SV
	0–10	0.3	0.1	0.1	0.0	0.0	0.0
	10–20	1.3	0.8	0.8	0.4	0.0	0.0
	20–30	2.1	1.0	0.7	0.4	0.4	0.4
	30–40	0.8	0.5	2.3	0.6	0.7	0.9
	40–50	2.5	0.2	6.4	0.4	3.6	0.9
	50–60	5.3	0.1	57.5	0.3	56.5	0.9
	60–70	111.0	0.1	437.2	0.1	3801.7	1.0
	70–80	0.0	0.1	0.0	0.1	20.7	1.0
FR frequency ratio, SV standardized values	80–90	0.0	0.1	0.0	0.0	0.0	1.0

were standardized for landslides, mudflows, and rockfalls. The geomorphological map is presented in Fig. 7.

4.2.3 Land-cover factors

Human activities such as slope cutting and filling along roads and the removing of forest vegetation are well-known factors for landslide occurrence (Glade 2003). Much work has been done to evaluate the effect of logging and deforestation on landslides (e.g., Furbish and Rice 1983; Ziemer et al. 1991). Table 5 shows the standardized values that were used based on the literature and expert weighting by several experts.

Road construction has a major influence on landslide occurrence, especially in sloping areas where road cuts are made. In this study, roads that are located on areas with slopes steeper than 20 degrees are taken into account with a standardized value of 1.

4.2.4 Meteorological and hydrological factors

Daily rainfall data were used from individual meteorological stations, and the average annual rainfall was interpolated over the entire country using an interpolation method (Co-Kriging) that incorporates height as a factor. The daily data were also used to generate a map of possible maximum 1-day precipitation for a 10-year return period as the input in the susceptibility assessment.

To represent the effect of river erosion, a map was generated showing the areas close to streams that have a slope steeper than 20 degrees.

Table 5 Frequency ratios and standardized values assigned to the land-cover types

Land-cover type	Landslides		Mudflows		Rockfall	
	FR	SV	FR	SV	FR	SV
Bare glacial moraine	0.1	0.4	8.4	0.4	6.4	0.6
Badland	1.0	0.5	14.5	0.4	77.8	1.0
Rocky	2.6	0.7	32.4	0.9	103.3	1.0
Dense forest	1.7	0.2	0.1	0.2	0.0	0.1
Open forest	3.4	0.3	7.4	0.2	2.6	0.1
Park	1.0	0.3	0.0	0.3	0.0	0.3
Orchard	1.2	0.4	1.0	0.4	3.0	0.3
Scrub	1.8	0.4	0.6	0.4	0.7	0.3
Urban park	1.7	0.5	82.0	0.5	20.7	0.6
Vineyard	1.8	0.6	2.9	0.4	0.9	0.3
Grass land	8.4	0.8	0.1	0.8	0.0	0.4
Island	1.3	0.7	7.5	0.4	0.0	0.4
Small city	8.4	0.9	13.9	0.9	13.5	0.9
Agriculture land	6.3	0.8	6.8	0.8	7.74	0.4
Bare river sand	1.7	0.2	52.9	0.9	46.5	0.5
Settlement area	17.1	1.0	5.4	1.0	7.1	0.9
Urban area	38.4	1.0	290.3	1.0	206.6	0.9
Cemetery	1.1	1.0	22.8	1.0	27.5	0.9
Railway	1.0	1.0	27.3	1.0	0.0	0.9

FR frequency ratio, *SV* standardized values

## 4.3 Landslide susceptibility and hazard assessment

After the selection of the indicator maps and their standardization, the next step was to define the relative importance of the indicators. The weights used in the criteria trees for the assessment for landslides, mudflows, and rockfalls are presented in Table 6.

The analysis was carried out using pairwise comparison of factors, in which the users indicate the difference in importance for each combination of the factors. This qualitative information is transformed by the system into weight values that add up to one. It is generally confirmed in the landslide literature that topography contributes most in mass movements. As shown in Table 6, slope steepness and lithology are considered the most important factors. Based on the weights' assignment, the susceptibility maps were generated by multiplying the standardized values with weights per pixel followed by adding up the resulting maps. The final weights of the resulting maps ranged from 0.05 to 0.92 (landslides), from 0.36 to 0.93 (mudflow), and from 0.15 to 0.88 (rockfall). The hazard maps were classified into three categories based on the histogram of the final weight maps: high, moderate, and low (see Fig. 8). The histograms of the final weight maps were used to evaluate the percentages of the country having a certain weight. Also, success rate curves were used in the classification of the weight maps. As a result, we classified the maps into three classes. The ranges of values for the three susceptibility classes are given in Table 7, along with the information on the size of the classes and the number of mass movement events per class.

The susceptibility maps were converted into hazard maps by estimating the spatial probability that a unit area of 1 ha may be impacted by one of the landslide types within a reference period of 50 years. In order to estimate the spatial probability as the landslide density, we analyzed the historical catalogues of the various landslide types and extracted the number of events that occurred in the past 50 years. The results are shown in Table 8. The minimum number of landslides per susceptibility class corresponds to the data for which the spatial location was known, and which are stored in the digital landslide inventories (Fig. 6). The maximum number of landslide events per susceptibility class is based on all collected historical data including those for which no spatial information is available (see Table 3). This was done because the number of events in the spatial database is probably a large underestimation of the actual number of events that have happened (due to the incompleteness of the historical inventory). The average area of an individual mass

Table 6 Weights applied for the spatial multicriteria evaluation for the susceptibility assessment for landslides, mudflows, and rockfalls

Factor maps	Landslides	Mudflows	Rockfalls
Slope steepness	0.16	0.21	0.2
Landslide buffer	0.14	0.11	0.07
Lithology	0.16	0.12	0.15
Land cover	0.11	0.08	0.11
Geomorphology	0.06	0.05	0.06
Physical geography	0.03	0.05	0.06
Distance from faults	0.11	0.07	0.12
Peak ground acceleration	0.08	0.03	0.09
Buffer around roads	0.06	0.02	0.06
Buffer around rivers	0.06	0.16	0.01
Precipitation	0.03	0.1	0.07
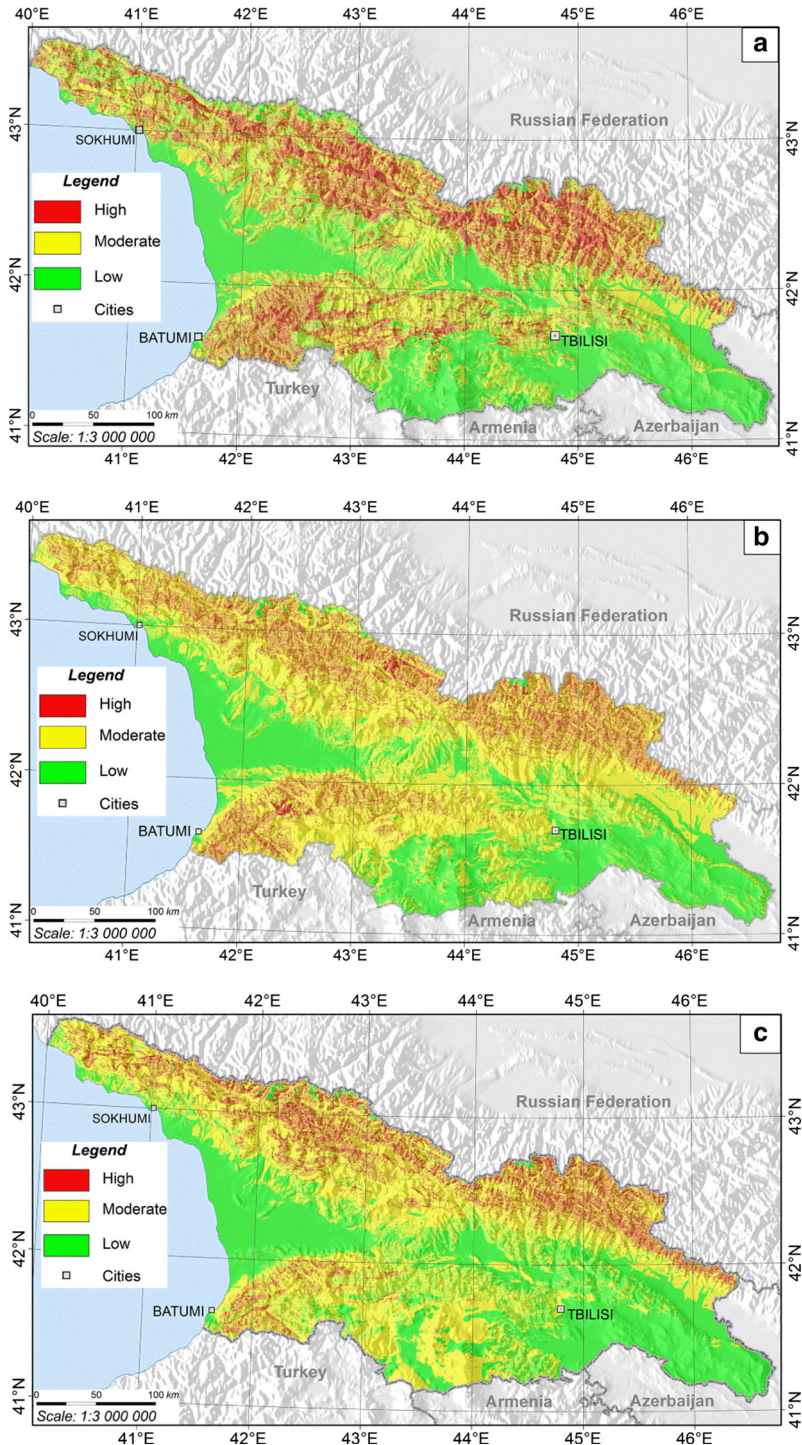
◄ **Fig. 8** Susceptibility maps of Georgia for **a** landslides; **b** mudflows; and **c** rockfall. Higher-resolution maps can be downloaded from http://drm.cenn.org/paper_atlas/RA-part-3.pdf

Table 7 Summary statistics for the landslide susceptibility classes for the three types of mass movements

Mass movement type	Susceptibility class	Range of values	Area (km^2)	% of country	Number of mapped events
Landslides	High	0.69–0.92	15,565	22	680
	Moderate	0.34–0.69	28,247	41	76
	Low	0.05–0.34	25,844	37	5
Mudflows	High	0.81–0.93	8621	12	383
	Moderate	0.56–0.81	39,294	56	41
	Low	0.36–0.56	21,741	31	5
Rockfalls	High	0.67–0.88	8047	12	92
	Moderate	0.44–0.67	34,988	50	10
	Low	0.15–0.44	26,621	38	0

The range of values indicates the minimum and maximum values of the composite index map resulting from the SMCE analysis used for classification. The area of each class is shown and the percentage of the country. And finally also the number of mapped mass movement events per class

movement event was estimated from the available digital landslide data for which also the extent of the landslide was available. The average values were 0.5 ha for landslides, 2.5 ha for mudflows, and 800 m^2 for rockfall events. These values were multiplied with the (minimum and maximum) number of landslide events to obtain the total (minimum and maximum) area that would be affected by landslides in a 50-year period. These values were divided by the total area of the susceptibility classes. This resulted in the minimum and maximum values for the spatial probability that a given pixel of 1 ha within the high susceptible zone would be affected by landslides within a 50-year period ranging from 2.18E−04 to 1.84E−03. For mudflow, these values range between 1.11E−03 and 5.62E−03, and for rockfall between 9.15E−06 and 7.72E−05. The spatial probability values for moderate susceptibility classes are much lower, and those for low susceptibility classes are almost 0.

The probability values are generally quite small, given the large size of the high and moderate hazard areas, and the limited number of events. If a better modeling approach could be used for the landslide susceptibility assessment, this would reduce the surface areas of the high and moderate classes considerably and give higher spatial probability values.

4.4 Landslide risk assessment

As indicated in Sect. 3.4, the risk assessment contained three steps: vulnerability assessment, exposure analysis, and risk calculation.

One of the most important components of the risk assessment is the exposure analysis, which was calculated by overlaying the three landslide hazard maps with administrative unit maps and with the following element-at-risk maps:

Table 8 Data used for the estimation of spatial probabilities for the classes of the three landslide susceptibility maps

Mass movement type	Susceptibility class	Area (km²)	Number of events		Single event area (km²)	Total event area (km²)		Spatial probability	
			Minimum	Maximum		Minimum	Maximum	Minimum	Maximum
Landslides	High	15,565	680	5739	0.005	3.400	28.697	2.18E−04	1.84E−03
	Mod	28,247	76	574	0.005	0.380	2.870	1.35E−05	1.02E−04
	Low	25,844	5	64	0.005	0.025	0.319	9.67E−07	1.23E−05
Mudflows	High	8621	383	1940	0.025	9.575	48.488	1.11E−03	5.62E−03
	Mod	39,294	41	194	0.025	1.025	4.849	2.61E−05	1.23E−04
	Low	21,741	5	22	0.025	0.125	0.539	5.75E−06	2.48E−05
Rockfall	High	8047	92	776	0.0008	0.074	0.621	9.15E−06	7.72E−05
	Mod	34,988	10	78	0.0008	0.008	0.062	2.29E−07	1.78E−06
	Low	26,621	0	9	0.0008	0.000	0.007	0.00E+00	2.59E−07

See text for explanation

- *Buildings*: The building map was generated using a national digital cadastral database, which was generated some years ago in a World Bank funded project (World Bank 2010). The project did not cover the entire country, so we had to use data derived from satellite image interpretation for the missing regions. We were able to extract the buildings from it as points in three different occupancy types (residential, non-residential, and others). We used these to calculate the number of buildings per pixel of 1 ha. A join frequency analysis in GIS was made between the building map, the three hazard maps, and the administrative unit map. We calculated the exposed number of buildings for each combination of hazard class, landslide type, and administrative unit.
- *Population*: The building map derived from the cadastral data was used in combination with population statistics at the district level, to model the population distribution. We only used the residential buildings and calculated the average number of persons per house within each district, by dividing the number of people per district by the number of houses. We then multiplied this average value by the number of houses per pixel of 1 ha to obtain the number of people per hectare, the number of houses, household map was generated, using population statistics per administrative unit, which were then redistributed on the basis of the type and number of buildings per hectare. We calculated the exposed number of people for each combination of hazard class, landslide type, and administrative unit.
- *Road network*: We obtained digital road maps from the National Environmental Agency and used these to calculate the length of exposed roads (highways and paved roads) for each combination of hazard class, landslide type, and administrative unit. We did the same for the network of oil and gas pipelines, which are very important for Georgia.
- We obtained digital maps of *Natural parks, forests and cropland* from the National Environmental Agency. Maps of forest and crops were obtained from the national cadastral database and from image classification for the parts of the country where no cadastral information was available. These maps were used to calculate the area (in hectares) of parks, forests, and crops for each combination of hazard class, landslide type, and administrative unit.

Further description of the methods for generating the element-at-risk maps can be found in the national multihazard risk atlas of Georgia (Van Westen et al. 2012). The results for the exposure analysis are shown in Table 9. Obviously, these exposure values are high, as they refer to all elements at risk that are located within the high, moderate, and low hazard classes. For estimating the actual expected losses, these exposure values should be multiplied with the spatial probability of mass movement occurrence within the three hazard classes and with the physical vulnerability.

For the physical vulnerability assessment, we used single vulnerability values for each combination of the element-at-risk type, landslide type, and hazard class. These values were obtained after discussions with landslide experts in Georgia from the National Environmental Agency and from the literature research. The values reported in Table 10 are expert-based and represent the expected degree of loss for different elements at risk exposed to the three types of mass movements, and in three classes of susceptibility.

The vulnerability values were estimated for the main types of elements at risk taken into account within this study: buildings, population, roads, pipelines, lines, forests, crops, and protected areas. The physical vulnerability values differ for the three types of mass movements as they may cause different degree of loss to the same element at risk. The values also differ considerably among the types of elements at risk. The values for

Table 9 Calculated exposure for the three landslide types and different elements at risk

Mass movement type	Hazard class	Exposed elements at risk to mass movements						
		Buildings (number)	Population (number)	Road network (km)	Pipelines (km)	Protected area (ha)	Forest (ha)	Crops (ha)
Landslides	High	124,069	466,060	3092	99	123,184	748,382	30,716
	Mod	549,343	2,012,446	12,693	271	195,847	1,631,863	182,889
	Low	714,699	2,507,327	16,833	711	132,545	597,980	599,752
Mudflows	High	12,167	36,184	354	14	92,206	503,223	3295
	Mod	554,876	1,871,537	13,748	422	269,187	2,141,527	259,703
	Low	821,068	3,078,112	18,515	645	90,183	333,475	550,359
Rockfalls	High	2712	8958	156	8	94,434	386,866	1084
	Mod	557,501	2,163,922	13,341	315	233,846	1,785,726	207,363
	Low	827,898	2,812,953	19,120	758	123,296	805,633	604,910

Table 10 Estimated physical vulnerability values for the main types of elements at risk and for the three landslide types

Mass movement type	Susceptibility class	Estimated physical vulnerability values						
		Buildings	Population	Transport	Pipelines	Forests	Crops	Protected area
Landslides	High	1	0.07	1	1	0.5	1	0.5
	Mod	0.5	0.05	0.8	0.5	0.1	0.8	0.1
	Low	0.01	0.01	0.5	0.01	0.02	0.5	0.02
Mudflows	High	1	0.1	1	1	0.5	1	0.5
	Mod	0.5	0.05	0.5	0.5	0.1	0.8	0.1
	Low	0.01	0.01	0.3	0.1	0.02	0.5	0.02
Rockfall	High	1	0.08	1	1	0.5	1	0.5
	Mod	0.5	0.05	0.9	0.5	0.1	0.8	0.1
	Low	0.01	0.01	0.8	0.1	0.02	0.5	0.02

buildings for example are higher than those for population, as they may be more protected inside buildings, and also would often be able to escape when an event takes place. The values are become lower from the high hazard to the low hazard class, as we assume that the intensity of the events in the high hazard class will be more.

The last step in the analysis was the calculation of the expected losses within a 50-year time period. This was done by multiplying the amount of exposed elements at risk per mass movement type and hazard class with the spatial probability of the particular mass movement hazard class, and the physical vulnerability of the elements at risk for that given combination of mass movement type and hazard class. The loss values for the three hazard classes were summed. The results are shown in Table 11. As can be seen, the calculated loss values seem to be very low. This is partly due to the fact that we used the spatial probability values calculated using only the 900 landslide events, 350 mudflow events, and about 100 rockfall events for which the location was known. To evaluate the effect of using a more complete landslide inventory on the resulting mass movement losses, we used also the more complete inventory (with 6377 landslides and 2155 mudflows), even though we did not know their location, and were not able to determine in which hazard class they occurred. Therefore, we assumed that 90 % of them occurred in the high hazard class, 9 % in the moderate, and 1 % in the low hazard class. We recalculated the losses using the spatial probabilities obtained from this larger landslide set. The results are shown in Table 11. As can be seen, the losses are now much higher, and the number of casualties is in the same order as the values obtained from the past inventory (Table 3). To illustrate the effect that the spatial probability values have on the losses, we also calculated a third scenario, in which we assumed much higher values: 0.01 for high hazard (which means that in 50 years, 1 % of all high hazard areas might experience a landslide), 0.001 for moderate hazard, and 0.0001 for low hazard. The results are also shown in Table 11.

5 Conclusions and recommendations

The resulting risk values are only approximations and contain a high degree of uncertainty as the analysis is based on a number of assumptions, related to the estimation of the hazard zones, the estimation of the impacted area, spatial probability, vulnerability, and exposure. Even though the results are highly uncertain, they do allow the comparison of the impact of the various types of hazards and the order of magnitude of expected impacts.

The resulting loss values in Table 11 show large differences between mass movement types, between element-at-risk types, and between the three scenarios of spatial probability used. It is clear that spatial probability is a very important component in this calculation and is determined by the completeness of the landslide inventory and the hazard classi-fication. A precise delimitation of the most hazardous areas in the susceptibility assessment allows to narrow down the zones where landslides are expected to occur and to increase the spatial probability significantly. The high hazard classes in our landslide susceptibility maps were still too large, resulting in rather low spatial probabilities. Reducing the size of the high hazard classes turned out to be difficult, as this class should contain the majority of the landslide. Landslide susceptibility assessment is generally an iterative procedure where a compromise should be found between narrowing down the areas with the highest pre-dicted susceptibility, which contains most of the historic landslides. Therefore, with the current available factor maps, it was not possible to narrow these more.

Table 11 Calculated losses for the three landslide types and different elements at risk for a period of 50 years

Mass movement type	Range	Expected losses in 50 years						
		Buildings (nr)	Population (nr people)	Road network (km)	Pipelines (km)	Forests (ha)	Crops (ha)	Protected area (ha)
Landslides	Minimum events[a]	31	9	0.76	0.02	84	9	14
	Maximum events[b]	257	71	6.35	0.21	707	75	116
	Larger spatial probability[c]	1515	427	37.27	1.21	3905	453	636
Mudflows	Minimum events[a]	21	7	0.58	0.02	285	11	52
	Maximum events[b]	103	33	2.89	0.11	1442	51	263
	Larger spatial probability[c]	399	130	10.41	0.35	2730	241	488
Rockfall	Minimum events[a]	0	0	0.00	0.00	2	0	0
	Maximum events[b]	1	0	0.02	0.00	15	0	4
	Larger spatial probability[c]	306	115	8.23	0.36	2113	177	496
Total	Minimum events[a]	52	15	1.34	0.05	371	20	66
	Maximum events[b]	361	104	9.26	0.32	2164	127	382
	Larger spatial probability[c]	2220	672	55.91	1.92	8748	871	1619

Losses are calculated for three scenarios: [a] using only the landslide inventory for which the spatial location was known; [b] using the larger landslide inventory including those events for which the spatial location was not known; [c] using fixed spatial probabilities indicated in the text

The effect of uncertainties in physical vulnerability is much smaller than the ones for spatial probability, and the effect of uncertainties in spatial probability results in differences in losses that are several orders of magnitude larger than those for vulnerability. Nevertheless, when spatial probability values are improved, it is also important to further focus on the improvement of physical vulnerability values, by evaluating the degree of loss for the historical landslides. Also for this a good landslide reporting system is essential.

Due to several reasons, Georgia still lacks a sufficiently complete landslide inventory covering the entire country that would allow the incorporation of statistical methods into the national landslide susceptibility assessment, and the correlation of landslide dates with precipitation and earthquakes in order to be able to convert the susceptibility into hazard maps. As there are also no event-based landslide inventories available, the generation of reliable rainfall thresholds is still not possible. The implementation of a national web-based system for a landslide reporting system coupled with a systematic survey of new landslides by the National Environmental Agency, and the digitizing of the archived data, could be the way forward to change this situation in the near future, if the various stakeholders are committed to it.

In the current version of the landslide susceptibility and hazard assessment, only the initiation of mass movements was taken into account. Future work should also incorporate regional-scale runout assessment, although this would be more relevant when zooming into larger scales than the national scale.

The results related to the expected losses shown in this paper are only indicative as the estimation was based on a number of assumptions, of which the main ones are:

- The hazard maps are general ones and consist only of three classes, and are made using simplified methods given the availability of data at a national scale.
- The spatial probability estimation depends to a large degree on the detail of the hazard estimation (the smaller the high hazard units are, the better prediction will be) and on the data of historical occurrences from the incomplete historical database.
- The vulnerability data are also a general approximation based on expert judgement and do not take into account the different degrees of intensity and the different classes of elements at risk (e.g., building types).
- The specific effects of earthquakes on the landslide susceptibility have not been taken into account. More research is needed to provide better earthquake-induced landslide susceptibility maps for Georgia.

The resulting landslide susceptibility maps are not static, as a number of indicators have a temporal variability, and the landslide susceptibility map should therefore be updated regularly.

Even though such landslide susceptibility, hazard, and risk maps at a national scale remain rather general, they are useful for provinces and municipalities for ranking their areas in order of importance for landslide risk reduction measures. The results have been used in web-based multihazard risk application where administrators can download hazard and risk reports for their own administrative areas at community, district, and regional levels (see: http://drm.cenn.org/index.php/en/community-profile).

This study was one of the first steps in the national landslide risk assessment, and it is necessary to follow it up with studies at a larger scale.

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