Regional Scale Multi-hazard Susceptibility Assessment: a case study in Mtskheta-Mtianeti, Georgia

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by

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Abstract

Natural disasters are the major economic, social and environmental problems of concern to many countries. Mass movements, as one of the major disasters, post great threat to people's life and property. Assessing the susceptibility of mass movements could help to mitigation the loss they brought. However, due to the limitation in available historical data, regional scale mass movement susceptibility assessment is not easy to operate. This research aims to apply a method for multi-hazard mass movement susceptibility assessment with runout in a mountainous area with limited information on past events at a regional scale. Here multi-hazard indicates different mass movements including debris flow, landslide, rockfall and snow avalanche. First, susceptibility for each type of mass movement is evaluated using Spatial Multi Criteria Evaluation (SMCE) in ILWIS. Then the cells with high susceptibility value are selected as source area to model the runout with software Flow-R. The runout maps are combined together to make a multi-hazard susceptibility map. Different scenarios of major trigger, moderate trigger and minor trigger are modelled. The results indicate that a heuristic susceptibility assessment can generate good results if the knowledge about the local environmental situation is well known. The runout included in the susceptibility assessment can delineate the susceptibility zone more realistically than an initiation susceptibility assessment only.

Key words: Multi-hazard, Susceptibility assessment, SMCE, Regional scale, Runout model.

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Yawen Ma
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1. Introduction

1.1. Research background and significance

It has been long recognized that natural disasters are the major economic, social and environmental problems of concern to many countries in all regions of the world. According to the World Bank Report (2005) on natural disasters, more than half of the world population (3.4 billion) lives in areas with natural disaster risk.

As one of the major disasters in the world, mass movements bring great threat to people's life and property. They post serious threats to settlements and structures that support transportation, natural resources, and tourism (Frattini, Crosta et al., 2008), cause considerable damages to highways, waterways, pipelines, and so on. The damage and impact is increasing in recent years with the growing population and expansion of settlements both in the developed and developing countries (Fausto Guzzetti, Carrara et al., 1999).

To minimize the impact of mass movements, avoidance is the most useful mitigation measure. Strategies before hazard events take place, such as monitoring as well as hazard mapping and risk assessment, should be used to indicate the hazard potential. Based on the result of these detections, mitigation measures such as structural measures (check dams, debris basins) or non-structural measures (e.g. land-use zoning, early warning) could be taken to reduce the risk (LaHusen, 2005).

Regional scale assessment is an important component for land use planning over large areas. It could:

- Identify the priority areas, which could be used for detailed local scale assessment.
- Help decision-makers to analyze the risk throughout the region in order to make suitable political and financial decisions dealing with mass movement hazard. For example to alert the local authorities in higher risk areas, to make allocations for risk mitigation budgets (Sukarna, Wirakusumah et al., 2009)
- Avoid unsuitable planning and construction in regional planning in areas where special attention is needed.

1.2. Research problem statement

Although the significance of regional mass movement assessment is obvious, the implication of it faces problems due to limitations in available data and knowledge

about the region. Information on historical events is essential for multi-hazard risk assessment as it provides the best information where events are likely to happen in the future, following the principle that "the past is the key to future". For example, they could be used to define the critical threshold of certain factors using heuristic methods (Castellanos Abella & Van Westen, 2008) or provide statistical results based on the relationship with causal factors; or calibrate and validate the physical models for runout modelling (Dahl, Mortensen et al., 2010; Willenberg, Eberhardt et al., 2009). They are also essential for validation of hazard and risk maps.

However, the availability of a mass movement inventory map is one of the major problems in a lot of areas of the world due to the limited resources available for research (Castellanos Abella & Van Westen, 2008) and due to the lack of historical information on landslide occurrences. Especially at a regional scale, there are normally incomplete inventories for the entire region. This makes the application of statistical and physically-based models difficult.

This research aims to apply a method for multi-hazard mass movement susceptibility assessment in a mountainous area with limited information on past events at a regional scale as a basis for spatial planning and risk assessment. Here multi-hazard indicates different mass movements including debris flow, landslide, rockfall and snow avalanche.

1.3. Research justification

1.3.1. Multi-hazard mass movement susceptibility assessment

Hydro-meteorological hazards, characterized by those events that have a trigger related to extreme precipitation which affect the hydrological extremes, such as flooding, landslides, debris flows and snow avalanches, are related to each other in terms of their triggering events (Kappes, Keiler et al., 2010). For example, a rainfall trigger could start debris flows; also it can increase the soil water content and result in landslides. Landslides could block the drainage system and cause a dambreak flood. Moreover, the trigger events such as rainfall, earthquake, volcanic eruption and sudden changes of temperature are able to trigger different hazards in the same area simultaneously. Also because the losses of the events, when analyzed separately, might not be the same as those of the effects happening at the same time, and interacting with each other.

There are many different types of mass movements, which all are related to the movements of a mass (be a rock, debris, soils, ice, snow or mixtures) under the influence of gravity. They differ in speed, type, size, frequency, and way of impact.

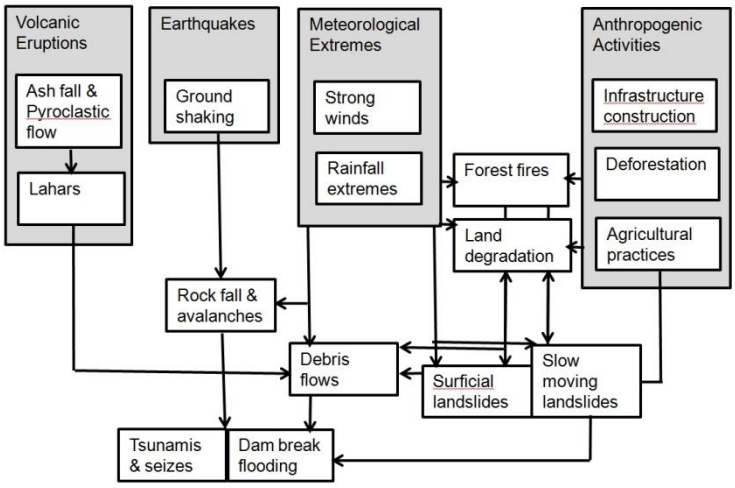

Figure1. 1. Causal factors, interrelationships and secondary hazards related to landslides (Van Westen, 2011 Unpublished)

1.3.2. Methods for landslides initiation susceptibility assessment

Landslide susceptibility assessment is defined as a quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding. It can be considered as the initial step towards a landslide hazard and risk assessment. But it can also be a final result in itself which can be used in land use planning. Especially in a small scale analysis, or in situation where there is no sufficient information available on past landslide occurrences in order to assess the spatial, temporal and size probability of landslides. Landslide susceptibility maps should indicates the zones where landslides may initiate and possibly also the runout zones.

Overviews and classification of methods for landslide initiation susceptibility assessment can be found in Dai, Lee et al.(2002), Soeters and van Western (1996) and van Western, van Asch et al. (2006). The methods are shown in Figure1. 2. The common recognized ones are classified into qualitative ones (landslide inventory analysis, and knowledge driven methods) and quantitative ones (data driven and physically-based models)

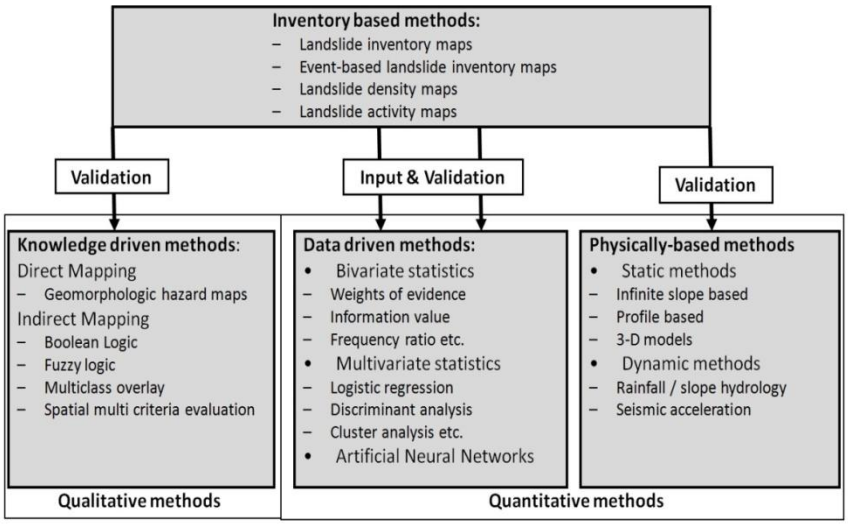

Figure1. 2. Classification of landslide susceptibility assessment methods (Jordi Corominas & Mavrouli, 2010)

Landslides inventory-based methods are the most straightforward initial approach to any study of landslide hazard. It is also required as a first step for all other methods, as they form the most important input and area used for validating the resulting maps. The presentation of landslides on inventory maps varies from detailed runout delineation to points representing locations of landslides, to a statistical number of cases within one administrate boundary (Malet, Thiery et al., 2009), depending on the property of disaster and the detail level of the records. The historic frequency of landslides in an area can be determined to provide estimates of landslide probability through that area.

Knowledge driven methods require expert opinion estimating landslide potential from data on preparatory variables (Hong, Adler et al., 2007; Malet, Thiery, et al., 2009; Nadim, Kjekstad et al., 2006). They can be divided into direct and indirect ones. In direct methods, the expert opinion plays a decisive role. The expert interprets the susceptibility of the terrain directly in the field, based on the observed phenomena, and the contributing factors such as geomorphological / geological setting. Apart from direct method, knowledge-driven methods can also be applied indirectly using GIS, by combining a number of factor maps that are considered to be important for landslide occurrence. On the basis of his expert knowledge related to past landslide occurrences and their causal factors with a given area, an expert assigns a particular susceptibility class to certain combinations of factors. This can also be done by combining all relevant factors using a GIS and assigning the

susceptibility class to each individual combination. Alternative, it can be done by giving weights to the classes of the individual factor maps and weights to the maps themselves. Several techniques can be used such as Boolean overlay, Fuzzy logic, multi-class overlay and Spatial Multi-Criteria Evaluation. One problem with the models is that they need long-term information on the landslides and the causal factors for the same site or for sites with similar geo-environmental conditions. Other limitations of this method are the reproducibility of the results and the subjectivity of weightings and ratings of the variables.

Data driven methods involve the statistical determination of the combinations of variables that have contributed to landslide occurrence in the past (Carrara, Crosta et al., 2008; Frattini, Crosta, et al., 2008; Ghinoi & Chung, 2005). However, the requirement of having a good landslide inventory holds back the use of multivariate statistical models. Statistical techniques are generally considered the most appropriate approach for landslide susceptibility mapping at medium scales, because on this scale it is possible to map out in detail the occurrence of past landslides, and to collect sufficient information on the variables that are considered to be relevant to the occurrence of landslides.

Physical-based methods are based on slope stability analyses, and are only applicable when the ground conditions are fairly uniform across the study area and the landslide types are known and relatively easy to analyse. They have been widely used to assess landslide probability in small areas (Chen & Lee, 2002). Trigger event is most involved in these methods (Soeters & van Westen, 1996). The advantage of deterministic models is that they have a higher predictive capability and are most suitable for quantitative assessment, while the main problem is that the data required for deterministic models are sometimes impossible to acquire, which makes the model not so effective.

Table1. 1. Recommended methods for knowledge driven landslide susceptibility assessment (Jordi Corominas & Mavrouli, 2010)

Approach	***References***
Geomorphological mapping	Kienholz, 1978; Rupke et al., 1988; Seijmonsbergen, 1992; Cardinali et al, 2002
Direct mapping method	Barredo et al., 2000; van Westen et al., 2000
Multi-class weighting method	Malet et al., 2009; Mora and Vahrson, 1994
Spatial multi-criteria analysis	Ayalew et al., 2005; Castellanos and Van Westen, 2007;
Analytical hierarchy process (AHP)	Yoshimatsu and Abe, 2005; Yalcin, 2008;
Fuzzy logic approach	Ercanoglu and Gokceoglu, 2001; Chung and Fabbri, 2001

There is a clear link between the scale of analysis and the type of method that can be used. It is related to the possibility of obtaining the required input data and the degree of detail. Generally qualitative methods (e.g. inventory methods and heuristic methods) are more suitable for national scale and regional scale; while quantitative methods (e.g. statistical methods, physical-based method) are more suitable for local scale (Cees J. van Westen, Castellanos et al., 2008).
The availability of data also limits the selection of method. For example, statistical method is not recommended if there are not enough historical event data. It should be noticed that in the case of lacking or incomplete landslide inventories, heuristic methods can still be applied.
Based on the above considerations, together with the available data and the proposed scale, a knowledge driven method was selected for this study.

1.3.3. How to deal with incomplete historical events

As mentioned in last section, even under the situation of lacking or incomplete landslide inventories, knowledge driven methods, or heuristic methods, can still be used. Since these methods require qualitative knowledge rather than quantitative knowledge. Expert knowledge on different mass movements could be used to decide the susceptibility level directly or indirectly.
In this sense, historical event data could help in providing the knowledge of the relationship between landslide and the geology and geomorphology factors. Moreover, historical events can be used to verify the modelled result.

1.3.4. Runout assessment for landslides

Compared to landslide initiation assessment, runout assessment for landslides is a much less common subject in assessing landslide susceptibility. It aims at outlining the areas that might be affected by the moving mass once it is detached. This movement can be in the form of flows, slides, falls, and avalanches. Methods for assessing landslide runout may be classified as empirical and analytical/rational (Hungr, Evans et al., 2001).
Empirical methods are usually based on field observation and on the analysis of the relationship between landslides and the ground truth parameters, for example, the volume of the landslide mass and the threshold angle taken from the top of the mass to the front of the moved mass (J. Corominas, 1996; Dieter Rickenmann, 2005).
Rational methods are based on the use of mathematical models. They sometimes include coupling of the mechanical behaviour with hydraulics and thermo mechanics (Dieter Rickenmann, 2005).

When assessing landslide susceptibility at a regional scale, most researches only focus on the analysis of landslide initiation susceptibility, while less work has been done on landslide runout assessment due to the uncertainties of runout prediction (Lee & Jones, 2004) and the large size of study area (Crozier, 2005; Frattini, Crosta, et al., 2008). However, delimiting the extent of endangered areas is fundamental to landslide risk assessment (Dai, Lee, et al., 2002) areas most of the damage to buildings, roads etc is caused by runout of landslides rather than by their initiation.
To assess the runout of at a regional scale, a regional debris flow runout model (Flow-R), developed by Pascal Horton and Michel Jaboyedoff from the University of Lausanne(Horton, Jaboyedoff et al., 2008), was selected in this research for modelling the runout for different mass movements.

1.3.5. From susceptibility to hazards

Landslide susceptibility assessment can be considered as the initial step towards a landslide hazard and risk assessment. The susceptibility maps can be converted into landslide hazard maps by including information of spatial, temporal and magnitude probabilities of landslides (Robin Fell, Jordi Corominas et al., 2008; Glade, Anderson et al., 2005; Fausto Guzzetti, Carrara, et al., 1999; Cees J. van Westen, Castellanos, et al., 2008).

1.4. Research objectives and research questions

The overall objective of this research is to assess the multi-hazard mass movement susceptibility (debris flows, landslides, rockfalls and snow avalanches) at a regional scale by combining an expert-based spatial multi criteria evaluation to define source areas with a simple runout model. The method is applied to a data scarce area in the Caucasus region of Georgia.
Sub objectives:

- Analyse the available historical information of mass movement occurrences and their relationship with triggering factors
- Analyse the relevant factors related to the occurrence of different mass movements types based on expert knowledge from literature and local landslide experts
- Develop a mass movement initiation model based on Spatial Multi Criteria Evaluation.
- Use the results of the initiation modelling in a simple empirical runout model for different mass movement types.

- Convert the landslide susceptibility maps into hazard maps by incorporating spatial probability information, based on a limited historical database and local expert opinion.
- Use the hazard map for regional infrastructure and human habitats risk assessment.

In corresponding to the sub objectives, the research questions are as follows:

- Which historical information on mass movement occurrences can be obtained from such a data scarce region?
- What kind of influencing information for mass movement initiation can be generated related to topography, lithology, land use and other factors?
- How to obtain information on the relative importance of each factor (weight) from literature and local experts?
- How does the resolution of Digital Elevation Model from different sources influence the results?
- How to generate the multi-hazard map from different types of mass movements?
- How to validate the result with limited historical events?
- How could the mass movement assessment at a regional scale be applied in spatial planning?

1.5. Methodology

The steps of the work are displayed in Figure1. 3. Based on the study of relevant parameters for mass movements, susceptibility maps are generated using a knowledge driven method: Spatial Multi Criteria Evaluation (SMCE). The susceptibility map is then used to derive the initiation for mass movements as the source for runout.

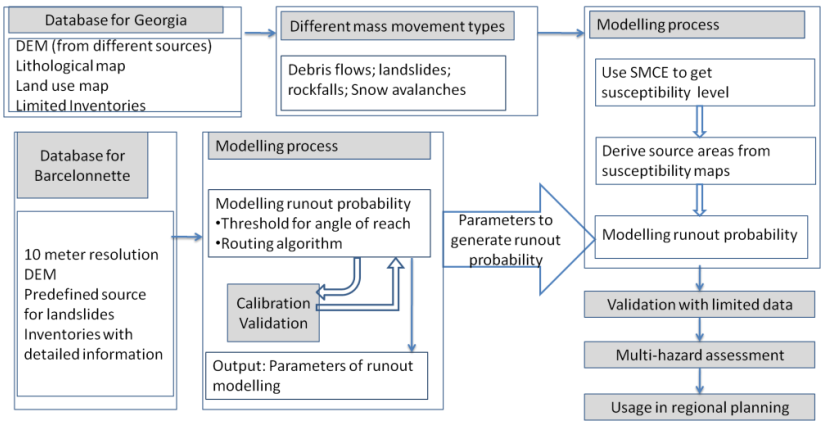

Figure1. 3. Flow chart of the research

1.6. Previous research on regional landslides susceptibility assessment

Recently several examples for multi-hazard mass movement susceptibility assessment covering countries or even at global level have become available. Same with the situation of this research, those assessments face limited data problem as well. Environmental factors are most common used in the assessments, while historical events data are hardly get. A good example can be found in the Hotspot project (Nadim, Kjekstad, et al., 2006) in which disasters including landslides and snow avalanche are assessed at a global scale for the World Bank to provide a guide for allocating resources for natural hazard risk management. This study combines a slope factor, lithology factor, soil moisture factor, precipitation trigger factor and seismic factor to produce a worldwide landslide susceptibility map with the equation:

$$H_{earthquake} = (S_r \times S_l \times S_h \times S_v) \times T_s \quad (1)$$

and

$$H_{rainfall} = ((S_r \times S_l \times S_h \times S_v) \times T_p \quad (2)$$

Where $H_{earthquake}$ and the $H_{rainfall}$ are the relative landslide hazard level triggered by earthquake and rainfall, S_r is the slope factor within a selected grid, S_l is lithological (or geological) conditions factor, S_h describes the soil moisture condition, S_v is vegetation cover, T_p the precipitation factor and T_s describes the seismic conditions.

Snow avalanche is also part of hotspot project. The hazard index for snow avalanche is decided with model:

$$H_{avalanche} = (0.4 \times S_r + 0.4 \times T_{pw} + 0.2 \times T_t) \times F \quad (3)$$

Where S_r is the slope factor, T_{pw} is a factor depending on precipitation for four winter months, T_t is the temperature factor, and F is a factor that depends on average temperature in winter months (F=0 if average monthly temperature in winter months >2.5◦C, F=1 otherwise) (Nadim, Kjekstad, et al., 2006)

The approach in Hotspots project for landslide hazard and risk assessment follows the flow chart in Figure1. 4.

SMCE is also used in another global landslide susceptibility assessment (Hong, Adler, et al., 2007) using satellite remote sensing data. In the study, six relevant landslide-controlling factors are derived from geospatial remote sensing data and coded into a GIS system. Then each factor is assigned continuous susceptibility value from low to high. The valued factors are then combined using GIS weighted linear combination based on each factor's relative significance to the process of landslide occurrence. Finally the combined susceptibility map is further classified into six susceptibility categories.

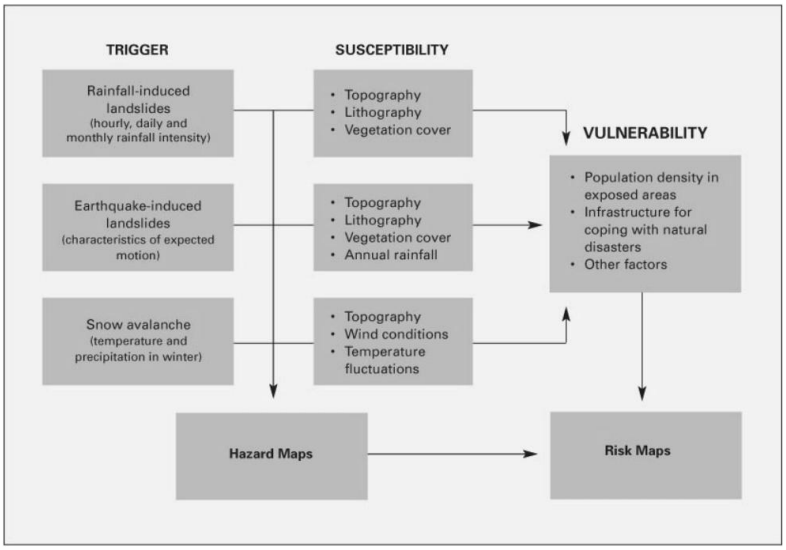

Figure1. 4. General approach for landslide hazard and risk evaluation in Hotspots project

Besides global scale, continent scale assessment is also operated. The European Soil Bureau Network has the aim to launch a project to map landslide susceptibility at the scale of Europe, which is part of the European Expert Group on "Guidelines for Mapping Areas at Risk of Landslides in Europe". The aim is to prepare a landslide susceptibility map to identify the potential areas subject to landslide types by expert knowledge using available thematic and environmental data, such as topographical attributes, bedrock/ engineer soil database, European major discontinuity map and so on. There are different levels in this project. The highest level, called 'Tire 1' assessment in the project aims at the general identification of areas potentially subjected to landslides, providing a low-resolution (1:1M scale) evaluation of landslide treats using existing thematic and environmental data. The 'Tire 2' assessment is intended to perform more detailed analyses in the area identified by Tire 1, and should provide results at a higher spatial resolution using existing and new data currently not available in all European countries.

France is chosen as Tire 2 study area (Malet, Thiery, et al., 2009). The minimum input data for the evaluation are: a slope gradient map; a soil map, and a land cover map(van den Eeckhaut, Hervas et al., 2010). These data are combined to analysis the susceptibility with SMCE technique available in ILWIS for different landslide type such as topple, collapses and slides. The susceptibility maps for each landslide are then combined to generate a multi-hazard map.

For rockfall assessment at a regional scale, one of the main difficulties is the identification of potential rockfall sources. Those source areas, are usually taken from distinctive evidence such as scree deposits below cliff faces, (Baillifard, Jaboyedoff et al., 2003) field and historical inventory of rockfall (Frattini, Crosta, et al., 2008). The simplest morphometric approach consists of defining a threshold angle of the slope (Frattini, Crosta, et al., 2008; F. Guzzetti, Reichenbach et al., 2003). More advanced methods were developed by combining the slope geometry extracted from a DEM with datasets such as rock type, slope curvature and land cover in a heuristic or probabilistic way. Also there are statistical methods based on DEM-based geomorphometric analysis to get the threshold of angle which will separate potential rockfall source area and non-source area (Loye, Jaboyedoff et al., 2009). Coe and Harp (2007) indicate that rockfall susceptibility on rock slopes, at a detailed scale, is analyzed based on a thorough geological survey, which helps to identify the source area of rockfall. Table1. 2 shows some different criteria in GIS-based method to identify source area for rockfall susceptibility assessment.

Table1. 2. Methods for rockfall susceptibility assessment

Input data	*Criteria*	*Source area*
Geological (structural analysis) Geomorphological (slope, aspect)	Structural analysis and geomorphological analysis	(Antoniou & Lekkas, 2010)
structural setting, land use, and morphology slope (cell size 10m)	>37°	(Frattini, Crosta, et al., 2008)
slope	>45°	(Baillifard, Jaboyedoff, et al., 2003)
Slope (cell size 10m)	>60°	(F. Guzzetti, Reichenbach, et al., 2003)
5 criteria: (1) the proximity to a fault, (2) a scree slope within a short distance, (3) a rocky cliff, (4) a steep slope, and (5) a road. (Cell size 25m)	(1) 150m buffer on both side (2) 100m buffer around scree slope (base document record) (3) base document (4) 45° (5)50m above the road	(Baillifard, Jaboyedoff, et al., 2003)
Slope (cell size from 1m to 25m)	Decided by geomorphometric analysis	(Loye, Jaboyedoff, et al., 2009)

2. Study area

2.1. Introduction about Georgia

Georgia is a sovereign state in the Caucasus region of Eurasia. Situated at the Juncture of Eastern Europe and Western Asia, it covers a territory of 69,700km2 and its population is about 4.44 million in 2010 (data from national statistical office of Georgia).

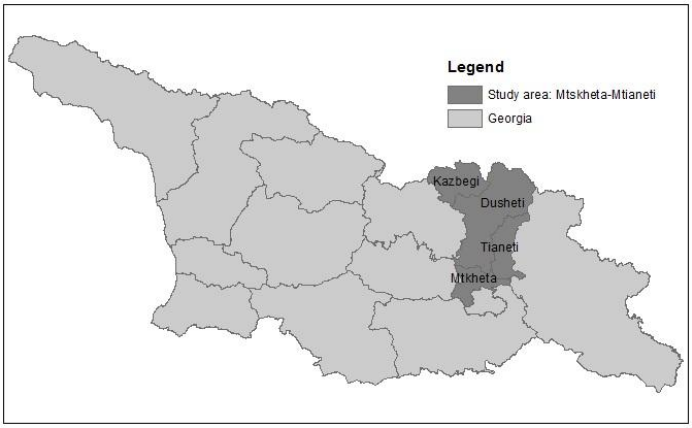

Figure2. 1. Georgia and the study area of Mtskheta-Mtianeti

As one of the highly disaster-prone countries, Georgia frequently experiences natural hazards such as earthquakes, floods, landslides, mudflows, avalanches. The existing disaster-prone environmental situation, together with its demographic change, unplanned urbanization, poor maintained infrastructure, socio-economic inequities, environmental degradation and climate variability, amplifies the frequency and intensity of disasters.

The territory of Georgia occupies the central part of the Black Sea and Caspian Sea basin. It is located in the central and west part of Transcaucasus. As part of Caucasus, Georgia is located between the Eurasiatic and Afro-Arabian plates at the junction of European and Asiatic branches of the Mediterranean (Alpine-Himalayan) fold belt. Its geological structure is built up mainly by Mesozoic and Cenozoic deposits. Early Precambrian and Paleozoic formations spread over a small area.

The tectonic units of the recent geologic structure of Georgia can be distinguished according to the degree of dislocation of the Earth's crust (Moores and Fairbridge 1997):

- The fold system of the Greater Caucasus (in the north and northeast part of Georgia),

- The Transcaucasia intermountain area (in the central part of Georgia)
- The fold system of the Lesser Caucasus (in the south part of Georgia)

The overall region can be characterized as being made up of various, interconnected mountain ranges (largely of volcanic origin) and plateaus. The Southern Georgia Volcanic Highland is a young and unstable geologic region with high seismic activity and has experienced some of the most significant earthquakes that have been recorded in Georgia.

Georgia used to be part of the Soviet Union from 1921 to 1991, in which period Georgia was under the control of the communism country and followed the system and pattern. During the Soviet Union period, Georgia had a systematic survey about geology, land cover, and natural disaster records. However, those precious data were partly destroyed in the war time against the Soviet Union since the rooms to keep records in the National Environmental Agency (NEA) which is now responsible for maintaining the records, were used as shelter for refugees in those hard times. The archives were even used to be fuel to provide heat. After the change the economy turned from a centrally planned one into a capitalistic one, and funding for government organizations such as NEA drastically declined. Therefore much less funding was available to carry out surveys and maintain monitoring records. Also the National Environmental Ministry has recently been abolished and the role of NEA is now quite uncertain. Due to these reasons there is no funding for maintaining records of hazardous events in the country.

The economy of Georgia experiences the ups and downs with its history. For much of the 20th century, Georgia's economy was within the soviet model of command economy. Since the fall of the Soviet Union, Georgia embarked on a major structural reform designed to transition to a free market economy. After experiencing a severe economic collapse at the beginning, it becomes one of the fastest growing economies in Eastern Europe with a 12% GDP growth rate in 2007. However, there are still problems such as inflation due to external and internal reasons, and a heavy dependency on outside funding.

Georgia's economy is becoming more devoted to services, moving away from the agriculture section. The country is developing into an international transport corridor. Several important pipelines go through Georgia, such as the Baku-Tbilisi-Ceyhan pipeline (BTC) and a parallel gas pipeline. Tourism is another increasingly significant part of the Georgian economy. According to the government, there are 103 resorts in different climatic zones in Georgia. There are overall 12,000 historical and cultural monuments, four of which are recognised as UNESCO World Heritage Sites.

Figure2. 2 shows a general assessment of some nature hazards mentioned above. Overall natural disasters such as landslides, soil erosion, floods and subsequent

degradation of ecosystems and agriculture lands are found all over Georgia's territory; however, the level of occurrence is higher in the mountainous regions.

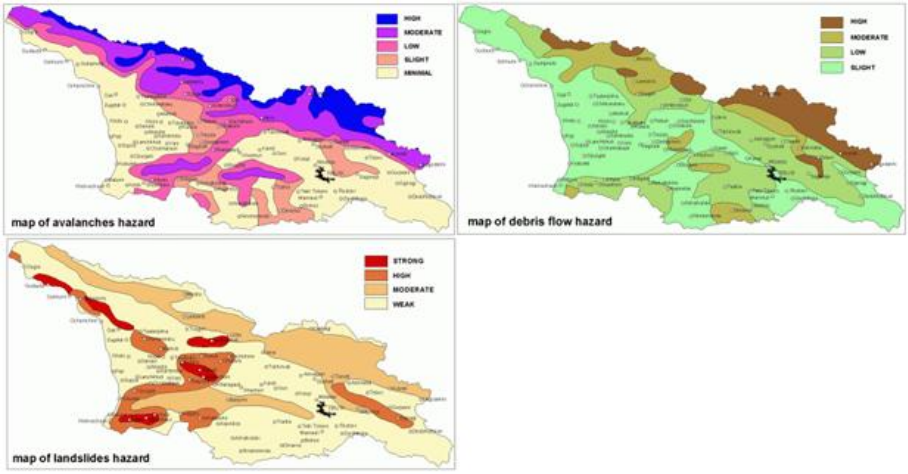

Figure2. 2. Some national hazard maps (Source: http://www.ggs.org.ge/others-natural.htm)

2.2. Disaster Risk Reduction

There are several reasons for the highly frequent and intensive natural disaster besides the environmental and climatic factors in Georgia. Poverty, unsustainable natural resource management and agricultural practices, improper infrastructure and urban development are all leading to a more fragile ecosystem and a higher exposure to natural disasters. The Soviet centralized planning system was responsible for the abandonment for traditional natural resources management methods as well as introduction of poor practice of spatial planning and infrastructure and urban development.

Natural disasters affect heavily local households leading to losing of agriculture lands and properties, decrease of land fertility, lesser yields, low quality crops and, finally, increase of poverty. Natural disasters have triggered migration of rural population (especially from the mountainous regions), disrupted economic development prospects, aggravated regional conflicts and instability, and threatened the lives and livelihoods of local people. Even though natural disasters have intensified over the past decade in Georgia and vast areas are now degraded, no proper measures have been taken at the central level to address this problem. Georgia also has a major earthquake hazard, which is being studied by national and international organizations (e.g. http://causin.org).

Several projects were initiated to support Georgia in disaster risk reduction over the last decade. One of them is the project "Institutional building for natural disaster risk reduction (DRR) in Georgia", implemented by ITC (Faculty for Geo-Information Science and Earth Observation, University of Twente) and CENN (Caucasus Environmental NGO Network). It aims to reduce poverty, enhance food security and income and ensure sustainable development by fostering good governance for disaster risk reduction. The goal of this project is to improve institutional capacity building in DRR via introduction of modern spatial approaches and technologies and risk communication strategy in spatial planning in Georgia.

The NEA (National Environment Agency) of Georgia has several departments involved in the project. The geology department of NEA is responsible for the assessment of natural geological hazardous processes and the analysis of effectiveness of mitigation and protection measures. The work of geology department includes creating a data base of different type of natural geological hazardous events, and using this for assessing the geological hazard and risk. The hydrology department of NEA is mainly responsible for hydrometeorology events such as collecting data of snow avalanches and floods, assessing the damage, elaborating of warning system and mitigation measure.

Figure2. 3. The deplorable situation of the remaining records of historical disaster events in NEA

Historical data collecting is part of the work for NEA. Within the above mentioned project NEA is trying to digitize the historical data recorded from the archive from the Soviet Union time. Though part of the archive has been damaged in the war time, there are still some left in paper-based media. The digitization of historical data is based on the description of disaster events in the archives. (Figure 2.3)

Also a Web-GIS is being built to collect disaster reports from all over the country (http://nea.cenn.org/). In the webpage, information about disaster events such as

disaster date, damage, and location could be provided. The Web-GIS is aimed at local authorities, school teachers, press and so on to report disaster events in a simple manner through the web interface. Staffs of NEA are then going to the sites to check the events, and include them in the official version of the disaster database. The database is then used to improve susceptibility, hazard and risk maps for the country. A preview of the webpage is as Figure 2.4.

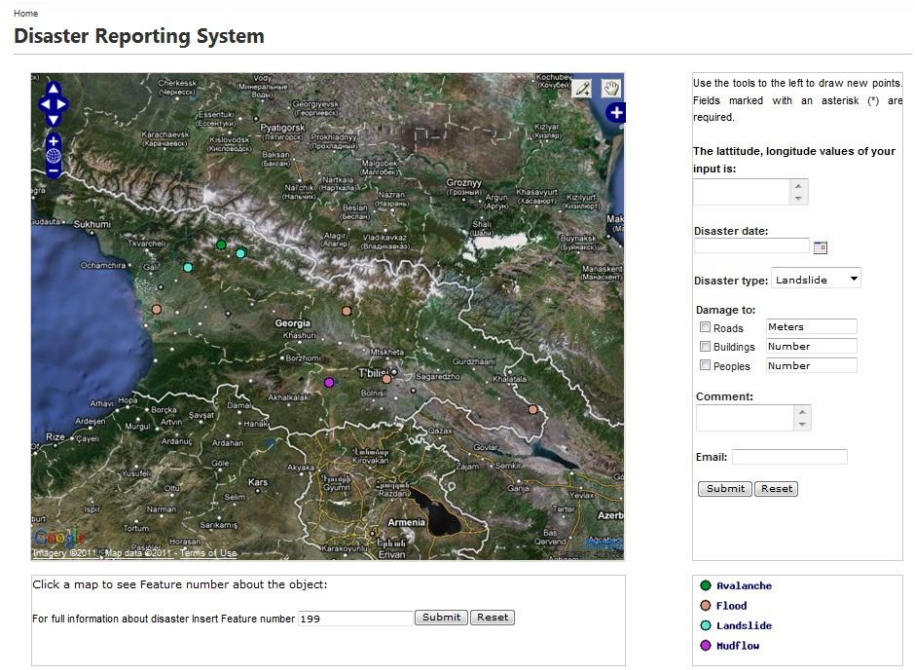

Figure2. 4. Webpage interface for reporting disaster events in Georgia

2.3. Who does what on Disaster Risk Management in Georgia

Different agencies and organizations are involved in DRR including the Georgian government, international (UN) organisations, international NGOs, scientific institutions and national organizations. The full list of agencies and organizations can be found in appendix1. Totally there are 41 organizations such as the department for geology hazard and geology management in the National Environmental Agency (NEA), and the Caucasus Environmental NGO Network.

Figure2. 5 gives a summary of agencies involved, according to a recent survey. According to the responses given, risk assessment seems to be one of the activities in which most organizations claim to be involved. However, in practice, there is very little development in this field, which is mainly due to the lack of reliable historical disaster information, and resources for data collection. Unfortunately, all

topographic data and recent imagery which were generated using international loans were made by commercial companies, who only provided hard copies to the government organisations, while selling the digital products at exaggerated prices.

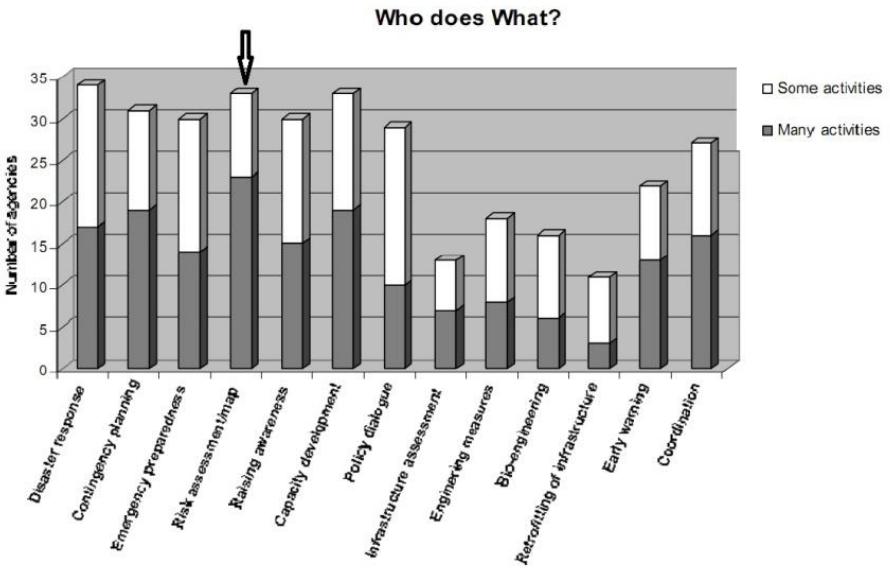

Figure2. 5. Numbers of agencies in different fields

2.4. About the study area

In this study the province of Mtskheta-Mtianeti is chosen as study area (Figure 2.1). Mtskheta-Mtianeti is a region in eastern Georgia. It consists of 4 administrative districts: Dusheti, Tianeti, Mtskheta and Kazbegi. The area of Mtskheta-Mtianeti covers about 5,700 km2, which makes up of 8.2% of the whole country. The population of this area is about 97,600 (2009), 2.1% of the whole population in the country. The climate of south Mtskheta-Mtianeti is mostly characterized as moderate humid subtropical climate. It has cold winters with average temperature between 0 - 2° in January, and long warm summer with average temperatures between 24 - 28° in July. However, in the northern mountainous region there is a different climate type of cold, sub-alpine and alpine nature.

The economic activities in this region are from different sources. Mtskheta-Mtianeti is mainly an agricultural region with fruit and vegetable growing developed in Mtskheta and animal farming in the Tianeti, Dusheti and Kazbegi mountainous areas. Industrial enterprises are mainly concentrated in Mtskheta and Dusheti. Tourism is also popular as the main skiing resort of the country, Gudauri, is located in the region. In the capital of Mtskheta, which was previously the capital of

Georgia, there is a historical center which is one of the four UNESCO World Heritage Sites in the country.

Several important infrastructures go through this region. The military road of Georgia, which stretches from Tbilisi to the Russian border, runs across this region. It is very important to the country considering that the road via Abkhazia is still closed and that the military road is one of the two roads connecting Georgia with Russia. There are pipelines transferring oil and gas through this region, one gas pipeline is almost parallel to the military road to Russia north-southly, and one oil pipeline at the west-east direction passes south of Mtskheta-Mtianeti.

Figure2. 6. Pictures of mass movement in Mtskheta-Mtianeti (1. The village of Mhleta in Dusheti municipality frequently affected by debris flows, 2. Landslides along roads in Dusheti municipality, 3. Rockfalls along roads, 4. Snow avalanche along the major military road)

Based on the recent work on the development of a national database for hydro-meteorological hazard events, some historical data about debris flows, landslides, rockfalls and snow avalanches have been collected for the study area. Since the points are digitized from paper-based records, the accuracy cannot be guaranteed.

In the study area, information on only 20 historical debris flow events is available. However, the date of the occurrence date is mostly missing: only 7 out of the 20 have temporal information. They happened in different years months and do not show any regular pattern Cross correlations with rainfall data was not possible due

to the lack of daily rainfall records for this area. Thus, the temporal information can be hardly generated in this research. About the spatial distribution pattern, 6 out of the 20 happened in this region, which is the upper part of Aragvi River. Since the temporal distribution is ignored in this research, the events occurring in the same location in different year are treated as one case. The location points of debris flows in the inventory map are mostly taken in the center of each debris flow fan, which means they are in the runout area rather than in the initiation zones.

Unfortunately, due to the limited historical information, there are only 9 recorded landslide events in the database. Also the landslide points are mostly taken in the runout part. This added to the inaccuracy in the spatial location of the points which explains the fact that most of the points are located in the low slope area. The historical events are all within 200 m from roads. This is partly because road construction influences the stability of the cutslopes, but also because more events are recorded along roads.

There are only 4 recorded historical rockfall events in the database, which all happen in the mountainous area in the north of Mtskheta-Mtianeti. Compared to other mass movements, it can be seen the slope for rockfall is much higher than the others. The distance from the rockfall event to roads is defined to be near if the distance is smaller than 150m.

The inventory contains only 7 snow avalanches event points. Besides the point inventory which shows the end point of the runout fan, there are polygon data showing the runout of snow movement and distance it reached. The events all happened along the road.

Table 2.1 shows the number of mass movements happened in different slopes, lithology types and land cover types. The relationship between the historical events and land cover, historical event and lithology do not explain a lot since the area proportion of the land cover types and lithology types are not taken into account. However, they tell some general rules such as landslides happen more in the newer-geology-period area.

Table2. 1. Relationship between historical mass movements and the environment factors (shown in numbers of mass movements)

		Debris flows	*Landslides*	*Rockfalls*	*Avalanches*
Slope	0°- 5°	2	0	0	0
	5°- 10°	7	5	0	1
	10°- 15°	5	1	1	1
	15°- 20°	1	2	0	0
	20°- 30°	0	0	1	3
	30°- 40°	0	1	1	1
	40°- 50°	0	0	1	0

Land cover	Grassland	10	4	4	6
	Dense forest	2	0	0	0
	Scrub	1	2	0	0
	Settlement Area	1	1	0	1
	Bare river sand	0	1	0	0
	Urban area	1	1	0	0
Geology	Quaternary	5	3	1	Not
	Neogene	0	3	0	related
	Paleogene	0	1	0	
	Cretaceous	7	1	0	
	Jurassic	2	1	2	
	Igneous	1	0	1	

3. Data collection and analysis

3.1. Digital Elevation Model

The data in this study are obtained from the National Environmental Agency (NEA) of Georgia. In this chapter, the properties of the data are discussed, with aspects such as the data collection method and accuracy. Digital Elevation Model

Topography influences both initiation and runout of mass movements most (Baillifard, Jaboyedoff, et al., 2003; Bonachea, Remondo et al., 2009; J. Corominas, Copons et al., 2003; Gruber & Bartelt, 2007). Digital Elevation Model (DEM) data can be used to derive topographic factors, other than simply elevation, including slopes, aspects, hill shading, slope curvature, slope roughness, slope area, and qualitative classification of landforms. DEM data can be also used to derive hydrological parameters (flow direction, flow path, basin and river network basin).

In this study, two DEM datasets are used for deriving topographic factors. The sources are:

- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM)
- Digitized contour lines with 20 meters contour interval from the National Environmental Agency (NEA)

ASTER GDEM data were developed jointly by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). It was contributed by METI and NASA to the Global Earth Observation System of Systems (GEOSS) and is available at no charge to users via electronic download from the Earth Remote Sensing Data Analysis Center (ERSDAC) of Japan and NASA's Land Processes Distributed Active Archive Center (LP DAAC). It covers land surfaces between 83°N and 83°S and is comprised of 22,600 1°-by-1° tiles. Tiles that contain at least 0.01% land area are included. It is in GeoTIFF format with geographic lat/long coordinates and a 1 arc-second (approximately 30m) grid. Pre-production estimated accuracies for this global product were 20 m at 95 % confidence for vertical data and 30 m at 95 % confidence for horizontal data (USGS, 2003).

Contour line data was obtained from NEA for the Disaster Risk Reduction (DRR) project, which is a collaboration between the Faculty of Geo-information Science and Earth Observation (ITC), University of Twente and the Caucasus Environmental NGO Network (CENN) with the National Environmental Agency (NEA) of the ministry of environment of the Georgian government as main beneficiary. The contour lines are digitized from topographic maps created in 1980s. They have 20 meters interval for the whole country.

Checking of the data shows that some contour lines are not properly coded: there may be one contour line contains two value of height with 20 meters difference. A number of wrongly coded contour lines have been manually corrected; but given the large size of the area, it was difficult to check all lines over the region.
The digital contour lines were interpolated to two raster DEMs with 50 and 15 meters resolution in ArcGIS10. The principle of the interpolation is to form a surface with respect to the connected drainage structure. The ASTER DEM of 30 meters resolution was resampled to 50 meters resolution. (The reason to choose this cell size is that this is the minimum cell size the runout model could handle for this large area) Taking a smaller area in the northwest part of the Mtskheta-Mtianeti as example (Figure3. 1), it can be seen that the DEM from ASTER is largely influenced by the grid pattern, while the 15 meters contour line interpolated DEM is influenced by the contour line pattern.

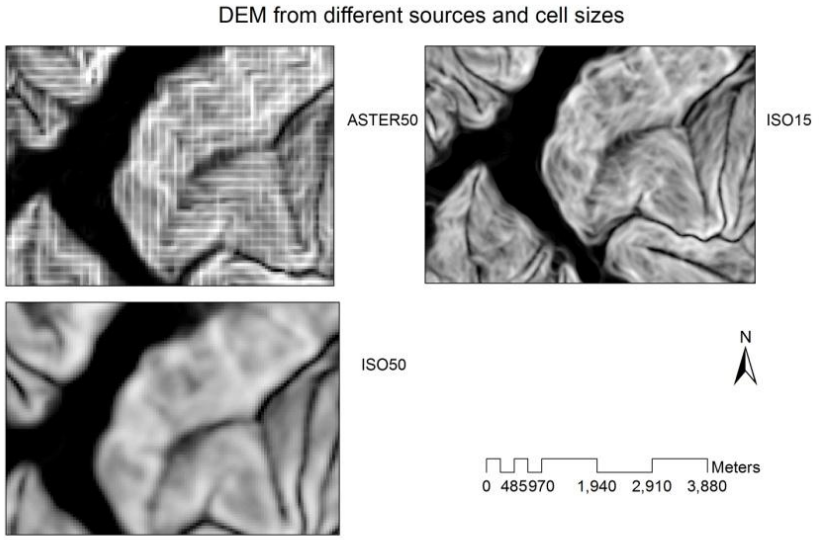

Figure3. 1. DEM from different sources and of different cell sizes

The slope histograms of these data sources were compared. The comparison takes into account both the source data and the cell size. First, the cell size of the two contour derived datasets was compared. The percentage of slopes of the two maps is shown in Figure 3.2.

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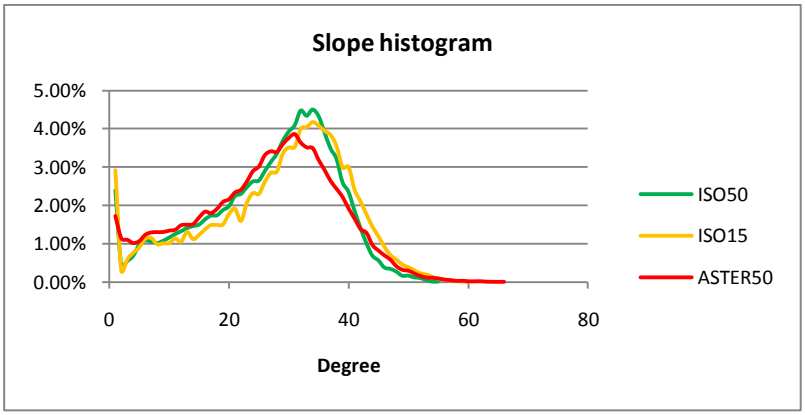

Figure3. 2. Slope histogram derived from different DEMs: ISO50: 50m resolution from contour lines, ISO15: 15m resolution from contour lines, ASTER50: 50m resolution from ASTER DEM.

The two maps have quite a large amount of slope with 0 degrees, due to the large river in the sample area. It can be seen that the slope distribution from contour lines (ISO50) are more concentrated: there are more cells with slope within 30 to 40 degrees in ISO50; while fewer cells with slope outside this range.
The comparison shows that smaller cell sizes leads to higher slope and data from contour lines give a more concentrated slope than ASTER data.
The difference between the DEMs of ASTER50 and ISO50 is calculated in ArcGIS. Result shows that the difference of altitude ranges from -359m to 236m, although most of the cells have small difference in altitude. Figure 3.3 shows the difference.

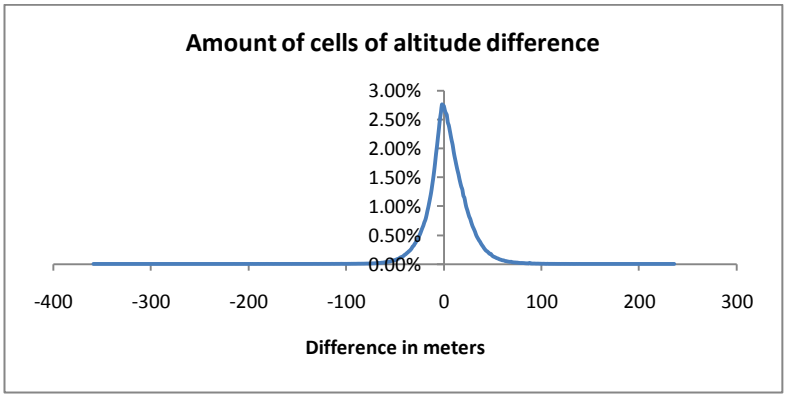

Figure3. 3. Difference in altitude of two DEMs (ASTER50 – ISO50)

3.2. Land cover map

According to NEA, the source of the available digital land cover data dates back to the 1980s in the Soviet Union time. Land cover was collected with a field survey and was made to a 1:50,000 scale topography map, which is digitized recently without any change. Unfortunately, after the independence no funding was available to carry out a more recent land use mapping for Georgia. Though the land cover map is not up to date, there is no large change according to local experts.

Land cover of Mtskheta-Mtianeti contains 23 types, among which forest and grassland occupy more than 90% of the whole area. This is due to the mountainous terrain, and the relatively low population density. Human activities related land use classes such as city, vineyards, orchards, cemeteries, parks, agriculture land and railways only take up 2.4% of the whole area. Others such as glacier, lakes take up 7.5%. Figure 3.4 shows the proportion of land cover types.

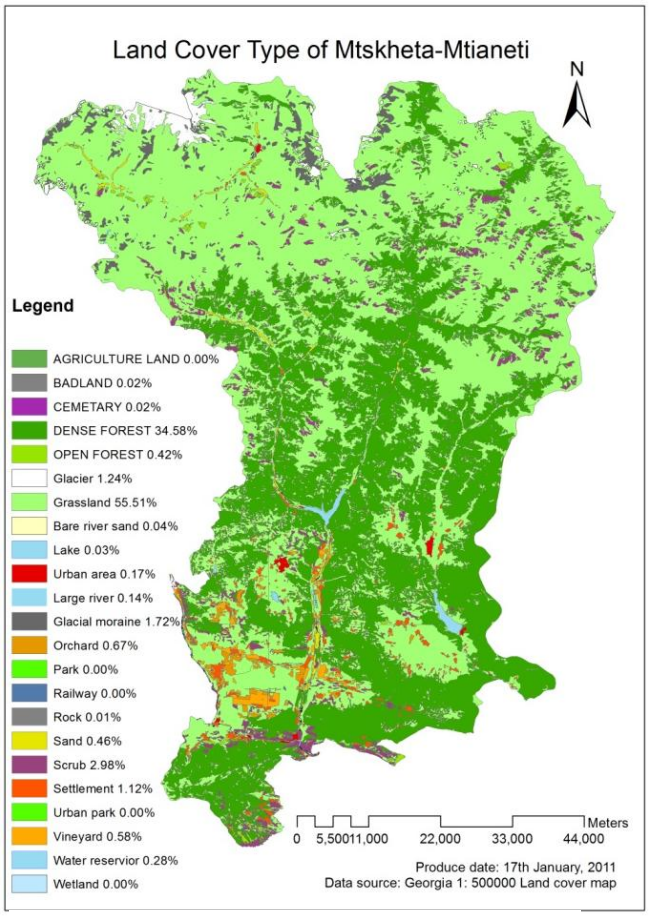

Figure3. 4. Land cover of Mtskheta-Mtianeti

The distribution of land cover type follows the geomorphology. In the north mountainous part, land cover is mostly grassland at the higher altitude areas, and forest at the lower altitude areas. Near the border between Georgia and Russian in the northwest part, where the highest point in this province locates, there is glacier land covered with ice all year around. (Figure 3.4)

In the southern part the terrain is relatively flatter, where the land is

possible to cultivate. In these areas land use types such as orchards, vineyards and agricultural land are more abundant.

3.3. Geology

Geology data is digitized in 2003 by NEA from a paper map which was made in the 1980s in the Soviet Union time. It is of 1:500,000 scale. The map was edited by the Georgian geologist I. P. Gamkrelidze in 2005.

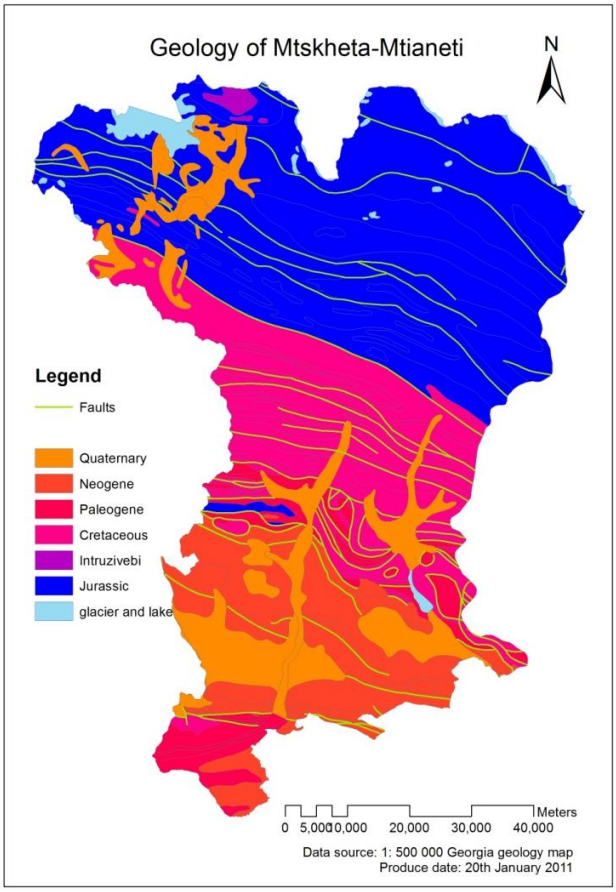

Figure3. 5. Geology period of Mtskheta-Mtianeti

In Mtskheta-Mtianeti higher altitude areas is of an older geological period generally. The north part of the province is along the Greater Caucasus Mountain range, with rocks mainly from the Jurassic. Only along valleys on the northwest part, there are rock types from the Quaternary, as are the morainic covers in the higher parts. The middle part of Mtskheta-Mtianeti is mostly from the Cretaceous period. The southern area has rocks from the Quaternary, Neogene and Paleogene. (Figure 3.5)

Faults are following the "Caucasian" pattern from NW to SE. Literature shows that in Georgia, the tectonic activity is still going on its recent stage of evolution ((Moores & Fairbridge, 1997)). Earthquake might happen in this area and might also trigger a substantial amount of landslides. However, in this study earthquake induced landslides are not considered.

3.4. Drainage and road networks

The drainage network was derived from the DEM which was made by interpolating contour lines into a DEM with 15 meters resolution. Certain types of mass movements such as debris flow mostly occur along drainage lines, where the morphology is concave and where water converges. With a given upslope area, the stream is formed and starts to flow down In this research the minimum upslope area is set to be 0.5 km2. Drainage was ordered using Strahler ordering method in ILWIS.

The road network was digitized from the topography map of the 1980s, which was later updated to include more recently constructed roads. Road construction in steep slope area influences the proneness to mass movement. A statistical result shows landslides happens more in the area nearer to road network (Gupta & Joshi, 1990). In this research, roads with a slope higher than 20 degrees are taken into account for mass movement.

3.5. MODIS snow cover data

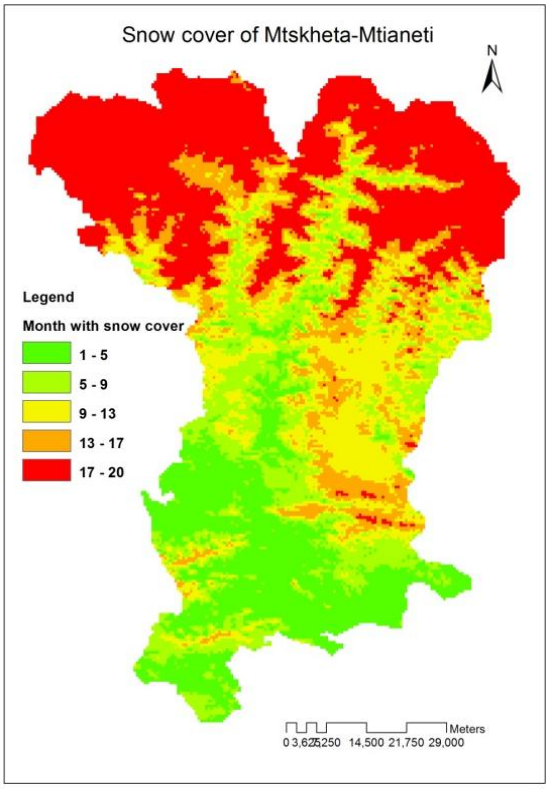

Figure3. 6. MODIS snow cover

In this study, MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid (MOD10A2) data are used to map the presence of snow, which is relevant for the snow avalanche analysis. The MOD10A2 data set contains data for maximum snow cover extent over an eight-day period and a chronology of snow occurrence observations. MOD10A2 consists of 1200 by 1200 km tiles of 500 m resolution data gridded in a sinusoidal map projection. The snow cover data are based on a snow mapping algorithm that employs a Normalized Difference Snow Index (NDSI) and other criteria tests (Hall, Riggs et

al., 2006).

According to the NEA in Georgia, snow avalanches happen in the period from December to March. In this research five-year data (2005- 2010) of these four months were downloaded from NSIDC (National Snow and Ice Data Center).

Since the data shows the maximum extent of snow cover in eight days, there are about four datasets in each month. In the research, the least disturbed dataset, which means datasets with least cloud or missing data, are chosen. The data was transferred into Boolean data separating snow cover and other areas. The 20 layers (4 months* 5 years) are summed up (Figure 3.6) and areas with more months of snow cover are set to be the mask of snow avalanche source area.

4. Mass movement initiation susceptibility assessment

A mass movement susceptibility map is a quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding (R. Fell, J. Corominas et al., 2008).

A susceptibility map can be used to produce a hazard map that indicates the probability of areas that are prone to landslides (Antoniou & Lekkas, 2010; Frattini, Crosta, et al., 2008). The models are typically made by exploring statistically the relationship between the existing occurrences of landslides and the impacting factors. However, a statistical evaluation model must be based on historical events, and the collection of this information is usually expensive and time-consuming to collect. Furthermore, the distribution and frequency of historical events are also difficult to collect due to inadequate records over larger time periods. Thus, given the limited information on historical events for the study area mass movement susceptibility assessment cannot be derived using statistical evaluation models.

Another type of models used for mass movement susceptibility assessment is the so called heuristic methods, in which expert information is used to evaluate the relative importance of the various causal factors. Spatial Multi Criteria Evaluation (SMCE) is used using expert knowledge when models based on objective information are not available. In this approach, susceptibility to landslides is estimated on the basis of expert judgments of contributing factors instead of empirical measurement data. In order to enable the use of expert knowledge, methods for transforming expert knowledge into a numerical form, as well as appropriate method to combine data, are needed.

One approach to SMCE in a GIS environment is the technique that the criterion scores are firstly standardized from 0 to 1, then each criterion is weighted by comparing it with others, and the total score for each factor is calculated by multiplying each criterion score by its weight. The sum of the results would be the evaluated score for certain unit of the study area.

This chapter will explain the way to derive the expert based weights, by assigning numerical values to each class in each factor. The next chapter will provide the information about how to combine them.

4.1. Standardization of factors for landslide initiaiton

4.1.1. Criteria for landslide susceptibility assessment

There is no universal guideline for selecting the parameters that influence landslides susceptibility mapping. Criteria vary in the literature. Mostly parameters are chosen according to the characteristics of the research areas (Frattini, Crosta, et al., 2008; C. J. van Westen, Rengers et al., 2003) and the availability of data (Malet, Thiery, et al., 2009; Yalcin, 2008).

In the Hotspot project (Nadim, Kjekstad, et al., 2006) landslide susceptibility is derived by combining the factors of topography, lithology, vegetation cover and soil moisture with spatial multi-criteria evaluation.

In the study of (Yalcin, 2008), three methods are compared: analytical hierarchy process, statistical index, and weighting factors. Parameters of lithology, weathering, land cover, and slope data were found to be important factors among other factors in the Ardesen area of Turkey, which is located along the Turkish part of the Lesser Caucasus.

According to literature, five factors are most often selected in landslide susceptibility mapping: slope, lithology, landuse, distance from drainage and roads.

4.1.2. Processing of landslide-controlling factors

The first step is to classify each landslide-controlling factor into categories. For continuous factors such as the slope gradient, factors should be classified into bins with certain interval; for discrete factors, they should be categorized into different classes. After categorization, each class would be assigned a value from 0 to 1 which indicates the relative susceptibility to landslides.

4.1.2.1. Slope gradient

Topography is one of the most important factors in landslides susceptibility assessment (Castellanos Abella & Van Westen, 2008). In literature, slope length, slope convexity, slope direction (aspect) and slope steepness are all studied, while the latter is mostly used (Dai & Lee, 2002). In the statistical analysis of Dai and Lee (2002), landslide frequency for slope classes is analysed. In the study of Thiery et al (2007), slope is analyzed for different types of slides using a cell size of 50 meter in the Barcelonnette basin.

Table4. 1. Slope statistics of landslides inventoried (Thiery, Malet, et al., 2007)

Landslides type	*Number of slides*	*Geometric average(°)*	*Standard deviation*
Shallow translational	50	31	9
Rotational slide	54	21	9
Translational slide	88	21	6

As analyzed in chapter 3, slope gradient is generally smaller when the resolution of DEM is larger, since larger resolution DEMs will ignore local variation of elevation between cells.

Based on literature study (Berti, Genevois et al., 2000; Catani, Casagli et al., 2005; Dai & Lee, 2002; Thiery, Malet, et al., 2007) the following standardized values for slope classes were used in this analysis, ranging from 0 to 1, in which 1 means very prone to landslides, and 0 means not prone to landslides.

Table4. 2. Normalized weight assigned of slope gradient for landslides

Slope gradient	*Standardized value*
0 - 10	0.1
10 – 20	0.8
20 - 30	1.0
30 – 40	0.5
40 - 50	0.2
> 50	0.1

4.1.2.2. Land use

Land cover is another criterion in deciding the susceptibility for mass movement initiation , (Horton, Jaboyedoff, et al., 2008).

According to other studies (Dilley, Chen et al., 2005; Hong, Adler, et al., 2007), the landslides susceptibility for global land cover are assigned with numerical values

In our study area Mtskheta-Mtianeti, there are 23 types of land cover. Table 4.3 shows the standardized values that were used based on the literature and expert weighting by several experts.

Table4. 3. Numerical value assigned to each land type

Category	*Standardized value*	*Land cover type*
0	0	Lake, glacier, water reservoir, large river, wetland
1	0.1	Bare glacial moraine, badland, rocky
2	0.2	Dense forest
3	0.3	Open forest, park
4	0.4	Scrub, Orchard,
5	0.5	Urban park
6	0.6	Vineyard
7	0.7	Grass land, island
8	0.8	Agriculture land
9	0.9	Bare river sand
10	1	Settlement area, urban area, cemetery, railway

4.1.2.3. Lithology and geological structure

Lithology may affect the likelihood of landslides to a large extent. There are many previous studies showing the correlation of landslide frequency with lithology (Catani, Casagli, et al., 2005; Dai & Lee, 2002). However, since lithology varies from place to place, the geological study of other areas cannot be extrapolated to Mtskheta-Mtianeti.

Previous studies on the relationship between lithology and landslides analyses lithology in different aspects. The weathering degree of the rocks (Karsli, Atasoy et al., 2009; Yalcin, 2008) and the lithological types (Akgun, Dag et al., 2008; Wang, Xie et al., 2009) are adopted as indicators. From the literature study it can be concluded that more weathered rock are more prone to landslides and that fine-grained rocks (shales, marls, claystone) and rocks with intervalations of fine materials are more prone to landslides (Akgun, Dag, et al., 2008; Sterling & Slaymaker, 2007; Wang, Xie, et al., 2009).The stratigraphy of the Mtskheta-Mtianeti region is of several geologic time scales: Quaternary, Neogene, Paleogene, Cretaceous and Jurassic.

Within each stratigraphical unit, there are 10 to 30 lithological units. These units were given a value for the likelihood of landslides by one Georgia geological expert and two non-Georgian geologists, with values ranging from 0 to 10, which were later on converted to a range between 0 and 1.

The weights assigned by non-Georgian geologists are more uniform within each stratigraphical unit, and the range of the weights is smaller, while the weights assigned by Georgian expert are more diversity and more related to the historical events. Some lithology units have the location attribute, which adds the clue for local expert with the knowledge of historical events. The weights from Georgia expert's opinion influences the weights in this study most. Together with the stratigraphy information, the weights of lithology units are assigned to the proneness of landslides.

4.1.2.4. Distance to the drainage network

For certain types of mass movements such as debris flows, the susceptibility is often related to the closeness to the drainage network, where the morphology is concave and where water converges. With a minimum upslope area, the stream is formed and starts to flow down and meet other streams at the meeting point of the network. In this research the minimum upslope area is set to be 0.5 km2.

Drainage is also influencing landslide due to the possibility of undercutting slopes. The Strahler strweam order was therefore used to assign standardized values to distance classes close to streams with different stream orders.

Compared with the existing landslide historical events, the first order and second order of drainage are found mostly contributing to the mass movement. Thus they are assigned value of 1 while others are assigned value of 0.

4.1.2.5. Distance to the road network

Construction of roads also influences the density of landslides, especially in sloping areas where road cuts are made. For example a study in the Darjeeling Himalaya (Gupta & Joshi, 1990) shows that landslide density is much higher along the road with a buffer of 150 meters than further away from roads. In this study, roads that are located on areas with slopes steeper than 20 degree and that are close to a road are taken into account with the value of 1, other areas are assigned value of 0.

4.2. Standardization of factors for debris flow initiation

Debris flows are among the most dangerous processes in mountain area due to their rapid rate of movement and long runout zones. They have more water content compared to landslides, and can be triggered by several process, such as landslide initiation, severe erosion in unconsolidated sediments and breaking of landslide dams. In literature there are generally three criteria considered to be most relevant to debris flow initiation: sediment availability, water input and slope gradient (Horton, Jaboyedoff, et al., 2008; Dieter Rickenmann & Zimmermann, 1993).

In this study, sediment availability is linked to lithology, since the grain size distribution, weathering and composition of rocks could decide the proneness of particle to be eroded. Also the soil cover on top of the bedrock plays a major role. However, in the available lithological map, soil cover is not well represented, and a separate soil thickness map was not available. Slope angle is another major criterion as well as land use. In addition, the drainage system is taken into account for debris flows and also roads, similar as for the landslides.

Since debris flows and landslides share almost the same controlling factors almost the same standardization method was used. However, there are still differences between the two types of mass movements such as water content. This will be reflected in the next chapter which is about assigning weights to each factor. For example, the drainage network will have more weight in debris flow assessment than in landslide assessment.

4.3. Standardization of factors for rock fall initiation

4.3.1. Criteria for rockfall susceptibility assessment

For rockfall susceptibility assessment at a regional scale, one of the main difficulties is the identification of potential rockfall sources. Those source areas are usually

taken from distinctive evidence such as scree deposits below cliff faces (Baillifard, Jaboyedoff, et al., 2003), and field and historical inventories of rockfalls (Frattini, Crosta, et al., 2008). The simplest morphometric approach consists of defining a threshold angle for slope (Frattini, Crosta, et al., 2008; F. Guzzetti, Reichenbach, et al., 2003). More evolved methods were developed by combining the slope geometry extracted from a DEM with datasets such as rock type, slope curvature and land cover in a heuristic or probabilistic way. Also there are statistical methods based on DEM-based geomorphometric analysis to get the threshold of slope angle for identifying potential rockfall source areas (Loye, Jaboyedoff, et al., 2009). Coe and Harp (2007) indicate that rockfall susceptibility at a detailed scale, is analyzed on the basis of a thorough geological survey.

Frattini et al (2008) report that structural setting, land use, and morphology are the most important factors that led to the initiation of rockfalls. In this study, slope gradient, land use, geology including lithology and faults, are taken into account.

4.3.2. Processing of rockfall-controlling factors

4.3.2.1. Slope gradient

Normally a threshold is used in literature for the slope gradient (Baillifard, Jaboyedoff, et al., 2003; Frattini, Crosta, et al., 2008; F. Guzzetti, Reichenbach, et al., 2003). Figure 4.1 shows the relationship between slope angle and rockfall frequency from the database of the Canadian railway industry (Andrew, 1994; Lan, Martin et al., 2010).

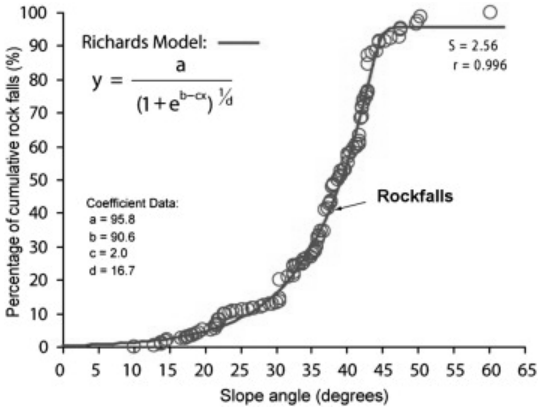

Figure4. 1. Relationship between slope angle and rockfall frequency obtained from the rockfall database and the 1-m DEM (Lan, Martin, et al., 2010)

Slopes from 0° to 50° are valued based on the statistics, while slope larger than 50° are assuming to be 1, which means they are prone to rockfalls (given that the

lithology is also susceptible). The values of the slope gradient for rockfall are assigned as the following table:

Table4. 4. Assigned numerical weight for different slope gradient for proneness to rockfall

Slope gradient (°)	*Standardization value*	*Slope gradient (°)*	*Standardization value*
0 - 20	0	30 - 40	0.8
20 – 30	0.2	> 40	1

4.3.2.2. Land cover

Land cover affects the susceptibility to rockfall initiation as well (Dorren & Seijmonsbergen, 2003). A higher density of forest vegetation results in less proneness to rockfall. Based on this principle, area with forests are valued smaller. Also the value system the material source is taken into account, which means that areas with little rock exposures will assigned lower values even if there is no vegetation. For example, river sand is assigned lower scores.

Table4. 5. Value assigned to land cover types as the index to rockfall

Category	*Standardized value*	*Land cover type*
0	0	Lake, glacier, water reservoir, large river, wetland
1	0.1	Dense forest
2	0.2	Open forest, park
3	0.3	Scrub, Orchard,
4	0.4	Agriculture land
5	0.5	Bare river sand
6	0.6	Urban park
7	0.7	Vineyard
8	0.8	Grass land, island
9	0.9	Settlement area, large city, cemetery, railway
10	1	Bare glacial moraine, bad land, rocky

4.3.2.3. Geology

Geology affects rockfall susceptibility in different aspects. Lithology and structural control of discontinuities (such as faults, bedding planes and joints) are the major ones (Baillifard, Jaboyedoff, et al., 2003). Unfortunately, no structural information is available on the density and orientation of discontinuities for the study area. For standardizing the lithological classes the same procedure was followed as with the landslides, although different standardized values were assigned based on expert opinion of the consulted Georgian expert.

For faults of the study area, buffers were created along the faults. Further distance will result in a smaller value assigned as in Table4. 6.

Table4. 6. Value assigned along faults

Distance to fault (m)	*Standardized value*
0 - 50	1
50 - 100	0.8
100 - 150	0.5

4.4. Standardization of factors for snow avalanche initiation

4.4.1. Criteria for snow avalanche susceptibility assessment

A lot of parameters control the initiation of snow avalanches such as topography, climate, land use and human activites (Ghinoi & Chung, 2005; Jaedicke, Solheim et al., 2008). Due to the lacking of climate data, most of the parameters chosen in deciding snow avalanches source areas are based on topography such as slope gradient, aspect, convexity and upslope area. Land cover is taken as another indicator based on the roughness of the surface. Roads are found to be an influence factor of snow avalanches according to the inventory. However that's probability because of the importance of the major road and more observation along roads. Finally, the previously described MODIS snow cover was chosen as the index of climate data to show the availability of snow (Georgievsky, 2009).

4.4.2. Processing of snow avalanche-controlling factors

4.4.2.1. Topography

Four maps are derived from the DEM data: slope gradient map; slope aspect map; convexities and concavities map; and flow accumulation map. The slope gradient map and slope aspect map were calculated in ArcGIS, and categorized based on previous statistical analysis (Ghinoi & Chung, 2005) and assigned value to show the likelihood of snow avalanche. Figure4. 2 shows the normalized frequencies of slope angle and slope aspect for three scenarios: major, moderate and minor events (Ghinoi & Chung, 2005).

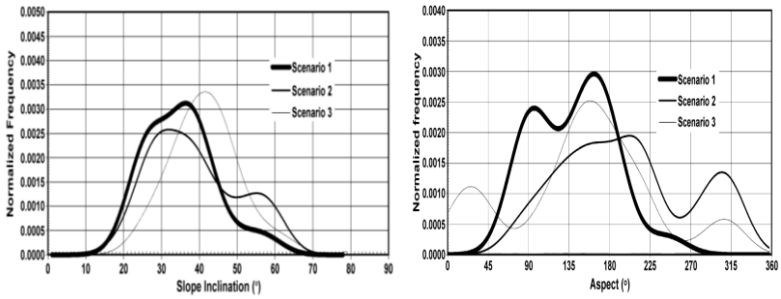

Figure4. 2. Normalized frequencies of slope angle (left), slope aspect classes (right) for snow avalanche initiation (Ghinoi & Chung, 2005)

Value of slope angle for snow avalanches are assigned according to the previous study as in Table4. 7.

Table4. 7. Assigned value to slope gradient

Slope gradient (°)	*Standardized value*	*Slope gradient (°)*	*Standardized value*
0 - 10	0	40 - 45	0.667
10 - 20	0.167	45 - 50	0.333
20 - 23	0.5	50 - 60	0.167
23 - 30	0.833	60 -90	0
30 - 40	1		

Slope aspect is calculated in ArcGIS choosing the direction of slope. In the result, -1 indicates the area is flat, while 0° to 360° indicates the direction from the north, for example 90° means the aspect is to the east, 180° means the aspect is to the south. The value of aspect for snow avalanche is assigned as follows:

Table4. 8. Numerical value assigned to slope aspect for snow avalanche

Aspect	*Standardized value*	*Aspect*	*Standardized value*
-1 - 0	0	80 - 190	1
0 - 63	0.33	190 - 205	0.67
63 -80	0.67	205 - 360	0.33

Plan curvature is also calculated in ArcGIS, as perpendicular to the direction of the maximum slope. Since it is the second derivative of the surface, and in McClung's study (2001), curvature is calculated as the tangent of slope, the result of plane curvature is calculated arctangent.

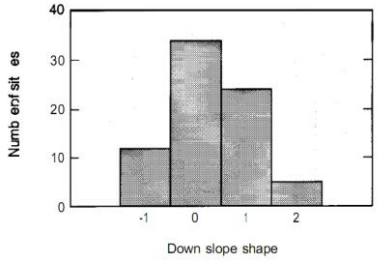

Figure4. 3. Statistical relationship between curvature and snow avalanche (McClung, 2001) (minus number indicates convex, which is opposite to ArcGIS)

Table4. 9. Value assigned to curvature for snow avalanche

Curvature	*Standardized value*
-1.5 - -0.5	0.66
-0.5 – 0.5	1
0.5 – 1.5	0.33

In the study of Gruber and Bartelt (2007), a minimum of 5000 m2 upslope area is one of the criteria for a potential snow release area. In this study, we set a gradual change for upslope area as the following table.

Table4. 10. Value assigned to accumulation for snow avalanche

Upslope area (m2)	*Standardized value*
< 5000	0
5000 - 10000	0.5
> 10000	1

4.4.2.2. Land cover

The roughness of the land cover influences the occurrence of snow avalanches (Ghinoi & Chung, 2005; McClung, 2001). The values assigned to land cover of snow avalanches instability are based on the roughness as the following table.

Table4. 11. Value assigned to land cover type for snow avalanche

Land cover	*Standardized value*
Lake, glacier, water reservoir, large river, wetland	0
Open forest, dense forest, park	0.2
Scrub, Orchard, Vineyard, Bare river sand, Urban park,	0.4
Grass land, island , Agriculture land	0.6
Settlement area, large city, cemetery, railway	0.8
Bare glacial moraine, badland, rocky	1

4.4.2.3. Roads

According to the limited snow avalanche inventory in Mtskheta-Mtianeti, most of the avalanches occurred along the road that connecting Russian and Georgia, which is a major road among the road system in Georgia.

A buffer zone was created for the three types of high ways as the following table.

Table4. 12. Value assigned to road buffer for snow avalanche

Distance to roads	*Standardized value*
0 - 50	1
50 – 100	0.8
100 - 150	0.5

4.4.2.4. MODIS snow cover

The MODIS Snow Cover data were used as an indication for the availability of snow. The dataset contains data fields for maximum snow cover extent over an eight-day compositing period and a chronology of snow occurrence observations.
Data from 2005 December to 2010 March are downloaded. The least disturbed dataset was chosen for each month (there are about 4 dataset per month).
Each dataset is transferred into snow cover area (1) and non-snow cover area (0). The disturbed areas such as cloud are assumed to be snow cover. Then they are summed up showing the months of snow cover for the study area.
As mentioned earlier the Boolean data for snow cover was used in the analysis. 9 months snow cover was set as the threshold in this study according to the inventory. That is to say, areas with 9 months or more than 9 months snow cover areas are set to be 1, other area are set to be 0.

4.4.2.5. Altitude

The abundance of snow, the widespread occurrence of steep (over 25°) slopes and numerous glacial troughs cause a high frequency of avalanches. In the Greater Caucasus, avalanches occur above 1500 m on the northern slopes and 500-800 m on the southern slopes; their frequency declines from west to east in line with the decline in precipitation(Rusnature, 2002).
Based on this information, mask is made. For the north slopes, areas lower than 600 m will be set to 0, while area higher than 600 m will be set to 1; for the south slopes, area lower than 1500 m will be set to 0, while area higher than 1500 m will be set to 1.

5. Generation of the susceptiblity maps including runout

The processed of combining factors for mass movement initiation assessment was carried out in the SMCE module of ILWIS (Integrated Land and Water Information System). The input is a set of maps that are the spatial representation of the criteria, which are grouped, standardized and weighted in a criteria tree. The theoretical weighting background for the multi-criteria evaluation is based on the AHP.
Given the situation of lacking historical event validation data, a basic sensitivity analysis was applied, on the weight of different factors for different mass movements, the DEM data used, and the cell sizes used. Different susceptibility maps were generated for the various types of mass movements: landslide, debris flow, rockfall and snow avalanche.
The source areas for runout modelling were selected from the susceptibility maps, from which the cells with the highest susceptibility were chosen. According to an assumed magnitude of triggering events, certain amounts of cells were chosen representing three situations: minor, moderate and major trigger source area. For example, about 1% of the whole area was chosen as source area of a minor triggering event for debris flows. The selection of the percentage of area affected from the susceptibility scores was done arbitrarily as it was not possible to base in on actual events, due to the lack of historical event information.
The source areas were then used to generate the runout in the model Flow-R. In the model several parameters need to be set such as the reach angle and the direction algorithm. They are set according to a previous study (Blahut, 2010) and the experiments done at an inventory-rich area (Barcelonnette, France). The results of experiments in the Barcelonnette are shown in appendix 2.
In the following sections first the methods will be further explained, after which the results will be presented.

5.1. Concepts and methods

5.1.1. Spatial Multi-Criteria Evaluation SMCE

Spatial Multi Criteria Evaluation is a GIS application that has been frequently used in fields such as natural resources and natural disaster management, for combining a series of spatial criteria using expert or consensus-based weighting, with the objective to locate the areas where a set of given criteria apply.
In SMCE the first step is to standardize the criteria. This is done using performance tables containing the evaluation or criteria scores of a set of parameters on the basis of a set of criteria, which has been down in the previous chapter. The next step consists of the weighting of the various criteria and the aggregation of the different

criteria scores using a specific aggregation procedure and taking into account the decision maker preferences, generally represented in terms of weights that are assigned to different criteria.

The Analytic Hierarchy Process (AHP) is used in this study for deciding the weight for each parameter in SMCE. The AHP is a structured technique for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution (Vargas, 1990). It helps decision makers find out the best suits their goal and their understanding of problem. AHP is widely used in site selection, suitability analysis, regional planning, and landslides susceptibility analysis (Yalcin, 2008). The process includes several steps: (1) break a complex unstructured problem down into its component factors; which are the parameters chosen in this study; (2) arrange these factors in a hierarchic order; (3) 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 & Vargas, 2001). When arranging the factors in a hierarchic order, there should be relative importance of one factor over another forming a pair-wise comparison matrix.

5.1.2. Runout Model used

Flow-R is a deterministic, empirical model working with regular grids. The debris flow runout can be mathematically estimated by two types of algorithms: the flow direction algorithms which decide the path that the debris flow will follow; the friction loss functions which determine the runout distance (Horton, Jaboyedoff, et al., 2008) .

Flow direction algorithms rule the direction of the flow from one cell to its eight neighbours. The selection of flow direction algorithms depends on the factors related to different types of landslides. Flow-R contains different flow direction algorithms which are suitable for certain conditions. For example, a multiple flow direction algorithm introduced by Quinn et al. (1991) and improved by Holmgren (1994) (equation 4) was used for the debris flow runout assessment in Valtellina Valley in Italian Central Alps (Blahut, 2010).

$$f_{si} = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}(\tan\beta_i)^x} \quad for\ all\ tan\beta > 0 \qquad (4)$$

Where i, j = flow directions (1…8), f_{si} = flow proportion (0…1) in direction i, $\tan\beta_i$=slope gradient between the central cell and the cell in direction i, and x = variable exponent.

The runout distance algorithms are basic energy-based calculations that define if a part of the mass movement can potentially reach another cell. Since the source mass

is unknown in a regional runout model, runout distance calculation is based on a unit energy balance (as indicated in equation 5), a constant loss function and a maximum threshold, (Horton, Jaboyedoff, et al., 2008).

$$E_{kin}^{i} = E_{kin}^{i-1} + \Delta E_{pot}^{i} - E_{loss}^{i} \qquad (5)$$

Where i = time step, E_{kin} = kinetic energy, ΔE_{pot} = change in potential energy and E_{loss} = constant loss.

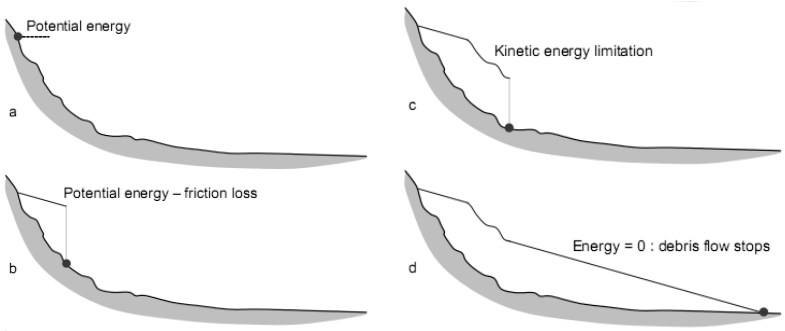

Figure5. 1. Illustration of the runout distance calculation principles

The probable maximum runout is characterized by an average slope angle (Huggel, Kaab et al., 2002), which is the slope between the starting and end point following the runout path. A constant friction loss, corresponding to the angle, would result in a runout distance equal to the probable maximum runout. The maximum velocity threshold is used to limit the debris flow energy to reasonable values. It also corresponds to maximum velocities of debris flow observed in the study area.

The runout model is applied in several study areas and generates good results with small cell size (10m). However, when using it at regional scale assessment, the input file size becomes too large for the model with 10m cell size. To compromise the limitation, cell size of the input data is set to be 50m for the Mtskheta-Mtianeti so that the model could be run.

5.2. Application and results

5.2.1. Landslide susceptibility assessment

The parameters that were explained in the previous chapter were combined in SMCE to produce a landslide susceptibility map. According to the AHP method, importance of every two parameters is set according to their contribution to landslides. For the weighting of the individual factors a comparison was made between the various factors using a pairwise approach. It is generally confirmed in landslide literature that topography contributes most in mass movements. Therefore, the slope always has the highest weight. Roads are quite important according to the

inventories in this region, while drainage is less important. The importance of lithology is considered more than land cover. The relative importance is given in Table5. 1. In the table if the number is larger than1, it means the horizontal factor is more important than the vertical factor, vice versa.

Table5. 1. Relative importance among the factors

	Slope	*Lithology*	*Drainage*	*Road*	*Land cover*
Slope	1	5	7	3	7
Lithology	1/5	1	3	1/3	3
Drainage	1/7	1/3	1	1/5	1
Roads	1/3	3	5	1	5
Land cover	1/7	1/3	1	1/5	1

Eigenvectors are calculated for the matrix and standardized in ILWIS. The inconsistency ratio is 0.03, which is in the range of acceptance. The susceptibility map is shown in Figure 5.2.

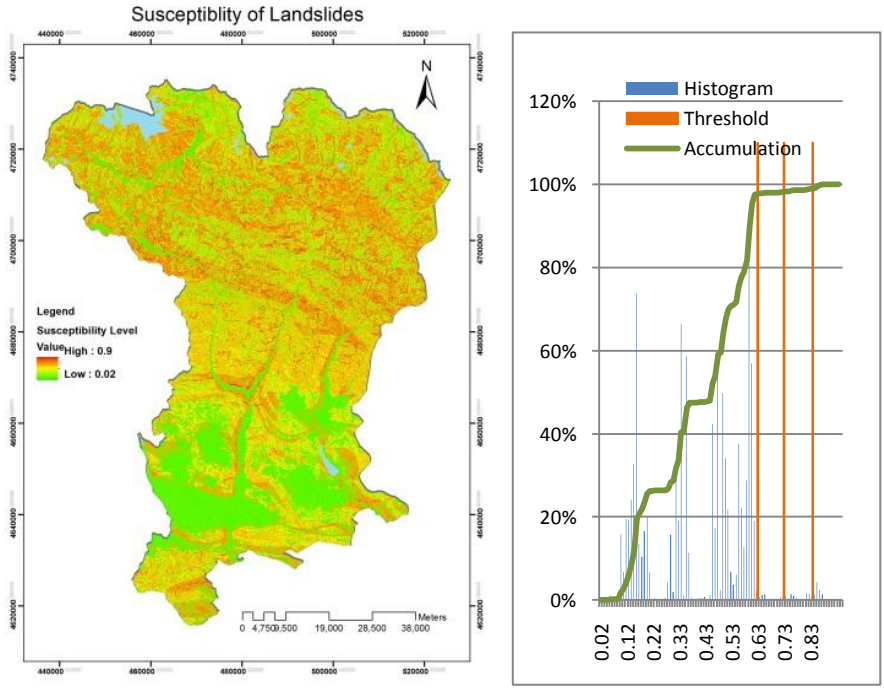

Figure5. 2. Susceptibility of landslide when lithology has more weight than land cover

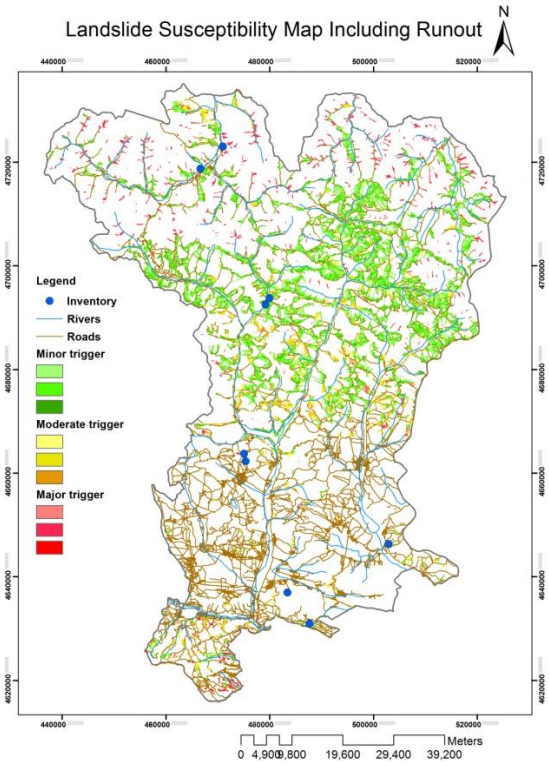

Figure5. 3. Landslide susceptibility map including runout

The highest 0.96% of the susceptibility value (amount chosen according to the histogram of the susceptibility value) is chosen as minor-trigger source areas, 1.79% as moderate-trigger source areas, and 2.26% as major-trigger source areas. This was done based on the following reasoning: if a minor triggering event would happen in terms of a rainfall event, than landslides would happen only in those places that are most susceptible (upper 0.96% of the area). When a moderately large triggering event would happen also those areas that have slightly lower susceptibility values would still be affected (additional 0.83%). When a major triggering event happens an additional 0.47% of the area might have landslides. Runout is modelled in Flow-R model with the criteria that 15° angle of reach, and exponential of 6 for the direction algorithm (equation 4) based on the experiment done for Barcelonnette. The runout is as figure 5.3. Amount of source areas and runout are displayed I in Table 5.2.

Table5. 2. Areas of predicted source and runout in percentage of the whole region

Magnitude of trigger	*Amount of source areas*	*Amount of runout areas*
Major	2.07%	12.27%
Moderate	1.98%	11.91%
Minor	1.13%	5.07%

5.2.2. Other mass movements

The same method is applied in other mass movement types. Table 5.3 shows the factors and the weight calculated in SMCE for each factor, and the parameters in using Flow-R to model the runout.

Table5. 3. Parameters chosen in assessing susceptibility for other mass movements

	Source area parameters		*Runout parameters*	
	Factors	Weight	Angle of reach	Algorithm selected
Debris flow	Slope	0.52	10°	Holmgren algorithm (equation 4)
	Lithology	0.13		
	Land cover	0.06		
	Drainage	0.26		
	Roads	0.03		
Rockfall	Slope	0.64	Not applicable	D8 algorithm
	Geology (lithology and faults)	0.26		
	Land cover	0.10		
Snow Avalanche	Topography (slope, accumulation, curvature, aspect)	0.64	20°	Holmgren algorithm (equation 4)
	Land cover	0.26		
	Roads	0.10		

The results are as follows:

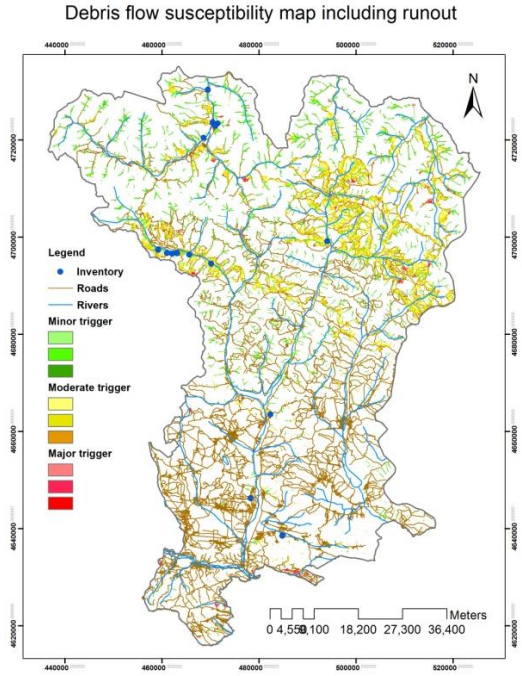

Figure5. 4. Debris flow susceptibility map including runout

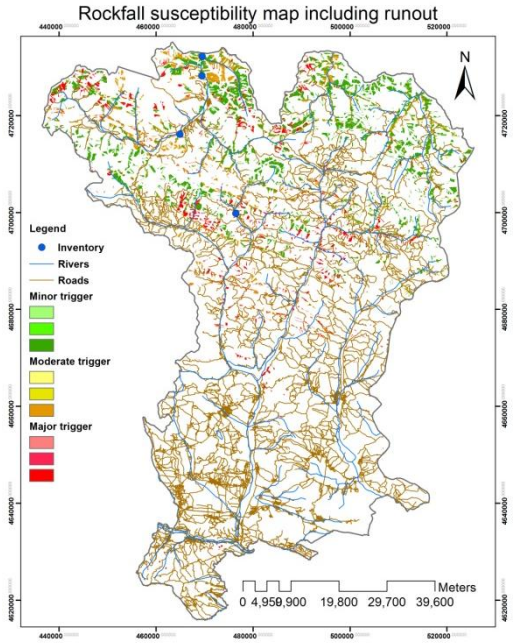

Figure5. 5. Rockfall susceptibility when using DEM generated from contour lines

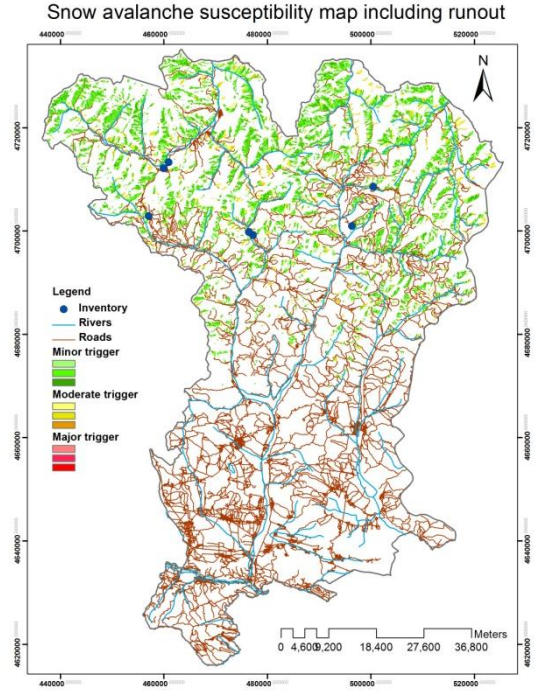

Figure5. 6. Snow avalanche susceptibility map including runout

6. Discussion and Conclusions

6.1. How the results fit the reality

The results were discussed with two Georgian experts: George Gaprindashvili and Irakli Megrelidze from the National Environmental Agency (NEA) of Georgia. They commented that the overall distribution of susceptible areas for each mass movement type matches the reality, and that in general the susceptibility is higher in the north part and lower in the south part.

For debris flows, the result map shows that the source areas for debris flow are mostly located along the drainage and road network, when the slopes are high. Overall, three classes of source areas (source area from major trigger events, moderate trigger events and minor trigger events) are mostly on the north of the province along the Caucasus Mountains. The other sources are found along the Aragvi River and a small hilly area on the south of the province next to Tbilisi, which is very similar to the reality that debris flows are along the Aragvi river and in the north (according to NEA knowledge and Google earth image).

The highest susceptibility areas, or the source areas that would be triggered by minor trigger events, are scattered across the mountainous region. The runout areas of the minor trigger events are not spread far away because the sources are mostly in concave areas. The source areas of moderate trigger events are covering a larger area than those for minor events, and are mostly on the northeast of Mtskheta-Mtianeti. They correspond with the lithology distribution pattern and the road network distribution. Areas with road cuts are included where the lithology for debris flows are susceptible. Since the source areas do not only exist in valleys but also hillsides, the runout area extends further. Major-trigger source areas are again larger than for moderate triggering events. The added source areas are generally located along roads and now also in the middle part of Mtskheta-Mtianeti, which has Cretaceous rocks. The runout pattern of major-trigger source area is the same with the previous sources: if source areas are in the valley, the runout is narrow and small; if the source areas are on the hillside, the runout spreads out more.

The susceptibility patterns for landslides are rather similar to those for debris flows. The difference lies in that they are more influenced by the roads than by the drainage network. Snow avalanche susceptibility is obviously more in the high mountain areas, and absent in the southern part of the study area.

Rockfall source areas and runout are also mostly located in the north part of the region, which is the same to the reality according to NEA experts. The distribution of high susceptible areas is quite similar to the distribution pattern of lithology. The

runout of rockfall is smaller than other mass movements since it is using a different direction algorithm.

Table 6.1 shows the number of historical events that are inside the predicted mass movement area.

Table6. 1. Number of historical events inside the predicted area

	Landslide	*Debris flow*	*Rockfall*	*Snow avalanche*
Major trigger	3	7	2	1
Moderate trigger	2	6	2	1
Minor trigger	2	5	1	0
No. of recorded events	9	16	4	7

Though the pattern of the susceptibility maps are considered realistic by Georgain experts, a comparison between these maps and the scarcely available historical events were less convincing. The reasons are several:

- The inaccurate location of the historical events. According the Georgian experts who did part of this work, the historical events are not exactly located in the area because the way to collect them was based on archive description.
- Second, the limited data used for modeling. Some data important for assessing the susceptibility were not available in this research, such as soil data for landslide assessment, wind direction data for snow avalanche. If those data are available, the result could be more similar to the reality;
- Third, the knowledge from literature cannot be extrapolated fully. Some of the factor standardization is generally based on studies of other areas. Though the principles are the same in different study area, it is better to have research on the local area.
- Fourth, the cell size of the study. In the runout model, the direction algorithm is based on the topography. Large cell sizes decrease the accuracy of runout prediction considerably.

6.2. How DEMs influence the results

Chapter 3 compared DEMs generated from different sources and of different sizes. The influence of DEM on the susceptibility map with runout will be compared in this section with an example of rockfall susceptibility analysis.

Three susceptibility maps (without runout) maps were calculated in SMCE for rockfall, with the same criteria. The histogram of susceptibility is shown in figure 6.1.

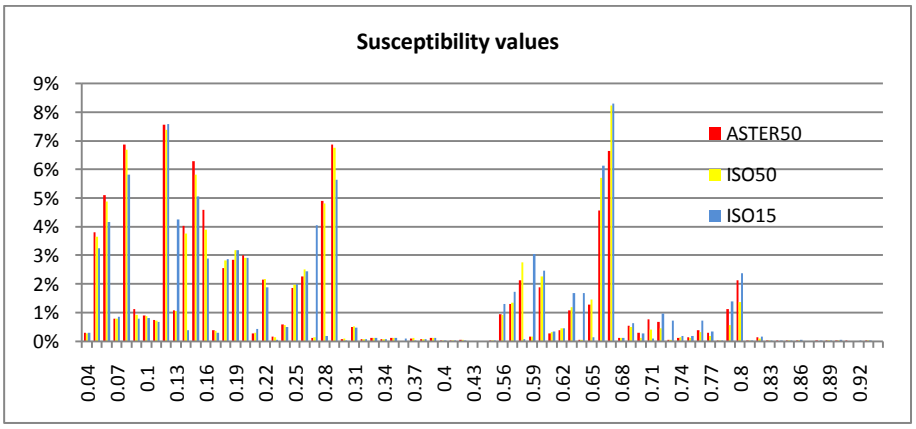

Figure6. 1. Histogram of susceptibility maps

The histograms of the susceptibility maps are not very different. The susceptibility map made with DEM of cell size of 15 meters (ISO15), has fewer low-susceptibility cells (susceptibility index < 0.32) but more high-susceptibility cells (susceptibility > 0.44) than ISO50. The susceptibility map made using the ASTER DEM has more high-susceptibility cells between the index ranges of 0.69 to 0.84, fewer low-susceptibility cells between indexes from 0.44 to 0.64 than from ISO50.
The ISO15 was not used in runout generation, as the Flow-R runout model software cannot handle large size input data due to the limitation of the model.

The final susceptibility including the runout was validated for ASTER50 and ISO50. First of all, the amount of predicted area including source and runout for rockfall is calculated.

Table6. 2. Areas of predicted source and runout in percentage of the whole region for two types of DEM sources

Magnitude of trigger	*ASTER50*		*ISO50*	
	Source areas	Runout areas	Source areas	Runout areas
Major	4.41%	10.69%	4.35%	8.21%
Moderate	3.55%	8.92%	3.34%	6.72%
Minor	2.43%	5.85%	2.08%	4.74%

Secondly, the historical events are compared with the predicted susceptibility. The number of historical events within certain distance from predicted source area, and the numbers of historical events within the predicted runout area are calculated. (Table 6.3)

It can be seen that even if the source area and the runout area for ISO50 is relative smaller than ASTER50, the result is more accurate with ISO50.

Table6. 3. Number of historical events located inside predicted runout area

	ASTER50	*ISO50*
Magnitude	Inside the Runout	Inside the Runout
Major trigger	1	2
Moderate trigger	1	1
Minor trigger	1	1

6.3. How different weights affect the results

An analysis was done on the effects of weighting different factors in SMCE due to the uncertainty of the contribution of some factors. The importance of lithology and land cover is compared in this study for both debris flow and landslides. Numbers of historical events within the predicted runout area are calculated for both mass movements.

Table6. 4. Areas of predicted source and runout for debris flow in percentage of the whole region

Magnitude of trigger	*Lithology more weight*		*Land cover more weight*	
	Amount of source areas	Amount of runout areas	Amount of source areas	Amount of runout areas
Major	2.07%	12.27%	2.25%	15.13%
Moderate	1.98%	11.91%	1.9%	10.85%
Minor	1.13%	5.07%	0.98%	4.90%

Table6. 5. Number of historical events located inside predicted runout area

Magnitude	*Lithology more weight*	*Land cover more weight*
	Inside the Runout	Inside the Runout
Major trigger	7	5
Moderate trigger	6	5
Minor trigger	5	5

Table6. 6. Areas of predicted source and runout for landslide in percentage of the whole region

Magnitude of trigger	*Lithology more weight*		*Land cover more weight*	
	Amount of source areas	Amount of runout areas	Amount of source areas	Amount of runout areas
Major	2.26%	16.20%	2.28%	16.21%
Moderate	1.79%	14.47%	1.81%	14.52%
Minor	0.96%	10.95%	1.04%	11.45%

Table6. 7. Number of historical events located inside predicted runout area

Magnitude	*Lithology more weight*	*Land cover more weight*
	Inside the Runout	Inside the Runout
Major trigger	3	3
Moderate trigger	2	2
Minor trigger	2	2

The analysis shows that in the study area, when lithology is given more weight, the results are better, especially for debris flow. For example, the number of historical event within predicted runout is more for debris flow. However, the weight doesn't influence landslide assessment too much.

6.4. Conclusion

The weights of factors influence the results in the SMCE for mass movement susceptibility assessment. In debris flows and landslides, lithology is found to have more influence than land cover for the susceptibility map. However, the conclusion is related to the property of the study area, of which the land cover type is quite uniform that more than 90% of the area is made up of grassland and forest.

Linear factors such as roads and drainage network influence the results a lot in SMCE. The highest susceptibility-value cells are mostly along linear segments. Though it is similar to the reality, for example, debris flow mostly happens along drainage.

Cell size matters in the research because on one hand, small cell size will generate higher slope, one the other hand, it will affect the amount of area in each class in the standardization process. What is more, the runout software cannot handle large input files (smaller cell size makes a large file).

Standardization should be detailed enough, that is to say there should be enough classes for each factor. Because if the standardization is too coarse, there could be situation that large areas have the same highest susceptibility value, which makes it difficult to generate the source area. (e.g., 9% of the whole cells have the same highest value of 1).

The DEM interpolated from contour lines at 50 meters is better in this susceptibility assessment than the ASTER 30 meters DEM. The results of the rockfall runout made with a DEM derived from contour lines, predicted less susceptible areas while there are more historical events located within these.

Runout assessment generally delineates the susceptibility zone according to topography. Spreading is always small if the source areas are in the valleys; and large if they are on a hillside.

About the study method, traditionally, for a small scale mass movement assessment only susceptibility assessment of the initiation areas is done. This research, however, also included a basic assessment of the runout of mass movements, which is relevant as most of the mass movement damage is caused by mass movements that originate upslope and affect elements at risk that are located in lower areas. From the research it can be concluded, that a heuristic susceptibility assessment can generate good results if the knowledge about the local environmental situation is well known. The runout included in the susceptibility assessment can delineate the susceptibility zones more realistically than an initiation susceptibility assessment only.

7. Recommendations for improvement

7.1. Use of susceptibility maps

As described in the first chapter, susceptibility map at a regional scale can be used in several aspects in planning: by defining the hotspots or priority area for more detailed local scale susceptibility assessment, as a guide for restrictive zoning I relation to future construction, or as a basis for reviewing the risk for constructions and human being that exists in the region.

A combined mass movement susceptibility map was generated, using the highest susceptibility value among the mass movements types for each cell (e.g. if a cell may be hit by landslide with 50% chance, and by debris flow with 30% chance, the result for this cell is 50% chance to be hit by mass movement). Together with the element at risk (road, pipeline as example), three maps of minor trigger, moderate trigger and major trigger risk are produced. (Figure 7.1, 7.2, 7.3)

With the multi hazard susceptibility maps, elements at risk can be generated with a relative dangerous level to the hazard. Take settlement for example:

Settlement indicates the location where there are villages. It scatters all over Mtskheta-Mtianeti. Most of the settlements are near the major roads and rivers. Totally there are 534 settlements in this region. Table 7.1 shows the number of settlements in risk. For example, if a major trigger happens, 22 villages could be in high risk of mass movements. Risk degree for other elements (major roads, pipelines, agriculture, and urban area) is shown in appendix3.

Table7. 1. Number of settlements in risk with different trigger magnitude

	numbers of settlements (Totally 534)		
	Major trigger	Moderate trigger	Minor trigger
High	22	20	14
Moderate	34	29	25
Low	32	31	25
Very low	44	40	32
None	402	414	438

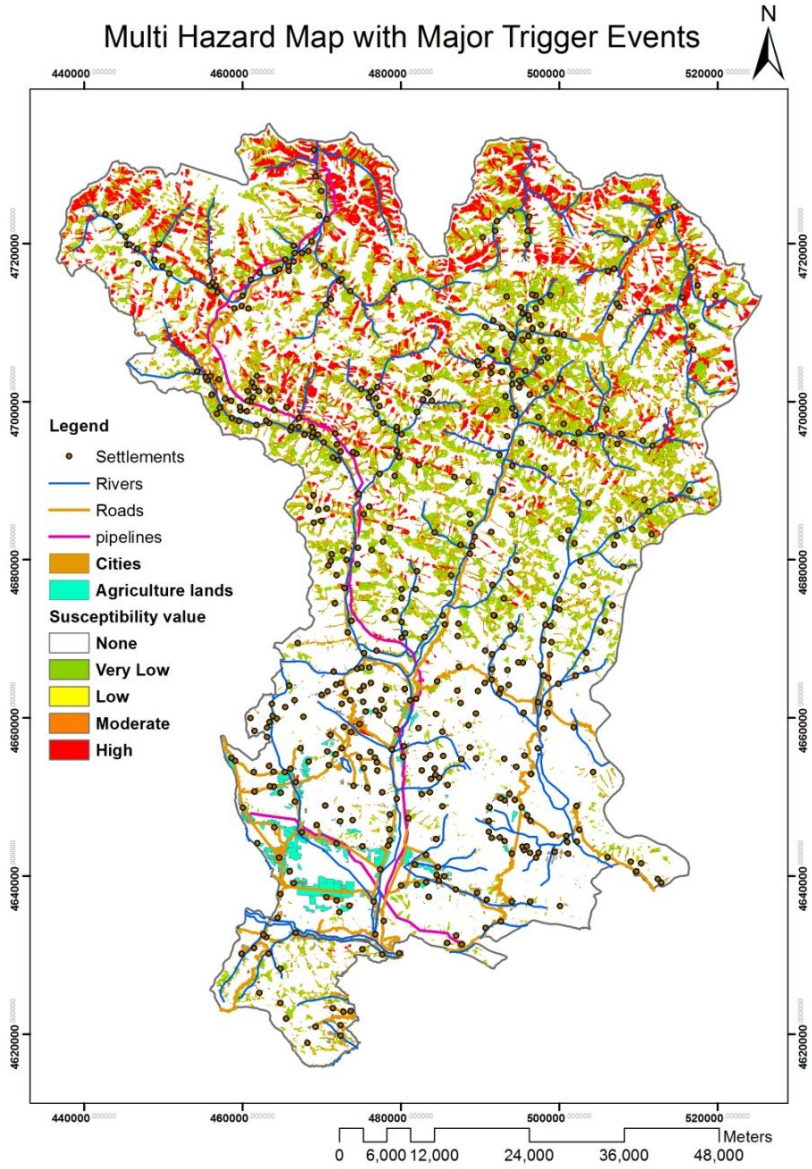

Figure7. 1. Multi hazard map with major trigger events

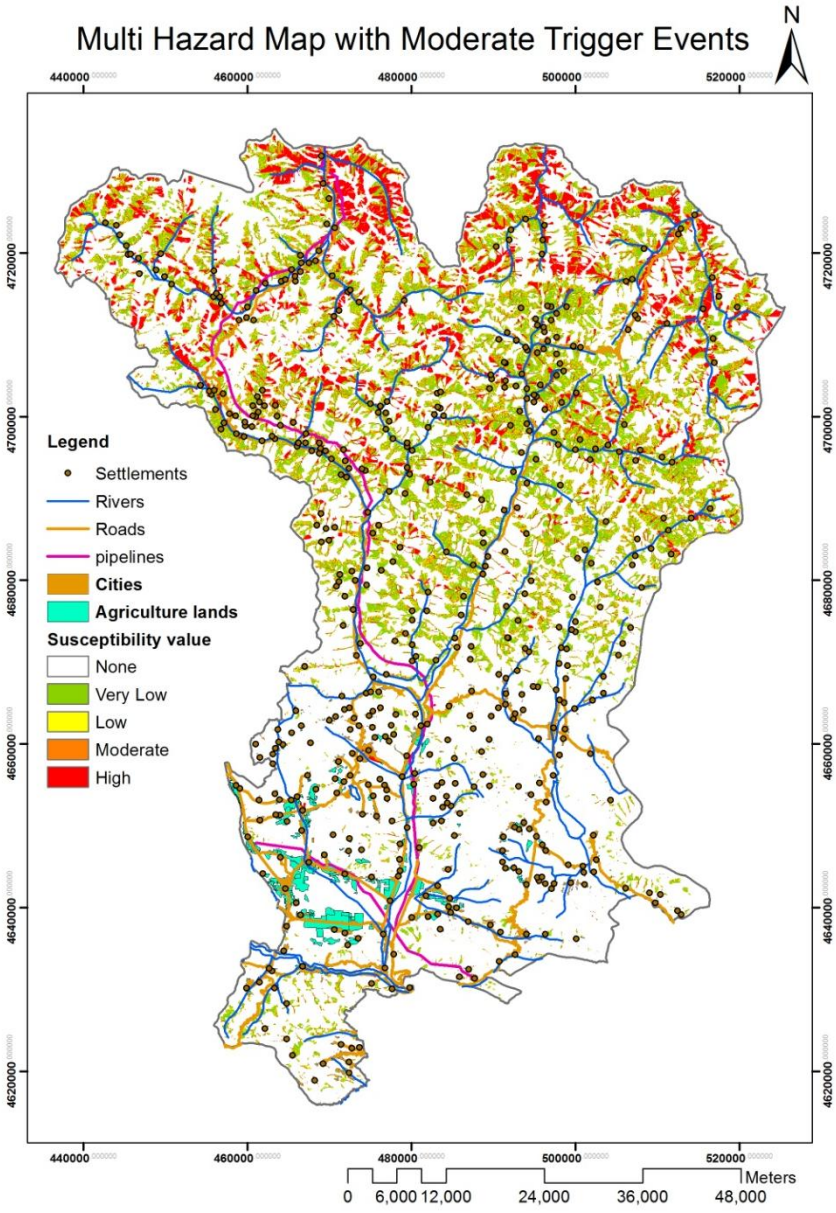

Figure7. 2. Multi hazard map with moderate trigger events

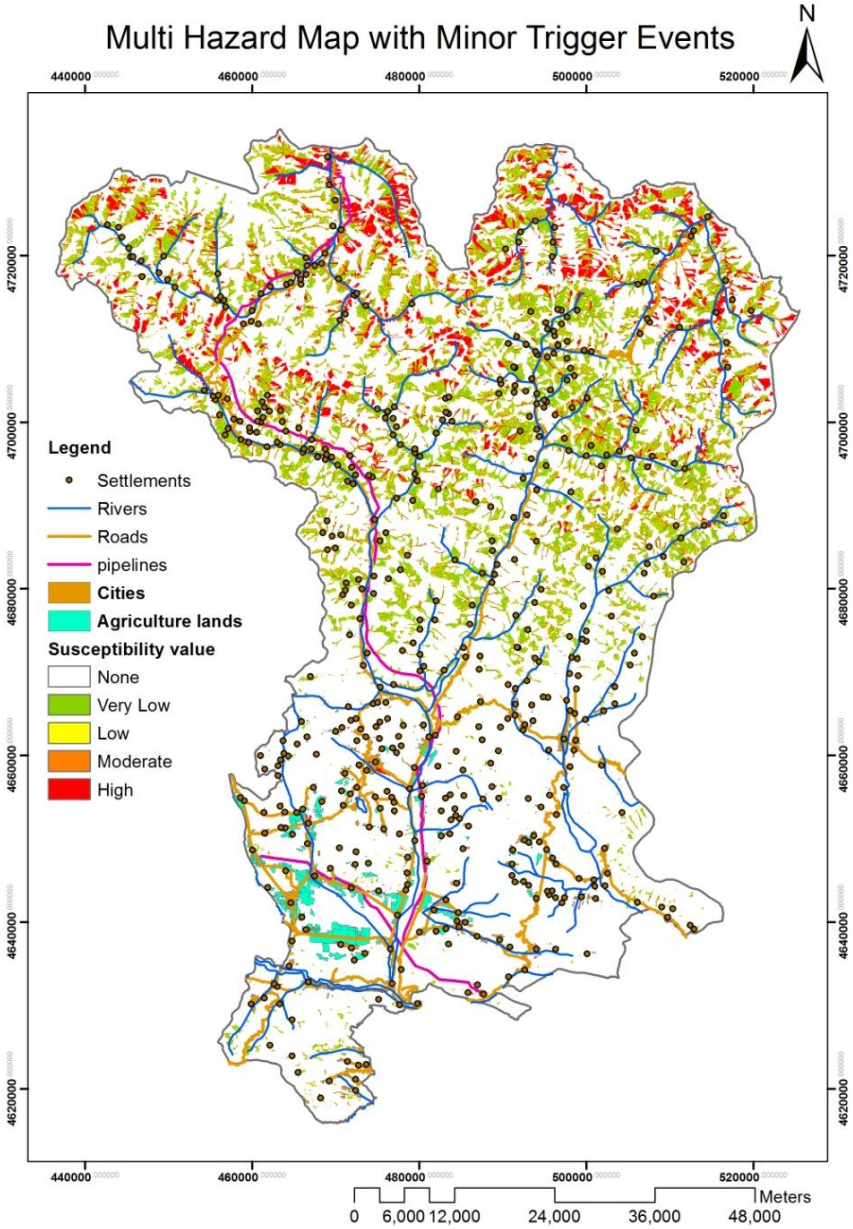

Figure7. 3. Multi hazard map with minor trigger events

7.2. Future researches

Due to the limitations of time and data, there are still a lot of improvements that can be suggested for future research. As mentioned in chapter 6, the results of the susceptibility assessments do not fit the historical events very well partly because of the limited data. Some data are useful in assessing the susceptibility while they are not available in this research, such as soil data for landslide assessment, wind direction data for snow avalanche. Future work can be done on collecting and analysis those data. The suggested environmental data are: soil data for landslides, geomorphology data for rockfall, wind direction for snow avalanche. Besides the environmental factors, trigger factors are also useful, such as temperature for snow avalanche, precipitation for debris flow and snow avalanche. However, by far the most important type of information is a historical database of landslides, snow avalanches, rockfalls and debris flows. Only by learning from the events that have occurred in the area, it is possible to improve the weight methods using the SMCE approach, or event apply statistical methods if enough historical data are available. The historical data is also essential for analyzing magnitude-frequency relationships and to obtain spatial, temporal and size probabilities that are important for subsequent quantitative hazard and risk assessment.

It is also possible to change the susceptibility map into a hazard map by adding temporal information. This research does not take temporal information into account, since there is rarely temporal information about historical events until now. As the completion of historical event data, there will be more events with date collected. Together with the frequency of the trigger events such as precipitation, a hazard map could be produced.

Earthquake induced mass movements are not considered in this study since one earthquake could trigger a significant amount of landslides. There could be another assessment on earthquake triggered landslides with temporal and magnitude information.

Improving the runout map is one method to improve the result. Since the runout model calculates runout based on topography, the susceptibility map is not continuous, for example, there may be small areas that are surrounded by probable hazard. Mass movement zoning can be done based on the distribution of source area and runout, which will produce more homogeneous areas that are easier to read and use.

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Appendix

Appendix1. List of agencies and organizations

Georgian Government

EMD Emergency Management Department (Ministry of Internal Affairs

MRA Ministry of Refugees and Accommodation

MRDI Ministry of Regional Development and Infrastructure

NEA (Geology) National Environmental Agency (Ministry of Environmental protection and natural resources of Georgia), Department of Geological hazards and Geological environment management)

NEA (Hydro) National Environmental Agency (Ministry of Environmental protection and natural resources of Georgia), Hydrometeorology Department

NSC Office of the National Security Council

International organisations and UN

British Emb. British Embassy

DTROG Defence Threat Reduction Office Georgia (U.S. Embassy)

FAO United Nations Food and Agriculture Organization

IFRC International Federation of Red Cross and Red Crescent Societies

IOM International Organization for Migration

SDC Swiss Agency for Development and Cooperation

UNDP United Nations Development Programme

UNFPA United Nation Population Fund

UNHCR Office of the United Nations High Commissioner for Refugees

USAID U.S. Agency for International Development

WFP UN World Food Programme

WHO World Health Organization

International NGOs

ACF Accion contra el Hambre

CARE CARE International

MC Mercy Corps

SC Save the Children

Tdh Terre des Hommes

Scientific institutes

BMA Batumi Maritime Academy

CRBRE Centre of Radiobiology and Radiation Ecology

GWMI Georgian Water Management Institute

IG M. Nodia Institute of Geophysics

IHM Institute of Hydrometeorology

Inst. Geography Vakhushti Bagrationi Institute of Geography

Inst. Geology Alexander Janelidze Institute of Geology

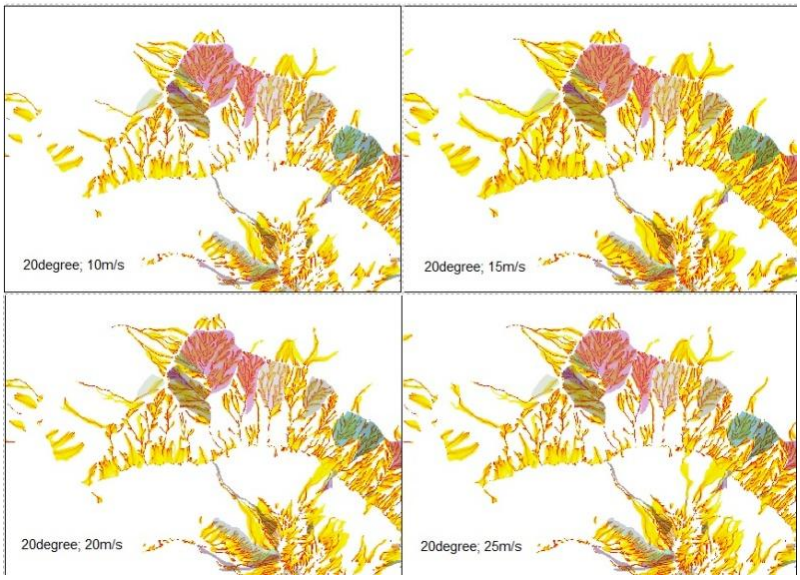
Inst. Hydrology Institute of Hydrology and Engineering Geology
Inst. Mineral Al. Tvalchrelidze Caucasian Institute of Mineral Resources
Inst. Radiology Institute of Agrarian Radiology and Ecology
ISMEE Kiriak Zavriev Institute of Structural Mechanics and Earthquake Engineering
NCDC PH L. Sakvarelidze National Centre of Disease Control and Public Health
NAM M. Sabashvili Institute of Soil Studies, Agro-Chemistry and Amelioration
TMI G.Tsulukidze Mining Institute

National Organizations

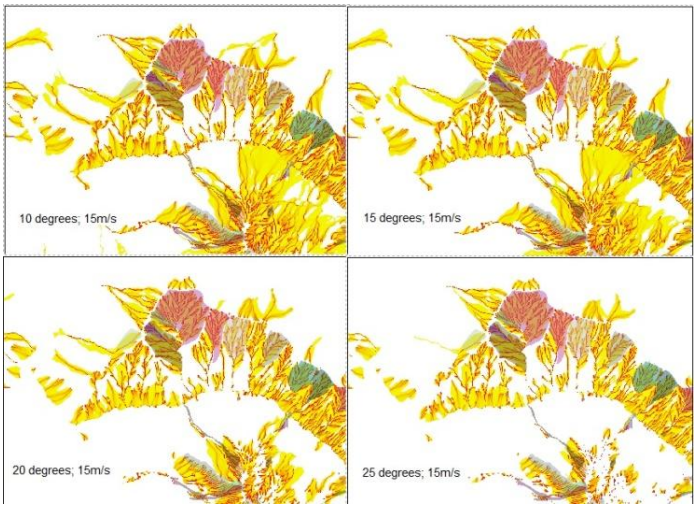
CENN Caucasus Environmental NGO Network
GA Association Green Alternative
GNCDRR Georgian National Committee of DRR and Environment Sustainable Development
GRCS Georgia Red Cross Society

Appendix2. Runout in Barcelonnette with different parameters

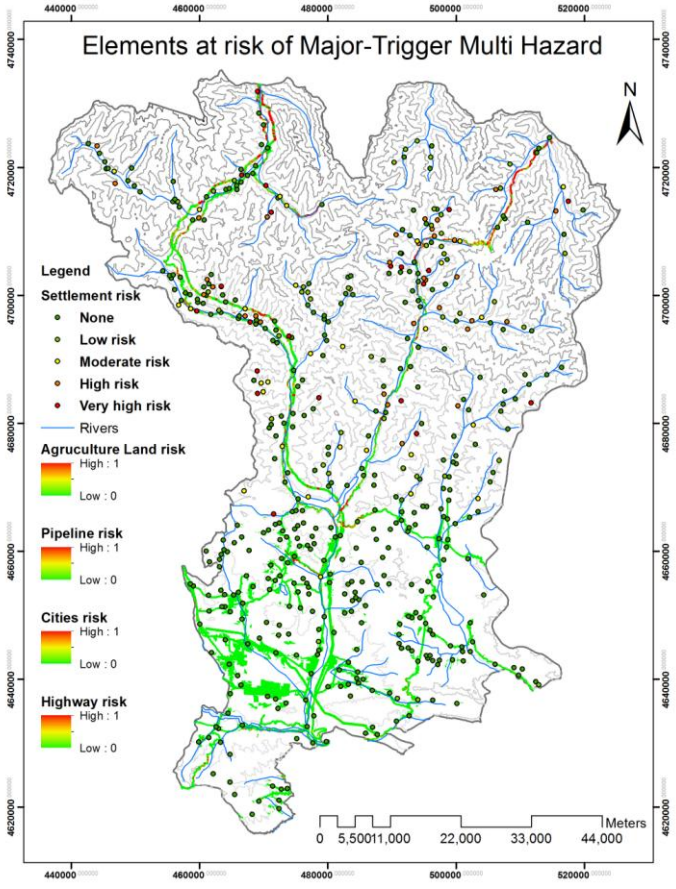
For snow avalanche, when the angle of reach is set to be 20 degree, with changing velocity limitation, the modelled runouts are:

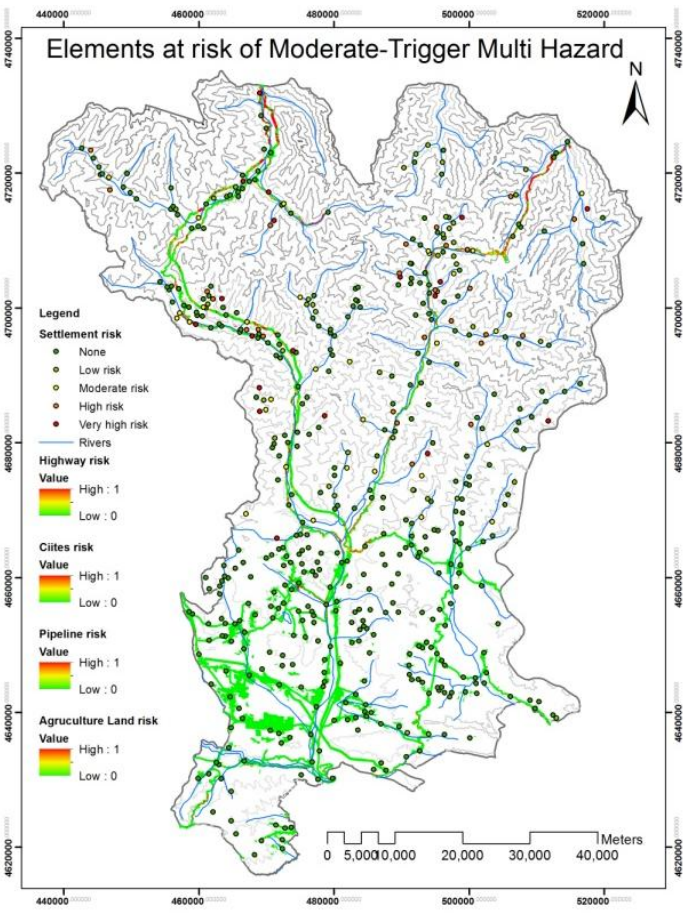


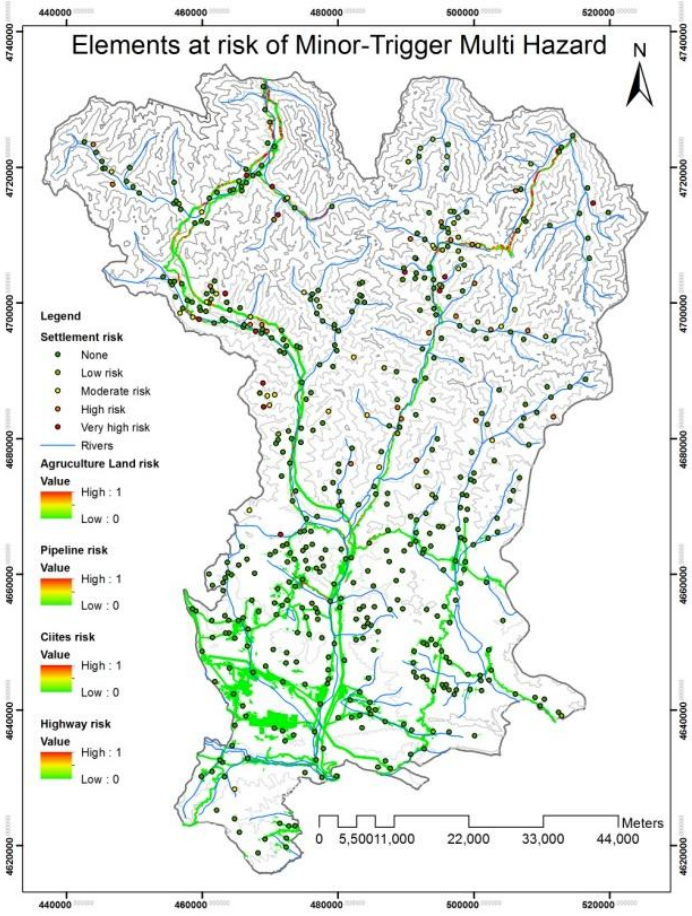
When the velocity limitation is set to be 15m/s, with changing angle of reach, the modelled runouts are:



Appendix3. Element at risk assessment map




Elements at risk of Moderate-Trigger Multi Hazard
N
Legend
Settlement risk
None
Low risk
Moderate risk
High risk
Very high risk
Rivers
Highway risk
Value
High : 1
Low : 0
Ciites risk
Value
High : 1
Low : 0
Pipeline risk
Value
High : 1
Low : 0
Agruculture Land risk
Value
High : 1
Low : 0
0 5,000 10,000 20,000 30,000 40,000
Meters


Elements at risk of Minor-Trigger Multi Hazard
N
Legend
Settlement risk
None
Low risk
Moderate risk
High risk
Very high risk
Rivers
Agruculture Land risk
Value
High : 1
Low : 0
Pipeline risk
Value
High : 1
Low : 0
Ciites risk
Value
High : 1
Low : 0
Highway risk
Value
High : 1
Low : 0
0 5,500 11,000 22,000 33,000 44,000
Meters