

METHODOLOGY FOR
SNOW AVALANCHE

MODELLING AND
MAPPING FOR GEORGIA



Methodology for

Snow Avalanche

Modelling and Mapping for Georgia

2021



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მრეწველობის
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Prepared by an international expert, Walter J. Ammann in partnership with the LEPL National Environmental Agency (NEA) of the Ministry of Environmental Protection and Agriculture of Georgia with assistance from the United Nations Development Programme (UNDP) and the Swiss Agency for Development and Cooperation (SDC). The views expressed are those of the authors and do not necessarily reflect those of UNDP and SDC.

The seven-year USD 73.6 million programme on reducing the risk of climate-driven disasters is implemented by the United Nations Development Programme (UNDP) and benefits from the USD 27 million grant from the Green Climate Fund (GCF), a USD 5 million grant from the Swiss Government, a USD 3.6 million grant from the Government of Sweden and USD 38 million in co-financing from the Government of Georgia. The programme consists of three interrelated projects:

GCF funded: Scaling-up a Multi-Hazard Early Warning System and the Use of Climate Information in Georgia

SDC funded: Strengthening Climate Adaptation Capacities in Georgia

SIDA funded: Improved Resilience of Communities to Climate Risks

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Abbreviations

Acronym	Meaning
CENN	Caucasus Environmental NGO Network
EMS	Emergency Management Service
CRED	Centre for Research on Epidemiology of Disasters
EU	European Union
EEA	European Environment Agency
EWS	Early Warning System
GCF	Green Climate Fund
GRF	Global Risk Forum
SLF	WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland
SOP	Standard Operating Procedure
MEPA	Ministry of Environmental Protection and Agriculture
MoESD	Ministry of Economy and Sustainable Development
MLC	Machine Learning Classifier
MP	Meteorological Post
MRDI	Ministry of Infrastructure and Regional Development
MS	Meteorological Station
MAHMM	Methodology for Snow Avalanche Modelling and Mapping
NCAR	National Centre for Atmospheric Research
NEA	National Environmental Agency
RD	Road Department
SDC	Swiss Development and Cooperation
SIDA	Swedish International Development Cooperation Agency
UNDP	United Nations Development Programme
WMO	World Meteorological Organization
CBEWS	Community Based Early Warning System
DEM	Digital Elevation Model
DRM	Disaster Risk Management
DTM	Digital Terrain Model
EN	European Standards
ESPO	European Spatial Planning Observation Network
GCF	Green Climate Fund
GIS	Geographic Information Systems
JRC	Joint Research Centre
LEPL	Legal Entity of Public Law

Abbreviations

LHM	Local Hazard Mapping
LiDAR	Light Detection and Ranging
LSHM	Large Scale Avalanche Mapping
NAPR	National Agency of Public Registry
NASA	National Aeronautics and Space Administration
NEA	National Environmental Agency
RAM	Risk Assessment Methodology
SDC	Swiss Development Cooperation
SIDA	Swedish International Development Agency
SLF	Swiss Institute for Snow and Avalanche Research
SOP	Standard Operation Procedures
UNDP	United Nations Development Programme
WMO	World Meteorological Organisation
WSL	The Swiss Federal Institute for Forest, Snow and Landscape Research

Executive Summary

Snow avalanches are reported to cause serious damage to roads, buildings, and the population in the mountainous regions of Georgia every year; in particular, in the north to north-west part of the country. Many settlement areas are located within snow avalanche hazard zones and might get cut off by avalanches since they block the access roads to the settlements. Some information on snow avalanches is available from the beginning of the 19th century and is associated with the regular traffic along the former Military Road of Georgia.

Snow avalanches cause serious damage to roads, buildings, and population in the mountainous regions of Georgia every year. Utilities (communications) and many settlement areas are located within snow avalanche hazard zones. Snow avalanches frequently cause the isolation of settlements (sometimes municipalities) since they block the access roads to the settlements. Snow avalanches occur more frequently in the western part of Georgia as compared to the eastern part. This is caused by the higher amount of precipitation and steep slopes. Snow avalanches are frequent, in particular, on the slopes of the Caucasus and Adjara Mountains. Strong activity of snow avalanches in Georgia was reported in the years 1975-1976, 1986-1987 and 1996-1998 which means that major avalanches do occur within a ten-year return period.

Avalanche hazard mapping serves a variety of actions and measures and is, in particular, based on snow avalanche modelling. Avalanche modelling is performed to produce avalanche hazard maps delineating the likely starting and transition zones of avalanches and, in particular, the runout areas of avalanche deposits. In addition, dynamic avalanche modelling provides the dynamic flow properties during runout such as flow and deposition heights, avalanche velocities and impact pressures on objects (buildings, infrastructure, etc.). The analysis of meteorological data and snow properties to determine model input parameters is key as well as the calibration of the dynamic avalanche modelling and the necessary boundary conditions that best describe the physical runout behaviour of avalanches based on the analysis of recent snow avalanche events in the region. Snow avalanche hazard and risk modelling is used to assist in the spatial land-use planning of existing or new settlements, buildings, transport routes, electricity transmission lines and other critical infrastructure in order to limit avalanche risk. It also provides the necessary input data for the efficient and the effective design of buildings, infrastructure, and protection measures.

Defining model parameters for avalanche modelling is challenging because the flow mechanics of avalanches are governed by avalanche release volume, topography, and terrain morphology and, in particular, the

snow properties, all of which may change on spatial and temporal scales. In principle, three different types of avalanches occur: dry snow dense flow avalanches, wet snow plug flow avalanches and powder snow

avalanches. Their occurrence depends on the physical characteristics of the snow cover and the topography and the morphology of the terrain. The snow cover characteristics over mountainous terrain change both seasonally and with respect to altitude and climatic situations.

There are several approaches to avalanche modelling, each of which requires calibration to past avalanche events with a greater or lesser degree of detail. The models have the goal of linking the avalanche starting conditions in the release zone with the runout dynamics through the transition zone to the stopping conditions in the deposition zone. The Methodology for Snow Avalanche Modelling and Mapping for Georgia (MSAMM) focuses on two main approaches in order to determine the maximum avalanche runout area with a) the α - β -model of McClung and Lieds and the internationally most applied software tool RAMMS::AVAL of the WSL Institute of Snow Avalanche Research (SLF) in Davos, Switzerland.

The SLF approach has the advantage that a first insight on the general avalanche risk situation is possible over a large area of the country by doing a large-scale hazard mapping LSHM. This approach uses basically the same technology which is used afterwards for the more detailed local avalanche hazard modelling by using a licensable SLF software called RAMMS::AVAL, the internationally most applied software tool for snow avalanche modelling, which allows for a detailed quasi 3D-analysis of avalanche runout paths and the corresponding dynamics along the transition and runout zones.

The MSAMM defines three phases for avalanche hazard modelling:

Phase 1: To conduct a nationwide, large scale hazard mapping based on an automated GIS-based procedure to detect snow avalanche release areas combined with the dynamic modelling of all of the potential avalanches which result in an indicative nation-wide avalanche hazard map. The physics and mechanics behind the numerical modelling are like the ones used in the RAMMS software for the single-track modelling. However, this LSHM modelling process is more generalised and uniform throughout the whole territory to be included in the simulation process and does not allow the taking of varying local (snow) information into account. The software is not licensable and, therefore, the simulation runs are to be done by the SLF in close cooperation with the client. The advantage with this simplified approach is in handling x-thousands of avalanche tracks throughout a large area (country size) at the same time in one run. An extremely high computational capacity is thus required. The simulation can be made for various avalanche return periods – also for 100-year or 300-year return periods where hardly any historical data exist on past devastating avalanches. Various outcomes such as avalanche release area contours, transition and deposition zone contours, avalanche pressure, flow height and avalanche velocities are the results of these simulations. The simulation results can be used for a number of subsequent applications such as the risk modelling in Phase 2 or for an overview on avalanche risks along a pass road, etc.

Phase 2: Linking the results of this large-scale avalanche hazard mapping with other GIS layers (population, buildings, settlements, roads, railways, and other critical infrastructure, etc.) results in a nation-wide avalanche risk map; the risk, thereby, being a mathematical construct as a multiplication of the avalanche hazard, the assets/values which are exposed to the avalanche hazard and the respective

vulnerabilities of these assets. The risk map can be used for classifying avalanche prone zones in (local) areas, e.g., in zones at high, moderate, and low risks, thereby giving the ability to prioritise the subsequent dynamic and more detailed avalanche modelling process in areas at risk at a local scale. This step is based on the outcomes of Phase 1 in combination with the economic risk analysis procedure and can be done independently of the SLF software used in Phase 1. Phase 2 is only partially addressed hereafter as the provision of the GIS based layers with information on the various assets exposed to avalanche hazards are not covered by this mandate. However, the LSHM methodology recommended hereafter is fundamental for the risk approach. The risk-based approach – in particular, the presentation of the results at the risk level – has to be the same for all hazards. It has to be agreed for the three risk levels for all hazards to be considered. Only a risk-based approach guarantees the appropriate priority setting for the various methods to be taken to cope with hazards.

Phase 3: The detailed local avalanche modelling process should start in areas at a high risk as a result of Phase 2. It is recommended to license the RAMMS software from the SLF Davos to do these track-specific numerical simulations. The software will need some basic training on the handling and on the verification and the interpretation of the results. Local specific data on snow and avalanches and local knowledge and expertise have to be integrated. The results of Step 3 are to be used many-fold – e.g., for land-use planning maps, the planning of technical avalanche prevention and protection measures and the decision making in early warning at a local scale, etc.

Avalanche hazard mapping nowadays should be based on existing powerful numerical software tools. Before entering into detailed local avalanche hazard mapping a country-wide large scale hazard mapping is required.

Fundamental to all avalanche prevention and protection solutions, be they the active application of technical avalanche protection structures or the implementation of an effective land-use planning or early warning system, is that there is an effective data collection and distribution system on avalanche hazards. A large number of the critical snow avalanche risks can be avoided by applying a combination of soft measures including effective land-use planning and early warning systems supported by an effective avalanche bulletin service.

While it is attractive to install fixed avalanche protection measures, such as avalanche dams or snow supporting structures in avalanche prone areas, it is often the case that the greatest impact on improving avalanche safety is made by implementing the organisational structure to deliver effective avalanche warning. Moreover, the prerequisite for the implementation of many of the technical structures is that there is a detailed history of the avalanche situation at a given site with ongoing avalanche weather and snow accumulation monitoring.

The assessment of avalanche hazards on a short time scale must be based on weather reports and snow measurements taken from the field on a regular basis. Experience and judgement in avalanche dangers is also of great importance.

Introduction

1.1 Background and Context

The Methodology for Snow Avalanche Modelling and Mapping (MSAMM) contributes to reducing the exposure and the vulnerability of communities in Georgia through the development of multi-hazard risk information and relevant capacities, particularly in for snow and avalanche hazards.

The National Environmental Agency under Ministry of Environment Protection and Agriculture of Georgia possesses the main information and historical data on hydro-meteorological and geological hazards and have respective databases. The staff is experienced in the monitoring, assessment, and mapping of natural hazards as well as the obtaining, collecting, and processing of respective data and information. However, there is no definitive hazard, risk, or vulnerability mapping methodologies for Georgia for any of the hydro-meteorological and geological hazards.

1.2 Goals and Objectives

The MSAMM will provide a unified approach for snow avalanche hazard mapping as a basis for a concise vulnerability and risk assessments.

The development of the methodologies and mapping approaches for hazard assessment will also serve to develop forecasting and early warning systems, identification, prioritisation and the design of risk mitigation measures, the development of river basin multi-hazard risk management plans, municipal emergency response plans, sector resilience plans and community DRM and CBEWS.

1.3 Purpose and Structure of the Report

The MSAMM is based on detailed desk research and a comparative analysis of avalanche practices both internationally and nationally and focusses on conducting a nationwide and large-scale hazard mapping based on an automated GIS-based procedure to detect snow avalanche release areas combined with a

rough dynamic modelling of each avalanche while also providing avalanche contours in the deposition zone. The result of this modelling is a nation-wide avalanche hazard map. Combining these results with other layers such as houses, settlements or critical infrastructure allows to create a country-wide risk map alongside a visualisation of potential human and economic losses. The MSAMM provides details on local avalanche modelling process in areas at high risk, based on the RAMMS software of the SLF, and on how to use the results in further activities such as establishing land-use planning maps or for technical avalanche prevention and protection measures, etc.

1.4 Definitions

Disaster - A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources. Comment: Disasters are often described as a result of the combination of the exposure to a hazard; the conditions of vulnerability that are present; and insufficient capacity or measures to reduce or cope with the potential negative consequences. Disaster impacts may include loss of life, injury, disease and other negative effects on human physical, mental and social well-being, together with damage to property, destruction of assets, loss of services, social and economic disruption, and environmental degradation. (UNISDR, 2009)

Disaster Risk - The potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period. Comment: The definition of disaster risk reflects the concept of disasters as the outcome of continuously present conditions of risk. Disaster risk comprises different types of potential losses which are often difficult to quantify. Nevertheless, with knowledge of the prevailing hazards and the patterns of population and socio-economic development, disaster risks can be assessed and mapped, in broad terms at least. (UNISDR 2009)

Disaster Risk Management - The systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies, and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster. Comment: This term is an extension of the more general term “risk management” to address the specific issue of disaster risks. Disaster risk management aims to avoid, lessen, or transfer the adverse effects of hazards through activities and measures for prevention, mitigation, and preparedness. (UNISDR, 2009)

Disaster Risk Reduction - The concept and practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events. Comment: A comprehensive approach to reduce disaster risks is set out in the United Nations-endorsed Hyogo Framework for Action, adopted in 2005, whose expected outcome is “The substantial reduction of disaster losses, in lives and the social, economic and environmental assets of communities and countries.” The International Strategy for Disaster Reduction (ISDR) system provides a vehicle for cooperation among Governments,

organisations, and civil society actors to assist in the implementation of the Framework. Note that while the term “disaster reduction” is sometimes used, the term “disaster risk reduction” provides a better recognition of the ongoing nature of disaster risks and the ongoing potential to reduce these risks. (UNISDR, 2009)

Early Warning System - The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss. Comment: This definition encompasses the range of factors necessary to achieve effective responses to warnings. A people-centred early warning system necessarily comprises four key elements: knowledge of the risks; monitoring, analysis and forecasting of the hazards; communication or dissemination of alerts and warnings; and local capabilities to respond to the warnings received. The expression “end-to end warning system” is also used to emphasize that warning systems need to span all steps from hazard detection through to community response. (UNISDR, 2009)

Forecast - Definite statement or statistical estimate of the likely occurrence of a future event or conditions for a specific area. Comment: In meteorology a forecast refers to a future condition, whereas a warning refers to a potentially dangerous future condition (UNISDR, 2009)

Hazard - A dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Comment: The hazards of concern to disaster risk reduction as stated in footnote 3 of the Hyogo Framework are “... hazards of natural origin and related environmental and technological hazards and risks.” Such hazards arise from a variety of geological, meteorological, hydrological, oceanic, biological, and technological sources, sometimes acting in combination. In technical settings, hazards are described quantitatively by the likely frequency of occurrence of different intensities for different areas, as determined from historical data or scientific analysis. (UNISDR, 2009)

Mitigation - The lessening or limitation of the adverse impacts of hazards and related disasters. Comment: The adverse impacts of hazards often cannot be prevented fully, but their scale or severity can be substantially lessened by various strategies and actions. Mitigation measures encompass engineering techniques and hazard-resistant construction as well as improved environmental policies and public awareness. It should be noted that in climate change policy, “mitigation” is defined differently, being the term used for the reduction of greenhouse gas emissions that are the source of climate change. (UNISDR, 2009)

Prevention - The outright avoidance of adverse impacts of hazards and related disasters. Comment: Prevention (i.e., disaster prevention) expresses the concept and intention to completely avoid potential adverse impacts through action taken in advance. Examples include dams or embankments that eliminate flood risks, land-use regulations that do not permit any settlement in high-risk zones, and seismic engineering designs that ensure the survival and function of a critical building in any like-

ly earthquake. Very often the complete avoidance of losses is not feasible, and the task transforms to that of mitigation. Partly for this reason, the terms prevention and mitigation are sometimes used interchangeably in casual use.

Risk Management - The systematic approach and practice of managing uncertainty to minimize potential harm and loss. Comment: Risk management comprises risk assessment and analysis, and the implementation of strategies and specific actions to control, reduce and transfer risks. It is widely practiced by organizations to minimise risk in investment decisions and to address operational risks such as those of business disruption, production failure, environmental damage, social impacts and damage from fire and natural hazards. Risk management is a core issue for sectors such as water supply, energy, and agriculture whose production is directly affected by extremes of weather and climate. (UNISDR, 2009)

Stakeholder Mapping

2.1 Introduction

Based on the discussions with NEA avalanche experts, only a very preliminary overview on some stakeholders exists. This aspect has to be further developed by NEA. The identification process should consider not only the various activities linked to the hazard mapping in the meaning of numerical avalanche modelling but also include the stakeholders involved in the various other activities listed hereafter.

Stakeholders will have to be identified considering national, regional and local disaster management agencies and institutions as well as scientific and technical agencies such as meteorological and hydrological organisations, health authorities and geophysical agencies, engineers, land-use and urban planners, researchers and academics (including from the sphere of social sciences) and organisations and community representatives involved in avalanche disaster/emergency and avalanche risk management.

2.2 Stakeholder Interests

Avalanche hazard mapping has a direct or indirect impact on various activities/processes and products and is used for:

- Land-use planning (snow avalanche hazard and risk modelling is used to assist in the spatial land-use planning of settlements, transport routes, electricity transmission lines and other critical infrastructure in order to limit avalanche risk. It also provides the necessary input data for the efficient and the effective design of buildings, infrastructure, and protection measures).
- Design of protection measures (galleries, dams, etc.).
- Assessment of the effectiveness of protection forests and vegetation in general.
- Avalanche early warning/forecasting/now-casting: identification of hazardous areas along critical infrastructure such as roads and railways, dynamic on-time hazard modelling (now-casting) often combined with a numerical snowpack modelling.

A variety of stakeholders are thus involved in hazard and risk assessment, modelling and mapping and come from many different areas of both the private and the public sectors and should include producers and users/beneficiaries of the hazard and risk maps and avalanche information as well as also

identifying those institutions in education and research and organisations which might be engaged in educating the broader public to raise their awareness to cope with avalanche risks. The public sector needs to be addressed from national, regional and community levels.

2.3 Stakeholder Identification

The stakeholder mapping should include stakeholders by categories such as:

- Producers.
- Advisers/contributors.
- Users/beneficiaries.
- Delivery stakeholders.

Stakeholder mapping and analysis examines how each stakeholder is involved in hazard and risk assessment and modelling and mapping as well as in the resulting products and it identifies those partners and networks that are important for hazard and risk assessments.

Stakeholder mapping identifies the expertise of each stakeholder/partner that is used or can be used in hazard and risk assessment, modelling and mapping.

Stakeholder mapping identifies the methods by which such stakeholders can be engaged in long-term hazard assessment and mapping and will:

- a. Develop plans on how to work with and involve relevant stakeholders/partners.
- b. Develop methods to integrate the existing functions of stakeholders to the hazard and risk process towards achieving the national goals of increasing, harmonising, and unifying the approach.
- c. Identify the needs of each stakeholder and how their needs may impact hazard and risk assessment, modelling and mapping, and the contributions that the stakeholders will make to the long-term hazard and risk assessment, modelling and mapping methodologies and the longer-term process.

Table 1 shows an overview of the various processes and products linked to the stakeholders with their expertise, their needs, and the importance of strengthening their role.

Table 1. Overview on Georgian Stakeholders of Snow Avalanche Hazard Analysis and Mapping

Process Product	Level (national, regional, communal)	Sector (public/private)	Category of stakeholder	Methods	Contribution to processes/products	Partners/Networks ¹	Expertise	Involvement	Needs	Importance (low, medium, high)
Forecasting services	National	Public/Private	Producers	N/A	Public Awareness	N/A	Considerable	National Environmental Agency (NEA)	Very high	High
Commercial avalanche warning services	National	Private/governmental	Producers	N/A	Avalanche safety plan	N/A	Considerable	National Environmental Agency (NEA)	Very high	High
Snow avalanche risk assessment and mapping	National	Public/private	Producers	N/A	Avalanche hazard mitigation and protection measures	N/A	Moderate	National Environmental Agency (NEA)	Very high	High
Safety of ski resorts	Local	Public	Contributors	N/A	Avalanche safety plan	N/A	Considerable	Mountain resort development company, avalanche control team, mountain rescue service, ski Patrol	Very high	High
Rescue services	National, regional, municipal	Public	Beneficiaries	N/A	Safety	N/A	Moderate	Emergency Management Service of the MIA of Georgia	Medium	Medium
Road safety	National, municipal local	Public/private	Beneficiaries	N/A	Transportation safety		Moderate	Roads Department of Georgia	High	High
Spatial planning and construction	Central, regional, municipal, local	Public/private	Beneficiaries	N/A	Avalanche hazard mitigation and protection measures		Moderate	National, regional, local authorities, private sector	Medium	Medium
Eco-migrant households' assessment	National, regional, municipal, local	Public	Beneficiaries	N/A	Hazard risk mitigation		Considerable	National Environmental Agency (NEA), Internally Displaced Persons, Eco-migrants, and Livelihood Agency, local authorities	High	High

1. According to the NEA (email from Vitali Machavariani, 22 March 2021). The NEA has no official partnership with other providers/networks regarding snow avalanches.

03

Review of Relevant International Legislation

(Including EU Directives, WMO Guidelines and Other Commitments)

Only a small amount of literature exists which focuses on the international standardisation of snow avalanche hazard mapping. The origin of (avalanche) hazard mapping dates to the 1960s when some countries were hit by strong avalanche winters causing deaths and damage to their assets. Hazard mapping then became popular following the Swiss example which had been developed by the WSL Swiss Federal Institute for Snow and Avalanche Research SLF in Davos.

In the 1990s, hazard mapping also became popular for other natural hazards following the example of snow avalanches. Heavy snowfalls in January/ February 1999 in the Alps led to more than 100 deaths and several billion USD in economic damage. Consequently, many countries reviewed their avalanche risk management procedures. The European Commission initialised a project to review procedures and standards (Hervas, 2003). The review was organised as a workshop by the EU Joint Research Centre in Ispra, Italy and led to some generally agreed conclusions (Hervas, 2003).

In 2010, the European Environment Agency made another review covering all relevant natural hazards (EEA, 2010). This report assessed the occurrence and impacts of disasters and the underlying hazards such as storms, extreme temperature events, forest fires, water scarcity and droughts, floods, snow avalanches, landslides, earthquakes, volcanoes, and technological accidents in Europe for the period 1998-2009. It also addressed the advances in disaster risk reduction and management through a set of instruments developed by the European Union as well as the establishment of national strategies and national platforms for disaster risk reduction. Moreover, the report focused on data gaps and the lack of information on past events and their impacts, and the possible ways to improve the knowledge base.

Systematic data sources outside of the alpine countries are still incomplete and the quality of information concerning both human and economic losses due to snow avalanches is variable throughout Europe. Global disaster databases like EM-DAT give a limited estimate of the overall impact of avalanches, since many smaller events are not recorded. This is shown by the much lower total recorded fatalities in EM-DAT (2010) for the period 1998–2009 (130 deaths) as compared to the International Commission for Alpine Rescue ICAR (2010) with 1,500 deaths for the same period.

Only very limited and very basic information on avalanches and their management is available from international organisations (UNDRR, WMO). In most cases, the main informational source is the WSL Swiss Snow and Avalanche Research Institute SLF in Davos. The following sections are, therefore, written with a close link to the Swiss situation and Swiss management procedures. In particular, with the exception of RAMMS: AVAL developed at the SLF Davos, no comparable quasi 3D-software exists at the international level.

Current research on guidelines, norms, and standards for the construction of avalanche protection measures focuses on the available literature in Switzerland. The documentation is mostly only available in German, French, and Italian with the exception of the guidelines for avalanche defence structures in starting zones. Guidelines will also be required in English.

Current literature on avalanches includes:

- **Avalanche structures in avalanche starting zones:** The guideline regulates the planning of snow supporting structures and the dimensioning of separated structures. The guideline is complementary to the relevant SIA standards. It is directed towards designers and project engineers.

Federal Office for the Environment FOEN, ASTRA, 2007, Defence Structures in Avalanche Starting Zones (PDF, 1 MB, 19.05.2010), p. 134, UV-0704-E

- **Avalanche protection galleries (only available in German, French and Italian):**

Federal Office for the Environment FOEN

https://www.astra.admin.ch/dam/astra/de/dokumente/standards_fuer_nationalstrassen/astra_12007_einwirkungeninfolgelawinenaufschutzgalerien2007v200.pdf.download.pdf/astra_12007_einwirkungeninfolgelawinenaufschutzgalerien2007v200.pdf \o "ASTRA 12007 Einwirkungen infolge Lawinen auf Schutzgalerien (2007 V2.00)

- **Rock-fall protection galleries (only available in German, French and Italian):**

Federal Office for the Environment FOEN, ASTRA, 2006 Einwirkungen infolge Steinschlags auf Schutzgalerien (2008 V2.03) (PDF, 897 kB, 03.09.2008)

04

Review and In-depth Comparative Analysis of International and National Best Practice in Avalanche Hazard Modelling, Mapping and Assessment

4.1 Avalanche Mapping History of Georgia

Snow avalanches are reported to cause serious damage to roads, buildings, and the population in the mountainous regions of Georgia every year; in particular, in the north to north-west part of the country. Many settlement areas are located within snow avalanche hazard zones and might get cut off by avalanches since they block the access roads to the settlements. Some information on snow avalanches is available from the beginning of the 19th century and is associated with the regular traffic along the former Military Road of Georgia. Some major historic events have occurred on:

- 7 March 1850: 68 residents of the village Ginati died.
- 14 February 1932: 112 residents of the village Arashenda died.
- 1987: 27 residents of the community of Mulakhi (Upper Svaneti) died.
- Strong activity of snow avalanches in Georgia was reported in the following winter periods: 1975-1976, 1986-1987 and 1996-1998.
- Between 1995-2017, a total of 261 avalanches caused the death of 35 people. The economic damage during that period amounts to GEL 78 million (EUR 20 million).

The numbers of fatalities over the last 20 years reveals an average of approximately two deaths/winter and caused economic damage of about EUR 1 million/winter.

A study was finalised in 2012 (CENN, 2012) which addressed several natural hazards, including snow avalanches. However, only avalanche release zones were considered, and runout assessments were

not performed in terms of a snow avalanche hazard map for Georgia. For the detection of potential release areas, a number of input parameters, such as altitude, slope, aspect, forest cover and plan curvature data, were derived from a digital elevation model (ASTER GDEM). A temporal satellite dataset from MODIS was used to map snow-cover distributions over several years. Land cover information was used from existing topographic maps, cadastral maps, and aerial images (forest cover for the occupied territories was obtained from Landsat satellite images). Seven layers of individual components were generated and weighted.

After weighting all of the seven layers, the final snow avalanche hazard map was made with a four-level classification: safe (it is not coloured on the map), low, moderate, and high. According to the obtained results, 10% of Georgia's territory appeared to be in the high hazard zone, 22% in the moderate zone and 6% in the low-risk zone with 62% of the areas not at risk. Additionally, some avalanche hazard zones were detected in semi-arid areas of Georgia. (CENN, 2012). Figure 1 shows the countrywide avalanche hazard mapping (based on potential release areas) and reveals that avalanche prone areas comprise roughly 40% of Georgia (30,000 km²).

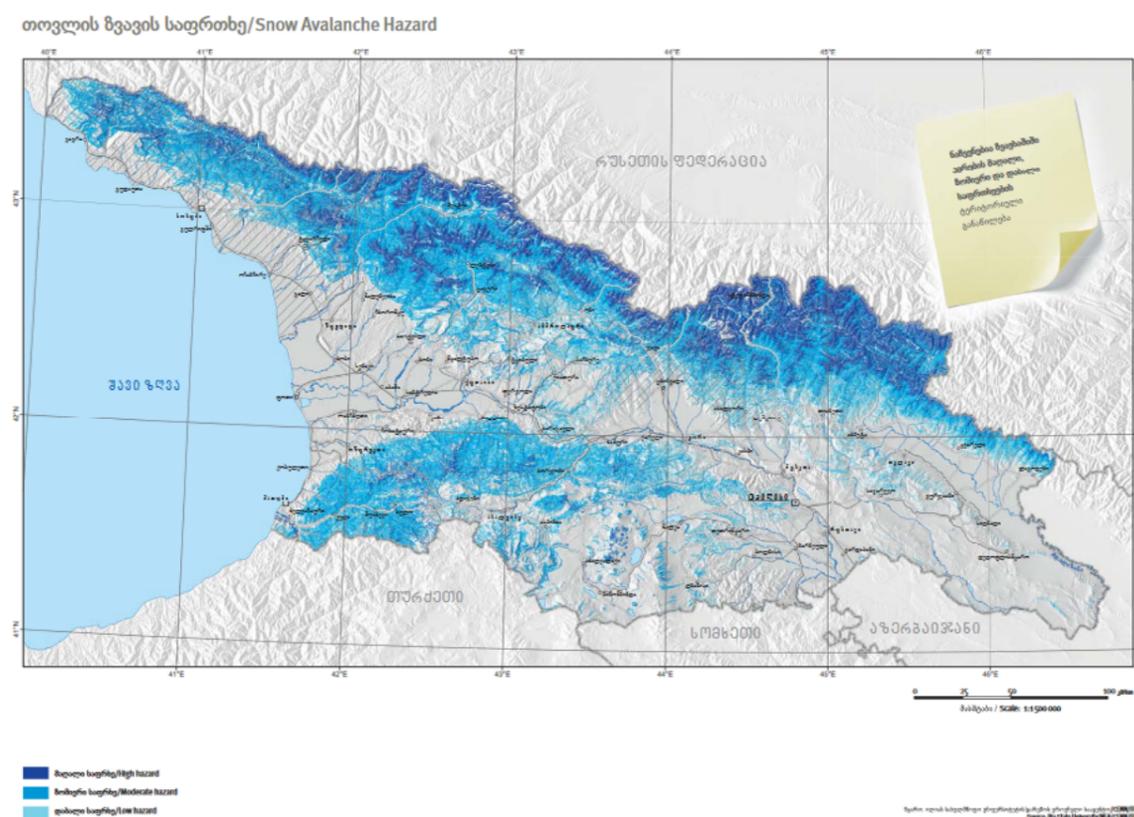


Figure 1. Existing Avalanche Hazard Map of Georgia

Source: CENN, 2012

4.2 Avalanche Hazard Simulation Methods – A Brief Overview

4.2.1 Introduction

There are two suitable approaches for large-scale hazard mapping: a simple empirical method the α - β -model (McClung and Lied, 1987) which uses an average runout angle based on regionally calibrated parameters and a much more sophisticated method which was developed during the past years is the numerical avalanche modelling software RAMMS::AVAL (Christen, et al., 2012 and 2013). The empirical α - β -model, only predicts runout potential, meanwhile RAMMS::AVAL software provides deterministic flow modelling approach applying various friction parameters and predicting not only runout potential but also flow dynamics parameters along the avalanche transition zone based on release volumes set by the fracture depth d_0 and the release area.

Each approach requires a selection of appropriate model parameters that best describe the physical process of avalanching snow within the bounds of the model. The calibration phase requires snow and meteorological data and sufficient evidence of past avalanches to accurately select model parameters that are representative of the characteristic avalanches of a given region. McClung and Schaerer (2006) suggest that an avalanche record over 30 years is required in order to ensure that an avalanche event with a return period of 100 years is adequately predicted (McClung, 2000).

When performing the large-scale hazard mapping of avalanches, it is unrealistic to expect that the necessary data be available in order to perform detailed avalanche modelling nationwide. In this instance, a much coarser approach is required which provides a conservative estimation of the potential avalanche runout and the respective hazard, i.e., the most extreme case is presented. Two main possibilities exist today for a large-scale avalanche hazard mapping:

- i) Avalanche reach angle, α - β -model.
- ii) RAMMS::AVAL, a numerical modelling software with generalised model parameters.

4.2.2 Hazard Mapping and the Use of Numerical Modelling

Numerical modelling in avalanche dynamics is used nowadays as a standard tool for hazard mapping; in particular, for single avalanche track analysis. Hazard mapping is crucial not only for adequate territorial development plans but also for evacuation and resettlement decisions, artificial avalanche release planning and many more direct and indirect applications. Numerical modelling is used in almost all domains and stages of avalanche risk reduction measures – even for early warning.

An important prerequisite for the numerical modelling of avalanches is the determination of the potential avalanche release zone. Over the last five years, the SLF in Davos, Switzerland has developed a method that automatically and efficiently pinpoints avalanche starting zones and combines these identified avalanche release areas with the dynamic avalanche simulation software RAMMS to model avalanches and their runout zones in order to calculate and visualise a potential avalanche hazard on a large scale.

The hazard maps highlight areas that could be endangered by avalanches and are thus very useful in territorial development (land-use planning, new infrastructure planning, etc.) and in assessing potential risks vis-à-vis existing settlements and infrastructure.

In alpine regions, it is especially important to know which areas are endangered by snow avalanches. In some countries, including Switzerland, hazard maps already exist. These have been produced based on land registry information, climate data, terrain analyses and numerical simulations of avalanche dynamics. Hazard mapping by experienced specialists is, however, a costly and technically very sophisticated process. For this reason, it can be adopted only for individual avalanche paths; in particular, those that pose a threat to settlements and key infrastructure.

Although large-scale indicative hazard maps are less detailed than regular local hazard maps, they can provide an initial broad overview of natural hazards based on numerical simulations spanning large areas. This is especially useful for places which, as is the case in most of the world's mountain regions, have only sparse records available regarding relevant events. Given that high-resolution digital elevation models, generated with the aid of modern remote sensing methods, are becoming available for more and more mountain regions as well, useful numerical avalanche simulations can now be performed for entire mountain ranges.

The ability to run dynamic avalanche simulations with the very latest software, such as RAMMS from the SLF Davos, depends on the precise identification of starting zones and fracture depths. The SLF has developed an algorithm to identify potential avalanche starting zones on the basis of terrain parameters. The estimation of fracture depths is based on the increase in snow depth in a period of three days.

Once the starting zones have been identified and the corresponding fracture depths have been calculated, a simulation is performed for each of the relevant terrain polygons with the aid of friction parameters that have been validated in connection with regular hazard mapping. The procedure can be applied for a variety of scenarios such as a return period of five-30 years (frequent) or 100-300 years (extreme). This allows for dynamic avalanche simulations to be performed efficiently and automatically, not only for individual avalanche paths but also in the context of large-scale applications at regional and national levels. This approach can also be used to assess the capacities of protection forests to avoid the occurrence of avalanches.

Empirical Large-scale Avalanche Hazard Mapping, the α - β -Model

The simplified α - β -model uses a terrain model or profile and projects a line at angle α from the release zone down to the maximum runout distance of avalanche deposits (see Figure 2).

Snow avalanche reach angle analysis is an empirical method to predict avalanche runout distances known as the α - β -model. The method is based on statistical evidence of snow avalanche runout and measures the angle α between the furthest runout point and the top of the avalanche release crown (McClung and Lied, 1987) (see Figure 2). The angle β looks at the intersection with the terrain in the runout zone with a slope angle less than 10° (zone where the friction forces begin to dominate the gravitational forces and the avalanche starts to decelerate). This model can be easily linked to a GIS sys-

tem and provide large-scale hazard mapping, but it is limited to only predicting the maximum runout of avalanches.

The reach angle analysis is performed in a GIS environment and requires the input of a terrain model and release areas delineating the avalanche release crowns. The selection of the appropriate α angle to perform the broad scale mapping of the potential runout extent is normally based solely on past avalanche events in the region of interest. The α -angle for mountainous regions like Georgia can be found in Delparte et al., (2008).

For hazard analysis concerning land planning and the management of avalanche threats to humans and infrastructure, typically the angle α is selected to represent an extreme 100-year avalanche event (Sinickas and Jamieson, 2014) and are on the order of $\alpha = 30^\circ - 45^\circ$ (Delparte et al., 2008).

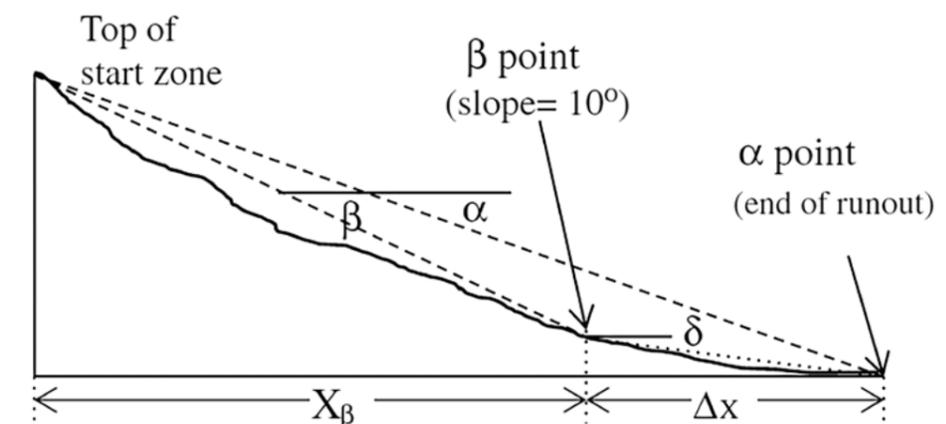


Figure 2. Avalanche Runout Geometry Depicting Angles α and β and Terrain Intersection Point at the First Onset of a 10° Slope. Avalanche runout using the α - β -model is based on statistical documentation of avalanche runout geometry which captures the farthest runout distance

Source: Sinickas and Jamieson, 2014

The deliverable of such an analysis consists of a map of the areas that are likely to be reached by extreme avalanches (avalanches with return periods of e.g., >100-year). However, this conservative approach has the caveat of overestimating the likely avalanche runout extent. Furthermore, the result of the analysis does not delineate the lateral extent of an avalanche, nor does it provide any information of avalanche dynamics, i.e., velocity, flow height and pressure. While limited in its application, the reach angle analysis provides a simple and easy step for following modelling tasks. The reach angle analysis with the α - β -model can assist in delineating the calculation domains for an automated application of a much more sophisticated numerical tool in the form of the RAMMS::AVAL software (RAMMS).

Deterministic Large-scale Avalanche Hazard Mapping (LSHM) with RAMMS::AVAL

The second approach is the deterministic avalanche flow model, RAMMS::AVAL (Christen et al., 2013). The model is based on Voellmy-Salm depth averaged fluid flow equations applying a dry friction parameter μ and an internal viscous friction parameter ξ dependent on flow velocity (Bartelt et al., 1999). The model requires an understanding of potential release volumes which are set by the fracture depth $d0$ and the release area wherein the most critical factor is the measurement of three-day snowfalls. The model also requires an understanding of the internal mechanics of avalanches including frictional processes (Bartelt et al., 2007 and 2010) and internal pressures (Buser et al., 2011) in addition to the entrainment of snow along the transition path (Vera Valero et al., 2015) and the influence of forest cover detrainning snow (Feistel et al., 2014). Additionally, there is a requirement for statistical evidence of avalanches involved with the model calibration and is based on decades of experience calculating snow avalanches (e.g., Christen et al., 2010). The RAMMS::AVAL avalanche simulation model is also based on decades of avalanche experimentation at the WSL Swiss Federal Institute for Snow and Avalanche research SFL test site (Ammann, 1999) where full scale avalanches are released and monitored exploring their internal dynamics and flow properties (Sovilla et al., 2008).

The application of the RAMMS::AVAL avalanche flow model on a large scale requires a number of model assumptions to parameterise avalanche flow friction parameters (μ , ξ) and release depth scenarios providing a $d0$. The dynamic avalanche modelling with RAMMS::AVAL produces results compatible with a GIS environment (Christen et al., 2012) thus providing avalanche prone areas at a large scale. The large-scale avalanche simulations use the same physics and mechanics as the conventional RAMMS::AVAL simulation software used for single avalanche tracks.

A challenge with this approach is that the characteristic avalanche will spatially change across Georgia due to different local climate conditions. To this end, the selected large-scale parameter set for RAMMS::AVAL must be generalised. Depending on the analysis of meteorological data, it a number of characteristic avalanche parameter sets might be required to apply in accordance with the avalanche zone, i.e., low land snow regions vs high altitude mountain regions.

For large-scale hazard mapping, the selection of the model friction parameters μ , ξ and $d0$ for the avalanche release depth should be selected to represent a worst-case scenario with, for example, a 100-year return period. Recommendations are available for the RAMMS::AVAL software (Christen et al., 2013) which are based on the well calibrated avalanche parameter sets used for Switzerland (see Table 2).

Table 2. Avalanche Parameter Set (Christen et al., 2013).

RAMMS::Avalanche 1.4 Friction Parameters

Large avalanche (> 60'000 m ³)		300-Year		100-Year		30-Year		10-Year	
	Altitude (m.a.s.l.)	μ	ξ	μ	ξ	μ	ξ	μ	ξ
unchannelled	above 1500	0.155	3000	0.165	3000	0.17	3000	0.18	3000
	1000 - 1500	0.17	2500	0.18	2500	0.19	2500	0.2	2500
	below 1000	0.19	2000	0.2	2000	0.21	2000	0.22	2000
channelled	above 1500	0.21	2000	0.22	2000	0.225	2000	0.235	2000
	1000 - 1500	0.22	1750	0.23	1750	0.24	1750	0.25	1750
	below 1000	0.24	1500	0.25	1500	0.26	1500	0.27	1500
gully	above 1500	0.27	1500	0.28	1500	0.29	1500	0.3	1500
	1000 - 1500	0.285	1350	0.3	1350	0.31	1350	0.325	1350
	below 1000	0.3	1200	0.315	1200	0.33	1200	0.345	1200
flat	above 1500	0.14	4000	0.15	4000	0.155	4000	0.16	4000
	1000 - 1500	0.15	3500	0.16	3500	0.17	3500	0.18	3500
	below 1000	0.17	3000	0.18	3000	0.19	3000	0.2	3000
Medium avalanche (25 - 60'000 m³)		300-Year		100-Year		30-Year		10-Year	
unchannelled	above 1500	0.195	2500	0.205	2500	0.215	2500	0.225	2500
	1000 - 1500	0.21	2100	0.22	2100	0.23	2100	0.24	2100
	below 1000	0.23	1750	0.24	1750	0.25	1750	0.26	1750
channelled	above 1500	0.25	1750	0.26	1750	0.27	1750	0.28	1750
	1000 - 1500	0.27	1530	0.28	1530	0.285	1530	0.295	1530
	below 1000	0.28	1350	0.29	1350	0.3	1350	0.31	1350
gully	above 1500	0.32	1350	0.33	1350	0.34	1350	0.35	1350
	1000 - 1500	0.33	1200	0.34	1200	0.355	1200	0.36	1200
	below 1000	0.36	1100	0.37	1100	0.38	1100	0.39	1100
flat	above 1500	0.17	3250	0.18	3250	0.19	3250	0.2	3250
	1000 - 1500	0.19	2900	0.2	2900	0.21	2900	0.22	2900
	below 1000	0.21	2500	0.22	2500	0.23	2500	0.24	2500
forested area ($\mu=\delta, \xi=fix$)		0.02	400	0.02	400	0.02	400	0.02	400

RAMMS::Avalanche 1.4 Friction Parameters

Small avalanche (5 - 25'000 m ³)		300-Year		100-Year		30-Year		10-Year	
	Altitude (m.a.s.l.)	μ	ξ	μ	ξ	μ	ξ	μ	ξ
unchannelled	above 1500	0.235	2000	0.245	2000	0.25	2000	0.26	2000
	1000 - 1500	0.25	1750	0.26	1750	0.265	1750	0.275	1750
	below 1000	0.265	1500	0.275	1500	0.285	1500	0.295	1500
channelled	above 1500	0.28	1500	0.29	1500	0.3	1500	0.31	1500
	1000 - 1500	0.3	1350	0.31	1350	0.315	1350	0.325	1350
	below 1000	0.31	1200	0.32	1200	0.33	1200	0.34	1200
gully	above 1500	0.37	1200	0.38	1200	0.39	1200	0.4	1200
	1000 - 1500	0.38	1100	0.39	1100	0.4	1100	0.41	1100
	below 1000	0.4	1000	0.41	1000	0.42	1000	0.43	1000
flat	above 1500	0.215	2500	0.225	2500	0.23	2500	0.24	2500
	1000 - 1500	0.23	2250	0.24	2250	0.245	2250	0.255	2250
	below 1000	0.245	2000	0.255	2000	0.26	2000	0.27	2000
Tiny avalanche (< 5'000 m³)		300-Year		100-Year		30-Year		10-Year	
unchannelled	above 1500	0.275	1500	0.28	1500	0.285	1500	0.29	1500
	1000 - 1500	0.29	1400	0.295	1400	0.3	1400	0.305	1400
	below 1000	0.3	1250	0.31	1250	0.32	1250	0.33	1250
channelled	above 1500	0.31	1250	0.32	1250	0.33	1250	0.34	1250
	1000 - 1500	0.33	1180	0.34	1180	0.345	1180	0.355	1180
	below 1000	0.34	1050	0.35	1050	0.36	1050	0.37	1050
gully	above 1500	0.42	1050	0.43	1050	0.44	1050	0.45	1050
	1000 - 1500	0.43	1000	0.44	1000	0.45	1000	0.46	1000
	below 1000	0.44	900	0.45	900	0.46	900	0.47	900
flat	above 1500	0.26	1750	0.265	1750	0.27	1750	0.275	1750
	1000 - 1500	0.27	1600	0.275	1600	0.28	1600	0.285	1600
	below 1000	0.28	1500	0.285	1500	0.29	1500	0.295	1500
forested area ($\mu=\delta, \xi=fix$)		0.02	400	0.02	400	0.02	400	0.02	400

The selection of the model parameters μ and ξ must be based on the validation of the RAMMS::AVAL model with detailed avalanche case studies running in the respective region. For Georgia, and assuming that insufficient field data of past avalanches is available, a proxy parameter set must be selected from well calibrated parameter sets for an avalanche region with similar characteristics. Well calibrated avalanche parameter sets are, e.g., available for Switzerland. Table 3 lists some possible values for the

avalanche release depth d_0 assuming that it represents a worst-case scenario with a 100 to 300-year return period.

Table 3. Scenario Based d_0 Selection for a Starting Zone at 2,500 m on a 35° Slope. The d_0 values are typical examples taken from a case study in Switzerland (L. Stoffel, SLF Davos, 2018).

Fracture dept d_0	T=10y	T=30y	T=100y	T=300y
d_0 : typical value for starting zone at 2500 m, 35°	0.80 m	1.00 m	1.20 m	1.35 m

The selection of d_0 requires detailed annual snowfall records wherein annual snow depth measurements are available which hold three-day new snow accumulation records. This is critical in defining the maximum depth of d_0 releasable in snow avalanche prone areas.

The inclusion of forest in avalanche simulation is essential because the braking effect of forest cover on the motion of avalanches has a strong influence on the runout and damage potential of avalanches (Feistel et al., 2014). Moreover, forests can act to prevent the release of avalanches (Feistel et al., 2015). In this respect, forests can be considered as an asset in avalanche areas and are also a viable protection solution when managing avalanche threat.

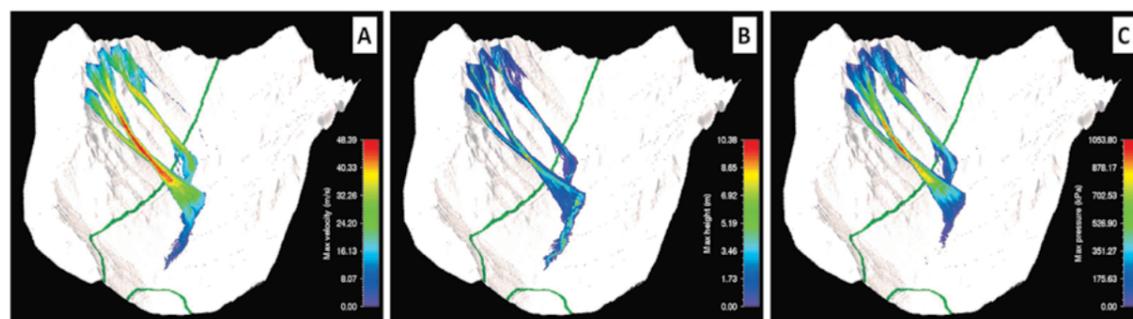


Figure 3. Initial Avalanche Simulation Results Performed along the Salang Pass in Afghanistan with RAMMS during Examination of the Available data. The simulation was performed using arbitrary parameters and does not reflect the hazard analysis. The results are presented as an example of what is contained in the runout area raster datasets. A) shows the maximum avalanche velocity (ms⁻¹), B) the maximum avalanche flow height (m) and C) the maximum avalanche pressure (kPa) (GRF own calculations).

It can be seen in Figure 3 that RAMMS is a quasi-3D modelling software and provides various information such as, for example, the runout areas of avalanches, avalanche velocity, flow height and pressure over the runout areas which can be exported to a GIS environment (Figure 3). The large-scale RAMMS::AVAL avalanche simulations refine the zoning of avalanche endangered areas in comparison to the reach angle approach. Moreover, the dynamic flow data provided enables an assessment of the avalanche damage potential with respect to assets located in the avalanche path which is an essential step in large-scale risk mapping.

The product of the large-scale avalanche hazard mapping should be viewed as a guide to identifying hot spot areas and delineating regional and local areas that require a more detailed assessment of the avalanche hazard. By doing so, avalanche modelling can then be applied to the selection and dimensioning of risk mitigation and reduction measures for avalanche control such as:

- i) Exploring options for territorial planning measures such as resettlements, rerouting of major traffic routes through the mountains, etc.
- ii) Exploring the impact pressures on buildings and settlements, and mitigation measures such as avalanche galleries.
- iii) Applying modelling to assess the maximum permissible avalanche release volume that does not result in damages in case of artificial release of avalanches (for early warning and monitoring systems wherein the artificial release of accumulating snow is necessary).

4.2.3 Steps Needed for Large-scale Numerical Avalanche Hazard Modelling and Mapping

To do a large-scale hazard mapping, a number of steps must be done, and a broad set of data must be available (Figure 4).

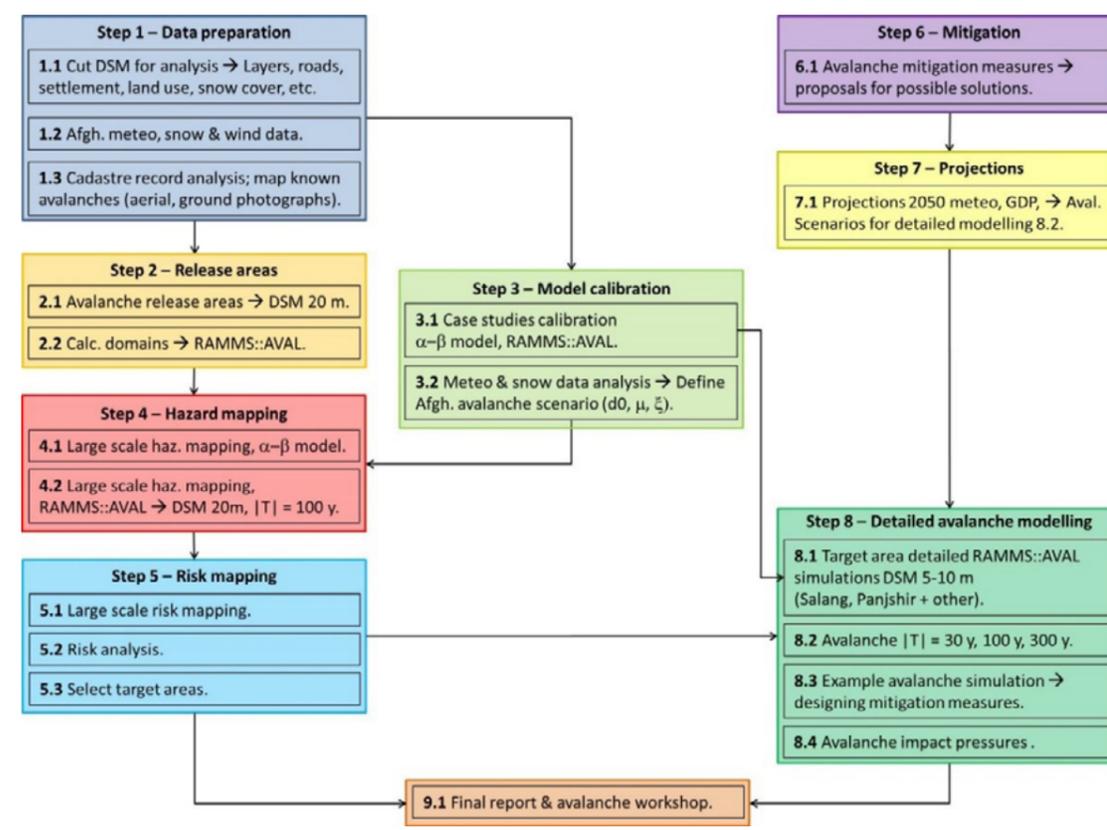


Figure 4. Workflow of a Large-scale Hazard Mapping Process (GRF own presentation).

STEP 1:**Prepare Terrain Models**

A 5-m DSM is an ideal resolution to perform detailed three-dimensional avalanche simulations. The caveat of applying a coarser grid is that the quality of avalanche release area detection and avalanche simulation is greatly reduced. However, for large-scale avalanche hazard mapping, it is necessary to resample the DSM resolution in order to avoid unreasonable computational times and permit the automation of the simulations that come with such a large area dataset (for example, for the 5-m DSM dataset, the calculation of avalanche release areas might be performed on a 10 by 10-meter grid and the final avalanche simulations on a 20 by 20-meter grid size).

STEP 2:**Identify Avalanche Release Areas**

Bühler et al. (2013) present a method to automatically detect avalanches using slope, curvature and ruggedness derived from the terrain model. The algorithm operates on a 10-m grid resolution and detects all possible release areas on the terrain. A key parameter in the identification of the release zones is the ruggedness of the terrain. For example, break points on the terrain, such as rocky outcrops, are common initiation points for avalanches and hence a relatively high-resolution terrain model is a prerequisite. It might also be possible to use a more detailed approach depending on data availability. The method proposed by Veitinger et al. (2014) not only uses the digital terrain model but also information of regional snow accumulation and prevailing winds. The additional parameters account for the effects of terrain roughness, terrain smoothing through snow accumulation, which is included in the roughness parameter, and snow loading due to snow drift from wind in a wind shelter parameter.

STEP 3:**Model Calibration RAMMS::AVAL and Model Parameter Selection**

Calibrating the RAMMS::AVAL avalanche model parameters involve collating all available snow data, avalanche data and information regarding the damages caused by avalanches. The aim is to define likely characteristics of avalanche release zones, their dynamic flow properties, and runout distances with which suitable model parameters can be selected to characterise avalanche behaviour. A comprehensive list of the required data for a full model calibration is given in the previous sections. The data are a mix of both qualitative and quantitative and describe snow properties, release volumes runout areas and damage reports. Furthermore, in order to be able to perform a robust analysis based on event magnitudes of a given return period (T), the calibration should be based on historic avalanche data that cover decades of avalanche events. All available data sources should be screened to ensure that the best possible parameter selection will be made.

STEP 4:**Snow Cover, Snow Depth and Potential Areas Affected by Avalanches**

The large scale of the avalanche hazard mapping task requires that the analysis of avalanche hazards is focused along areas that are affected by substantial snowfalls. Moreover, for these analyses, the amount of snowfall should be enough to generate a depth of snowpack that is conducive to a 100-300-year avalanche hazard scenario. In areas with limited terrestrial snow data, snow cover from satellite data might help. However, it should be noted that this dataset does not contain data of snow depth and as all zones with snow are marked as areas for potential avalanches. This leads to a conservative selection of likely avalanche areas as it is not possible to indicate an intensity level according to snow depth.

The detail of snow and weather data required to perform a rigorous parameter selection for a nationwide large-scale avalanche hazard mapping is extensive. To be able to perform this mapping in greater detail, it would be necessary that data on snowfall are available on a daily base throughout the year for many consecutive years and with a broad spatial coverage over Georgia.

An option for getting more information on snowpack depth also exists in using the General Climate Model (GCM) dataset to generate snow water equivalents (SWE) based on the assumption that snow falls when there is precipitation and a (freezing) temperature of $<0^{\circ}\text{C}$ at a given location in the GCM. It is important to note that SWE measurements do not give a direct measure of snow height. The conversion of SWE to a snow height can be made by assuming a nominal snow density. In the case of the examination of the modelled SWE values, a bulk snow density ρ_b of 300 kg m^{-3} could be assumed to equate snow height HS (Jonas et al., 2009).

4.3 Hazard Mapping and Territorial Planning at a Local Scale**General**

An avalanche hazard map is meant to help a governmental body at national, regional or community levels to take the avalanche danger into consideration. All activities that have an impact on land-use (issuing and approbation of directional plans and land-use plans, concepts, sector plans and the necessary basics for the planning and construction of buildings and infrastructure of any type, granting licence and concessions, issuing subsidies, etc.) can be affected by an avalanche. For already existing endangered buildings, the avalanche hazard map is the basis for required protective construction or for measures of the communal avalanche service (evacuation, closures of roads, etc.). For the drafting of avalanche hazard maps, the avalanche hazard should be assessed and considered with the same criteria and standards for the whole of the country. To achieve this, adequate legal regulations and technical guidelines might have to be developed.

Methods for the Development of Local Avalanche Hazard Maps

Basics

The creation of an avalanche hazard map – be it at a large-scale regional or at local level – must exclusively follow scientific criteria. The following basics can be helpful:

- Avalanche cadastral map (historical data about past events - might be missing).
- Terrain assessment based on local topographic maps.
- Physical terrain assessment and observation upon inspection (e.g., assessment of existing avalanche tracks).
- Local weather and climatic conditions.

Resulting products of such an avalanche hazard analysis process are:

- Avalanche cadastral map: The avalanche cadastral map (scale 1:25,000 or 1:10,000) contains the date, the impact area, and the damage of each observed avalanche.
- Avalanche hazard map: The avalanche hazard map (scale 1:10,000, equidistance 10 m) depicts the hazard areas based on the periodicity and the avalanche pressure. The hazard areas are separated into zones with different hazard levels. The borders of these zones are formed by lines of equal avalanche hazard. The avalanche hazard map is a document (without legal implications) which aims at depicting the avalanche danger with objective criteria.
- Land-use plans: Land-use plans (scale 1:2,000 or 1:5,000) contain, for example, building and hazard zones. One can also see them as modified and interpreted avalanche hazard maps. In particular the runout zones impact the land-use plans and determine limitations such as construction prohibition, regulations on building enforcements or operational measures such as evacuation. Unlike the avalanche hazard map, it is a legally binding document.

General Procedure

Local avalanche hazard maps are generated for inhabited areas which show signs of avalanche danger. Large-scale hazard mapping helps to identify all settlements and critical infrastructure at a local level which have avalanche-prone zones countrywide. A well-defined procedure in consideration of national, regional, and local authorities will have to be defined in order to transfer hazard maps into legally binding land-use planning regulations.

Criteria for the Classification of Hazard Levels

Periodicity and Avalanche Pressure

As a measure for the hazard level, the periodicity (frequency) and the avalanche pressure (intensity) of an avalanche are being used.

Periodicity and Frequency

The frequency of an avalanche with a certain dimension is specified by its periodicity. The periodicity is the reciprocal value of the frequency and corresponds with the mean time interval in which the event occurs at least once in a certain size if a long enough time period is considered.

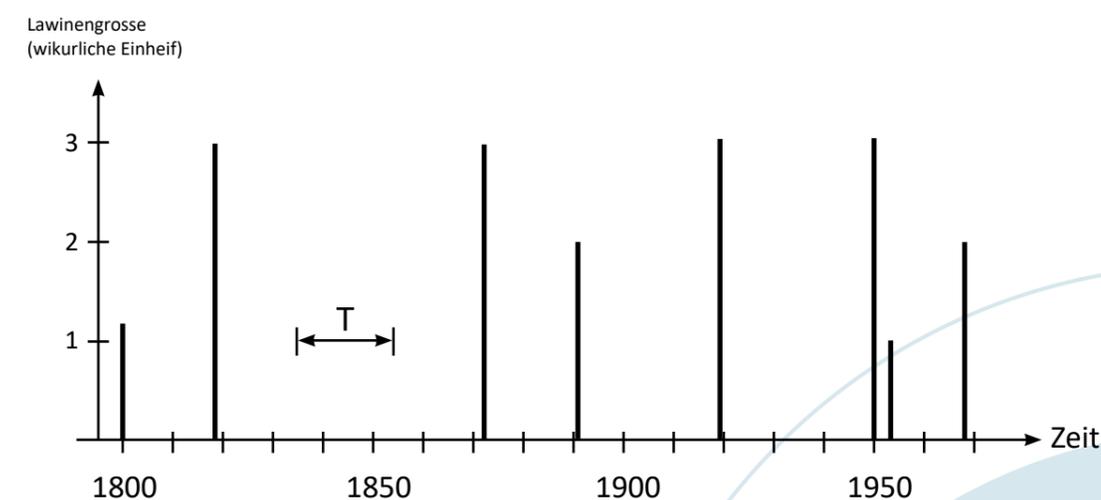


Figure 5. Frequency of the Salezertobel Avalanche (Davos) between 1800 and 1975

Source: GRF own presentation

If in Figure 5 the size of the avalanche is not considered, the periodicity T of the Salezertobel avalanche, as an example, is 22 years ($T = 175/8 = 22$ years).

Avalanche Pressure

The avalanche pressure is defined as the impact force level which acts on a large plane obstacle perpendicular to the direction of the avalanche flow. The avalanche pressure is proportional to the density of the snow and the squared velocity ($p_n = \rho v^2$; $\rho_{\text{dense flow avalanche}} = 300 \text{ kg/m}^3$). For hazard mapping, the snow density is considered as a constant value at 300 kg/m^3 .

The fracture depth, and with that also the avalanche velocity, which is the avalanche pressure, is coupled with the periodicity. In general, the periodicity depends on the slope angle. With a low slope gradient ($\Psi \approx 30^\circ$), avalanches are rather rare but will be of a large dimension if they occur (destructive avalanches). On the other hand, steep slopes ($\Psi \approx 50^\circ$) will discharge the snow at modest snow depths. Therefore, steep slopes show a lower periodicity than those less steep.

Levels of an Avalanche Hazard Map

The avalanche hazard map differs between four degrees of hazard (see also Figure 6). They are distinguished by colours (red, blue, yellow, and white). The criteria for the various zones may slightly differ and must be defined at a national level. The following criteria are for Switzerland.

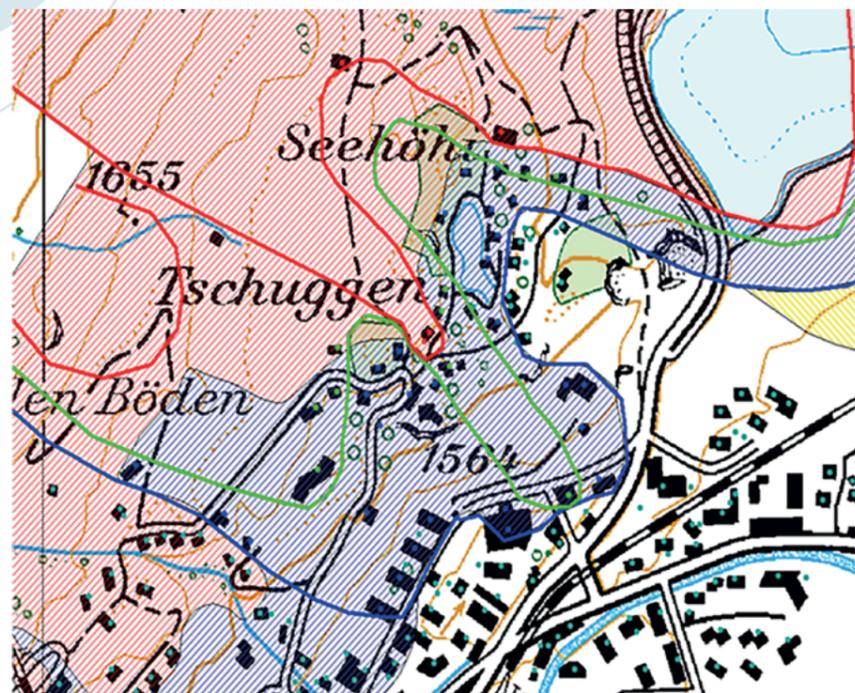


Figure 6. Example of an Avalanche Hazard Map (extract of Davos, Switzerland).

RED ZONE

Criteria: Considerably endangered area and there is no doubt about the existence of an avalanche hazard.

An area is attributed to the red zone if:

- 1) $p_n \geq 30$ [kN/m²] if $T \leq 300$ years return period
- 2) $0 \leq p_n \leq 30$ [kN/m²] if $T \leq 30$ years return period

Each of the conditions 1) or 2) by itself is sufficient for being attributed to the red zone.

Buildings within the red zone – if built according to standards – are expected to fail. Therefore, people's lives are in danger, also within buildings (condition 1). Smaller but more frequent avalanches threaten people mainly outside of buildings (condition 2).

Some other countries, like Italy and Austria, use different values for the pressure limit and the return period. In Italy, for example, a return period of $T = 100$ years is used but with a reduced pressure threshold of $p = 15$ kN/m² which results in quite similar zone borders as in Switzerland with $T = 300$ years and a pressure level of $p = 30$ kN/m² (Hervas, 2003).

BLUE ZONE

Criteria: Areas which will only be reached by rare avalanches with low intensity or there might be doubts as to the existence of an avalanche hazard.

An area is attributed to the blue zone if:

- 1) $p_n < 30$ [kN/m²] if $30 < T \leq 300$ years
- 2) $p_n < 3$ [kN/m²] if $T < 30$ years (only applies for powder snow avalanches)

Destruction of buildings during a typical lifetime of a building (50-70 years) is not practically expected if certain construction standards and additional building regulations (strengthening of walls, windows, etc.) are considered. A certain hazard exists outside of buildings which is acceptable (if certain construction measures are observed).

YELLOW ZONE

Areas with a very low avalanche hazard.

The definition of a yellow zone is optional. An area is attributed to the yellow zone if:

- 1) $p_n \leq 3$ [kN/m²] if $T \geq 30$ years (only applies for powder snow avalanches)
- 2) p_n unknown; $T > 300$ years (applies for statistically not detectable dense flow avalanches)

Damage to buildings in this area are very unlikely and the risk for people is usually only in terms of limitations to access.

WHITE ZONE

In this area, it is very unlikely that avalanches will be expected.

Border Lines of the Various Zones

The position of the hazard zones follows certain patterns. Usually, the red zone is bordered laterally and below by the blue zone and the blue zone is bordered by a yellow zone, if necessary.

The border line between the red and blue zones is where the avalanche pressure reaches the value of 30 kN/m². Based on this value, a postulated snow avalanche density of $\rho = 300$ kg/m³ and the quadratic dependency between resulting pressure and velocity results in a border line velocity of $v_{(30 \text{ kN/m}^2)} = 10$ [m/s].

Gliding and Creeping Snow Cover

In lower altitudes and on slopes exposed to the sun, the snowpack creeping and gliding phenomenon may occur and deform and move the snow cover over several meters without developing an avalanche. However, gliding snow can exert massive forces on an obstacle in its deformation vector. Walls of buildings might have to be reinforced in order to sustain the impacting forces.

In some specific cases, it is, therefore, recommended that hazard maps should also indicate areas prone to snow gliding. Whereas the procedure for the assessment of extreme avalanches is relatively well defined, the criteria as to whether the hazard on a small hillside should be handled as an avalanche area, a snow gliding area or if the hazard can even be neglected at all are not well established. During winter 2011/2012 in Switzerland, as an example, snow gliding was a widespread threat in the Swiss Alps and revealed the need to establish some guidelines (Margreth, 2016). The procedure proposed is based on seven factors vis-à-vis how the hazard of snow gliding can be assessed (soil surface roughness, slope angle, slope exposition, snow height, length of the slope, terrain texture and soil surface humidity).

Practical Procedure for the Development of a Local Hazard Map

Analysis of the Avalanche Cadastral Register

If avalanche cadastral maps exist, they should be analysed. In general, the resulting extent of the hazard zones will not be the maximum as potential extreme avalanches can often not be included due to the rather short observation time. Therefore, potential avalanches with a return period of 300 years should also be considered to really cover an extreme event.

Detailed Assessment of the Terrain

For a detailed assessment of the terrain, maps and aerial photos are valuable tools to complement an on-site visit by avalanche experts.

Examination of "Indirect Avalanche Witnesses"

Indirect witnesses, for example, include the condition and the age of the forest and visible damages. Additionally, tree ring analysis sometimes provides useful data on the occurrence of damaging avalanches at a specific site. Entrained material, originating from avalanche depositions (e.g., tree trunks) and scraping marks on the ground are additional hints about former avalanche activities.

Definition of Starting Zones

A visual inspection on-site helps to determine the size of a potential avalanche starting zone. A realistic starting zone is often not identical with the total potential catchment area as local vegetation, surface roughness, ridges, etc., influence the surroundings of a starting zone. Dominant wind directions must also be taken into consideration as large volumes of snow can be transported

by the wind from the luv to the lee side where huge volumes of drifted snow might accumulate and represent a potential starting zone.

Assessment of the Fracture Depth d_0 for $T=30$ and 300 years

The assessment of the fracture depth is very important as the runout distance is almost proportional to it. Further, the fracture depth is linked with the periodicity which renders the runout distance to a statistical dimension with a certain probability of occurrence.

The main influencing factors for d_0 are:

- **New fresh fallen snow**

This considers the climatically possible maximum amount of snow for three consecutive days. The consideration of precipitation periods longer than three days has shown to be irrelevant. Thus, it can be assumed that large avalanches – unlike the so-called skiers-avalanches – are always caused by snowfall and that basically only new snow is released. Studies have confirmed this despite the occasional fracture within the old snow cover. The periodicity of new snow growth is assumed to be identical to the respective avalanches (unfavourable assumption).

- **Slope angle**

The shear strength limits the amount of new snow that can be deposited on a slope. Thus, the snow will slide off before the climatically possible maximum amount of snow is deposited. The strength is linked to the Mohr-Coulomb law known in geotechnics and is increasing with heavier snowfall as well. Otherwise, the fracture depth for equal slope angles would – assuming similar strength – always be the same, independent of the periodicity.

- **Snow drift**

On the lee side of mountain ridges, the new snow accumulation and, therefore, the fracture depth, is locally larger (considering the prevailing wind direction during snowfall).

The determination of the fracture depth needs some further considerations. The mean fracture depth d_0 perpendicular to the slope is defined as:

$$d_0 = d_0^* \cdot f(\psi)$$

where:

d_0^* = base value depending on the local climate (potential snow accumulation in three days) and on the periodicity T [years]. An example is given for Switzerland in Table 4 below.

$f(\psi)$ = gradient factor, determined by the snow strength

Table 4. Recommended Base Values d_0^* for $\Psi=28^\circ$ (example taken from Switzerland).

Periodicity T	Base value d_0^* for $\Psi_{om}=28^\circ$ Climatically possible snow accumulation for three days	
	Small [m]	Large [m]
Years		
30	0.88	1.50
100	1.06	1.81
300	1.23	2.10

In the case of Switzerland (the applicability to the Georgian conditions seems reasonable), the recommended base values are valid for an altitude of 2,000 m.a.s.l. For higher or lower starting zones, 5 cm per 100 m of altitude must be subtracted or added. In high areas, the wind influence is dominant and the added value for the altitude only has a secondary influence. For snow drift, the base values for d_0^* should be enlarged by 0.3 to 0.5 m. The base value d_0^* is used along the whole starting zone. It is also interesting to see that the base values for the climatically possible snow accumulation within three days for the 300 respectively the 30-year periodicity only differs by about 40%.

$$\frac{d_0^*(T=300)}{d_0^*(T=30)} \cong 1.4$$

The 300-year periodicity snow depth is only 40% higher than the one for the 30-year return period.

The dependence of the fracture depth and the slope angle can be expressed by the following factor (see Table 5):

$$f(\psi) = \frac{0.291}{\sin \psi - 0.202 \cdot \cos \psi} \quad (6.3)$$

Table 5. Slope Angle Factors $f(\Psi)$. The angle Ψ_{om} describes the mean slope angle in the fracture zone.

Gradient Ψ_{om} [°]	$f(\Psi)$ [-]	Periodicity T [years]
28.0	1.00	Rather large
30.0	0.90	
32.5	0.79	
35.0	0.71	
37.5	0.65	
40.0	0.60	
45.0	0.52	
50.0	0.46	Rather small

example

Wanted: fracture depth d_0 of a snow slope with an angle of 35° for a 300-year avalanche

Solution: $T = 300$, $d_0^* = 2.10$ m

$\Psi = 35^\circ \Rightarrow f(\Psi) = 0.71$

Resulting fracture depth: $d_0 = 2.10 \cdot 0.71 = 1.49$ m

The numerical simulation of avalanche paths can be done with the RAMMS software which is described in some detail in the previous section. This 3D numerical approach also allows the evaluation of the lateral distribution of the avalanche in the runout zone.

Minimum Requirements for the Different Hazard Zones

As an example of how to translate the hazard maps into a legal framework in order to make them useful for the land-use planning process, the Swiss situation is explained in some greater details. This will enable getting some ideas on how to adapt the zoning process to Georgia. The following minimum requirements apply for settlements and are only briefly described. For other purposes, such as communication lines, roads, tourist infrastructure, etc., they have to be adapted.

RED ZONE

No buildings are allowed in the red zones of an avalanche hazard map. This is also the case if an existing building has been damaged or destroyed by an avalanche. Reconstruction is not possible. New buildings or the reconstruction of buildings for people and the sheltering of livestock – even if it is only of a temporary nature – are only permitted if they do require exactly that particular location due to forestry or agricultural reasons. The same applies for infrastructure (water catchment, sewage plant, etc.). In these cases, experts have to be consulted in order to guarantee the highest possible security.

BLUE ZONE

In the blue zones of the avalanche hazard map, building zones should be defined very conservatively. If there are still existing land reserves in areas which are not at risk, they should be used with priority. New buildings and reconstruction are permitted with certain limitations but, in general, building activities should be restrained. Buildings and infrastructure, which gather large numbers of people (e.g., schools, hotels, restaurants, sports facilities, etc.), should be avoided. Conversions and changes of purpose of buildings are only permissible if the number of people at risk does not increase considerably.

YELLOW ZONE

There are no special building regulations.

WHITE ZONE

Areas which are marked as white zones on the avalanche hazard map do not require any particular safety measures.

Organisational Measures and Access to Zones

For people living in the red or the blue zones, an early warning and alert system has to be installed in order to ensure that people are evacuated from the red zone and not leaving their houses in the blue and the yellow zones.

Areas which can only be accessed by passing through a higher avalanche hazard zone are treated as areas with this higher hazard level. For example, an area belonging to the blue zone, but which can only be accessed by travelling through a red zone, must be treated as a red zone as well.

05

Data Requirements and Availability for Avalanche Hazard Modelling and Mapping

5.1. Snow Avalanches and General Data Requirements for Avalanche Modelling

Snow avalanche modelling is performed in order to produce avalanche hazard maps delineating the likely starting and transition zones of avalanches and, in particular, the runout areas of avalanche deposits. In addition, dynamic avalanche modelling provides the dynamic flow properties during runout such as flow and deposition heights, avalanche velocities and impact pressures on objects (buildings, infrastructure, etc.). Model input parameters are terrain data, meteorological data, and snow properties. The calibration of the dynamic avalanche modelling and the necessary boundary conditions that best describe the physical runout behaviour of avalanches based on the analysis of recent snow avalanche events in the region are also important.

In principle, three different types of avalanches occur. Their occurrence depends on the physical characteristics of the snow cover, the topography, and the morphology of the terrain. The snow cover characteristics over mountainous terrain change both seasonally and with respect to altitude and climatic situations (Ammann, 2003 and McClung, 2006).

- Dry snow dense flow avalanches: they are characterised by a density of about up to 300 kg m^{-3} and nominally reach up to 30 m s^{-1} .
- Wet snow plug flow avalanches: they are characterised by slow velocity plug like flows as low as $5 - 10 \text{ m s}^{-1}$ which, due to the high density of snow involved (up to 450 kg m^{-3}), still exert high flow pressures (Kern et al., 2009 and Sovilla et al., 2008).
- Powder snow avalanches: they are characterised by plume like high velocity flows up to $60 - 80 \text{ m s}^{-1}$ which, due to their low density (up to 10 kg m^{-3}), exert nominally lower pressures while traveling greater distances and impacting larger areas (Ammann, 2003).

For hazard mapping and, in particular, in large-scale avalanche hazard analysis and mapping, the focus of analysis is on dry snow avalanches. It is, of course, possible to simulate the other two types of avalanches with the RAMMS::AVAL software, e.g., powder avalanches (Bartelt et al., 2013) and wet snow avalanches (Vera et al., 2015). However, these types of avalanches are less frequent and remain applications for local hazard mapping. In this respect, they are beyond the scope of this project for large-scale hazard mapping but need to be considered in risk analysis for local settlements and infrastructure.

Snow avalanche hazard and risk modelling is used to assist in the spatial land-use planning of settlements, transport routes, electricity transmission lines and other critical infrastructure to limit avalanche risk. It also provides the necessary input data for the efficient and the effective design of buildings, infrastructure, and protection measures.

There is a number of approaches to avalanche modelling, each of which requires calibration to past avalanche events with a greater or lesser degree of detail. The models have the goal of linking the avalanche starting conditions in the release zone with the runout dynamics through the transition zone to the stopping conditions in the deposition zone (see Figure 7).

Defining model parameters for avalanche modelling is challenging because the flow mechanics of avalanches are governed, among others, by snow avalanche release volume, topography and terrain morphology and, in particular, the snow properties, each of which may change on spatial and temporal scales (see Figure 7). Snow avalanches develop on slopes with an inclination between 28° and 55°, a sufficient snow cover depth which flattens surface roughness reducing base friction and a specific amount of freshly fallen snow. Snow cover along with both daily and three-day snow accumulations are, therefore, critical parameters in forming avalanches.

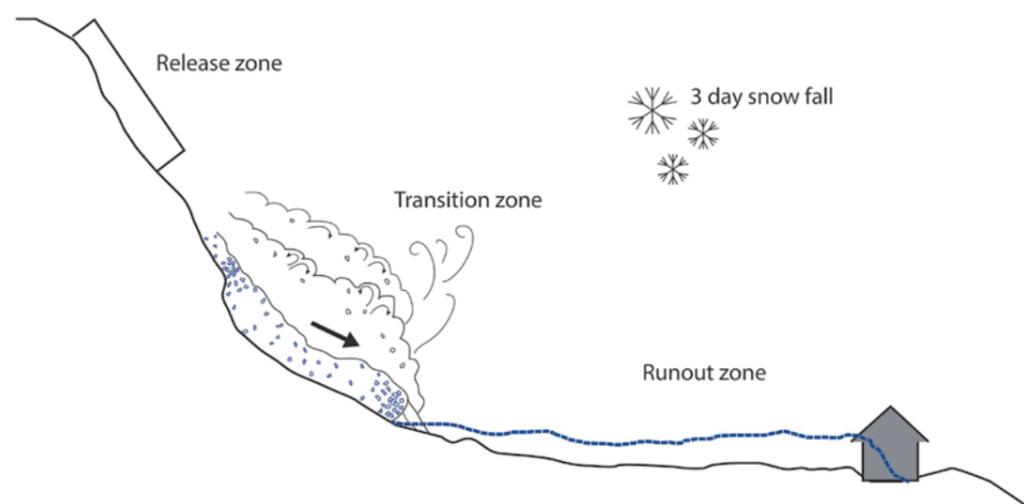


Figure 7. Modelling Snow Avalanches Needs to Combine: i) the snow conditions in the release zone such as potential snow slabs (upper left rectangle) to, ii) the flow dynamics in the transition zone such as avalanche velocity, flow depth and pressure and iii) to predict the runout distance or path of the avalanche runout zone and the nature of the avalanche deposits (e.g., the blue dashed line) which can impact buildings and infrastructure.

Avalanche modelling is based on the assessment of the snow data and executed in two steps: a) the identification of avalanche release areas on the terrain and b) the dynamic avalanche runout modelling. Release area detection assesses slope, curvature and ruggedness derived from the terrain model (Bühler et al., 2013). Avalanche model validation needs to be done by comparing available historical avalanche events with numerical avalanche simulations. The validation process enables calibrating the various model parameters which depend on regional snow properties and terrain surface roughness.

5.2 Data Inventory for Avalanche Hazard Modelling

Required and Available Data for Avalanche Modelling

Snow avalanche hazard mapping based on numerical modelling requires various items of information such as:

- i) Snow properties and local weather conditions.
- ii) Avalanche release area (geometry, morphology, etc.).
- iii) Avalanche transition and runout geometry.
- iv) Topographic dataset.
- v) Avalanche cadastre (historical or recent avalanche events).

For each of these datasets, some guidance is provided for reviewing the existing data and conducting a detailed analysis of all of the available data for undertaking avalanche hazard modelling, mapping, and assessment (to assess data availability, quality and needs for avalanche hazard modelling and mapping).

(i) Snow properties and local weather conditions are important because they provide indications on the amount of snow to be released in the avalanche starting zone. Of major importance are:

- a) Snow height (total).
- b) Freshly fallen snow height (within in 24, 72 hours).
- c) Snow profiles.
- d) Wind speed and direction (wind transports snow from luv to lee over large distances and causes additional snow accumulation in lee slopes which increases the avalanche fracture height d_0).

Of some minor importance are:

- a) Snow density ρ (kg m^{-3}).
- b) Snow water content.
- c) Snow temperature.
- d) Air temperature.

Commonly, these are taken from direct field measurements or automatic weather stations providing the continuous time series measurements of these properties. It is of great importance that these measurements are taken daily over a yearly period. This is because snow accumulations that result in avalanches are closely coupled with the weather and the climate. Therefore, only daily measurements of the prevailing snow properties on an annual basis will give sufficient insight into the characteristic avalanche situation for a given location.

The availability of the data is also an influential factor in defining the target areas for detailed investigation, amongst other factors. Rainfall data, for example, is only of interest when coupled with temperatures below freezing in order to make estimates of snow height. Additionally, it is important to calibrate some climate change impacts for the future as the data compares precipitation data over a period of time in Georgia.

As mentioned in section 3, data must be available for about one-third of the desired time span in order to be able to extrapolate and predict data for a certain annuity and with some statistical evidence. For example, to predict a 100-year avalanche with a sufficient accuracy, continuous snow height measurements over 30 years and more should be available. If these data are not available, assumptions must be made on best expert judgment.

Throughout Georgia, the meteorological data provided are not exhaustive and are more on a regional/local scale. These data on snow measurements are useful for local modelling, however, they are not sufficient for a national large-scale avalanche hazard assessment. As the meteorological dataset is incomplete for a national snow avalanche assessment, it is recommended to use available local data in order to generate an elevation standardised approach which will then be used for the national assessment/modelling.

If snow data are missing, the avalanche model parameter selection would need to be based on similar avalanche regions of the globe. One option could be to rely on Swiss standard parameters. Switzerland is set in a similar inland alpine region and has probably the most extensive dataset available worldwide. Moreover, the modelling parameters are based on years of avalanche mapping and back calculations of avalanches in addition to a depth of avalanche experimentation. In this respect, the Swiss avalanche parameters would be a good proxy on which to base the parameter selection.

(ii) Avalanche release volume has a dominant influence on the runout distances and the dynamics of an avalanche. Avalanches are classed as small (5-25,000 m³), medium (25,000-60,000 m³) and large ($\geq 60,000$ m³) (Bartelt et al., 2007). The release volume is derived from the release area and depth of snow in the release area known as the d_0 parameter. The snow depth can vary significantly from year to year. Extreme avalanche events are dominated by snow height. An avalanche with a 100-year return period is thus characterised by the 100-year snow depth.

Obtaining an idea of daily snowfall and accumulation over the years is of great use in generating the profile of the Georgian avalanche situation. In the case that no further snowfall or snow depth data is available, it is suggested to reconstruct the snowfall from climate datasets such as EUWATCH. A problem with this approach is that these data are coarse with a grid resolution up to 1 km and will only provide a generalised estimate of the total annual snowfall and the respective snow height.

(iii) Mapped avalanche runout and deposits from recent or historic events are required to calibrate the runout and deposition models. Where mapped avalanche deposits are available, they provide an essential benchmark with which to calibrate. Simulations are performed to tune parameters which match the boundaries of runout deposit documents from field investigations or mapped from remote sensing such as satellite or aerial imagery which capture avalanche deposits (Buehler et al., 2009). In an ideal case, historic data delineating avalanche runout paths and deposits are available and can be used to calibrate avalanche models (Christen et al., 2010).

The data available might not include mapped avalanche runout paths or deposits. In this respect, it makes the model calibration task particularly challenging. A solution could exist in assessing aerial or satellite imagery of avalanche affected areas such as along the Jvari Pass Military Road. With such data, it could be possible to map the runout deposits of past avalanches and use them for model calibration purposes.

For the case that mapped avalanches are not available, it is also possible to perform a crude delineation of avalanche deposits with the use of photographs of avalanche events taken on the ground. The boundaries of the deposits are then drawn directly into the Digital Surface Model (DSM) by hand. However, this is prone to error, involves much guess work and often photographs of avalanches do not encompass their entire extent.

iv.) Terrain models and topographic datasets

The process of avalanches involves the accumulation of snow on slopes in release zones which can lead to failure of snow layers which causes avalanche runout. Each of these stages is strongly conditioned by the topography and the morphology of the terrain (release area, transition zone, runout/snow deposition zone). In this respect, avalanche release zone detection and runout modelling demand relatively high-resolution terrain models. The recommended DEM resolution for avalanche modelling is between a 2- 20 m grid (Christen et al., 2013).

The drawback with applying a coarser terrain model is that the terrain becomes smoothed and many of the critical terrain features for an avalanche, such as gullies and ridge lines, are lost. A further issue is then the compatibility of datasets as they are set in differing grid resolutions. A coarser terrain model can be resampled to a finer grid both for simulation and data presentation. However, critical terrain morphology for the avalanche is nonetheless still lost.

Given the drawbacks of having to apply a coarser terrain model for the analysis, the effect on the results must be considered by practitioners and engineers when applying the hazard maps produced with such data. A DSM of Georgia with a mesh of 5 m would be ideal to undertake the national and local snow avalanche assessments and would be an ideal resolution to perform detailed three-dimensional avalanche simulations for hazard mapping and risk modelling. If available, satellite imagery and aerial photography of the areas under investigation would be of high importance. Snow cover and forest cover information might be available within the land-cover dataset; however, the information will not be sufficient for a detailed modelling and general assumptions will need to be taken.

The large scale of the avalanche hazard mapping task requires that the analysis of avalanche hazards is focused along areas that are affected by avalanches and where avalanches pose a threat to human life, buildings, traffic routes and infrastructure. For large-scale avalanche hazard mapping, it might be necessary to resample the DSM to 10 - 20 m to avoid unreasonable computational times and permit the automation of the simulations that come with such a large area dataset. Furthermore, it is necessary to cut down DSM to only focus on avalanche affected areas that pose a risk, i.e., the avalanche hazard analysis should not be performed in remote high-altitude areas where there exists no human activity or infrastructure.

The process of cutting the DSM involves a GIS analysis which zones the DSM based on the available snow cover data, roads, settlements, buildings, and land use. Additionally, a dataset of glaciers in Georgia will be sought and included in this analysis as a check on the available snow cover data to ensure it is complete in all areas. Main centres of glaciation are related to the elevated Greater Caucasus watershed range and the Kazbegi massif. The inclusion of the glaciers will also assist in identifying any potential catastrophic avalanche areas that could arise from extreme avalanche events as a result of glacial collapse and which are often associated with earthquake events (Mahboob et al., 2015), or glacier lakes as a consequence of temperature induced ice melting might out-break and cause flooding in down-stream areas.

v.) **An avalanche cadastre**, i.e., geo-referenced datasets of historic events with the avalanche release zone, the transition and deposition zone and the snow volume would be of high relevance for the precise modelling of snow avalanches. The quality of these eventually existing data is not known. If the data cannot be collected, a standardised modelling approach will be used. Cadastre information will also provide insight into the vulnerability of building types and typical infrastructure which is also relevant for the hazard and risk analysis. Individual historical avalanche recordings might exist from the 1987 Svaneti avalanches² where a series of massive avalanches in the northwest Caucasus highlands occurred, hitting the Svaneti region in January 1987; namely, the Mestia and Lentekhi districts (a total of 105 people died in the disaster. More than 2,000 houses were damaged and about 8,500 people had to be resettled).

vi.) Scenario selection and avalanche return periods

The application of return periods of 30, 100 and 300-year events is the standard international practice in avalanche hazard analysis. Whereas the 30 and 100-year return periods are based – if possible – on the continuous acquisition of relevant meteorological and snow data, the 300-year return period is based on historically recorded events (worst case avalanche). To be able to perform an adequate analysis for a 100-year period, the available data would have to cover at least a continuous period of about 30 years (about one-third of the extrapolation phase). The main parameter is the snow height to be activated in the release zone to form an avalanche. If most of the available data are not covering a period of about 25-30 years, an extrapolation to 100 years is – from a purely statistical perspective – not justifiable. One might, therefore, have to rely upon a generalised dataset based on traditional data, e.g., from Switzerland.

² Wikipedia, the 1987 Svaneti Avalanches, https://en.wikipedia.org/wiki/1987_Svaneti_avalanches, accessed 28 January 2021.

In flood, earthquake and landslide modelling, data capturing events that extend back in geological time is available and it is, therefore, possible to make predictions for more extreme events. In this respect, the practice of snow avalanche hazard analysis does not tend to extend beyond a scenario of a 300-year event. To this end, it is recommended that the hazard analysis for snow avalanche be performed according to convention in avalanche practice.

Satellite Data

Satellite data could probably be found and help detecting avalanche paths in specific areas (e.g., along the Jvari Pass). In general, it is difficult to identify avalanche release zones if the images are taken after a couple of days from the event but in most cases, the avalanche deposition zone remains visible for at least some weeks, indicating that at least one avalanche occurred at the specific avalanche track during the winter. Satellite imagery can also be helpful in detecting and localising infrastructure and settlements for an improved exposure analysis. The GeoEye satellite series might contain snow and avalanches, revealing avalanche release areas or avalanche transition zones and deposition zones.

Short Outlook on Avalanche Risk Analysis and Consequences of Data Availability

Much of the available data required for the hazard analysis is also relevant for the risk assessment but it must be adapted to a form from which risk relevant calculations can be performed. These data are of importance when performing the risk analysis in conjunction with the hazard maps because the avalanche runout paths will give an indication of the total affected area of a given settlement. It will only be possible to make a detailed risk assessment of the affected area with details of building strength and population density as an example. Nevertheless, trends and estimations of the required metrics can be made in order to perform such a risk assessment.

Socio-economic datasets (population, land cover [agriculture], settlements, roads, critical infrastructure such as schools, universities, airports, bridges, hospital and health facilities, irrigation systems, power plants, etc.) are very relevant for snow avalanche risk assessment. This geo-referenced data allows for a risk assessment and can be integrated into the hazard vulnerability and exposure map/GIS system.

5.3 Data Availability for Avalanche Hazard Modelling and Mapping

A variety of data are necessary for the numerical avalanche hazard modelling and analysis, for both the LSHM and for the local hazard mapping. A number of recommendations and requests have already been made in the previous section 2. This section will briefly summarise the basic situation. The lack of data or gaps in data are a permanent issue and have to be compensated to some extent by expert judgement and reference to other countries with a more comprehensive data set. The necessity of data for the large-scale hazard analysis with the calibration process as a prerequisite, and for the local avalanche hazard mapping process are summarized. The data requirements for early warning vis-à-vis avalanche forecasting and now-casting processes are not covered in this section (reference is made in the data report on snow and avalanches).

All data relevant vis-à-vis snow avalanche hazard and risk mapping and modelling are summarised in Table 6. The table describes the required data and their relevance for conducting avalanche hazard and risk modelling and mapping.

Table 6. Table of Necessary Data and Their Availability

Datasets	Dataset/Name ³	Remarks, Recommendations
DTM Georgia; Format: xyz, txt, ascii; Res.: 5 - 10 m	<ul style="list-style-type: none"> XYZ DTM 5m resolution 	<ul style="list-style-type: none"> Important for any numerical modelling, 5 m raster allows sufficient precision for large-scale hazard mapping
Topographic map; Format: Raster, tiff, tfw	<ul style="list-style-type: none"> ECW 25K,50K,100K,200K,500K MDB 50K 	
Aerial and satellite imagery avalanches; Format: Raster, image, tiff, twf; Res: 0.1 - 25 m	<ul style="list-style-type: none"> ECW Resolution: GSD 20 cm 	<ul style="list-style-type: none"> Will allow the use for back calculations of historical avalanche events Allows detailed studies of specific release areas (surface roughness estimation, vegetation, blocs, etc.)
Snow cover; Format: Raster, tiff, tfw, ascii; Res.: 10 - 100 m Snow (countrywide Raster) available?	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Would be helpful for evaluating the relevant areas for the large-scale hazard mapping (LSHM)
Administrative boundaries; Format: Polygon, raster; Res.: 10-100 m	<ul style="list-style-type: none"> Polygon Shp-shapefiles, Admin Boundaries: Reg-Zone, RegSector 	<ul style="list-style-type: none"> Relevant for risk assessment
Forest cover, density, Format: Raster, polygon, point, xyz; Res.: 10- 100 m	<ul style="list-style-type: none"> MDB Based on 50K Topo Maps 	<ul style="list-style-type: none"> Relevant for LSHM
Precipitation & temp below freezing; Format: Raster; Res.: 1 - 2°	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Relevant for snow cover analysis as a base for LSHM
Weather station - temp, wind, rain, snowfall, snow-depth Format: Time series, point (xyz), Multiple locations Spatial Resolution: 10 - 100 km	<ul style="list-style-type: none"> Time series 	<ul style="list-style-type: none"> How many stations are available? What is the time period of available data?
Three-day snowfall; time series, (xyz)	<ul style="list-style-type: none"> Time series 	<ul style="list-style-type: none"> It is important to have the daily measurements to build the three-day total
Wind direction/strength; Time series (xyz)/raster; Res.: 10 - 100 m, km	<ul style="list-style-type: none"> Time series 	<ul style="list-style-type: none"> Relevant for snow drift estimates in mountainous areas
Annual Snowfall, Snow depth Format: Raster, Time series, point (xyz), Multiple locations Spatial Resolution: 10 - 100 m, km	<ul style="list-style-type: none"> N/A 	<ul style="list-style-type: none"> Will be important for technical measures
Proxy Meteo Data; Format: Time series (xyz)/Raster	<ul style="list-style-type: none"> N/A 	
Event histories, avalanche type, inundation area, snow type, volume. Format: Report, inventory, point, xyz	<ul style="list-style-type: none"> MDB Not full coverage 	<p>Will be important for:</p> <ul style="list-style-type: none"> Back calculations to define friction parameters for the numerical modelling Risk analysis (e.g., return period estimates)
Avalanche maps; Format: Polygon, raster, ASCII; Resolution: 5 - 10 m	<ul style="list-style-type: none"> Polygon Shp-shapefiles; Coverage-Partially 	<p>Will be important for:</p> <ul style="list-style-type: none"> Back calculations to define friction parameters for the numerical modelling Risk analysis (e.g., return period estimates)

³ Information provided by the NEA on 11 March 2021 by email.

Damage reports Format: Report, inventory Spatial Resolution:	<ul style="list-style-type: none"> xlsx 	<p>Will be important for:</p> <ul style="list-style-type: none"> Back calculations to define friction parameters for the numerical modelling Risk analysis (extent of potential damages)
Release areas; Polygon, raster, ASCII; Res.: 5 - 10 m	<ul style="list-style-type: none"> Polygon Shape; Coverage-Partially 	<p>Will be important for:</p> <ul style="list-style-type: none"> LSHM (for validation of the automatised release area detection procedure)

5.3.1. Data Necessary for the Calibration of Numerical Models

The RAMMS numerical model requires adequate data for calibration to the Georgian conditions. The calibration can be done based on well documented avalanches which have occurred in the past. It is important to know about these past avalanches and have information on them.

- Snow height in the avalanche release zone (+/- 5 cm).
- Release area evaluation (contours in the terrain, if possible based on a topographic map, DTM model).
- Flow heights along the transition zone (visible marks on the terrain).
- Deposition zone: geometrical extension, snow height, snow volume.
- Type of avalanche: dry or wet dense snow avalanches, powder snow.
- Damages (to estimate the avalanche pressure – broken tree branches, impact/damages on buildings, roads, poles, etc.).
- DTM of the whole area (mesh size 2-5 m).
- Aerial and satellite imagery avalanches (Format: Raster, image, tiff, twf; Resolution: 0.1 - 25 m).

The information on some documented avalanches available at NEA will be used for the calibration process.

Data for Large-scale Hazard Mapping

Country-wide, numerical, and large-scale avalanche hazard mapping requires the avalanche friction parameters, the release, or the fracture height of the snowpack for avalanches of a 30, 100, and 300-year return period and detailed maps and DTMs of the potential release areas, the transition zones and the avalanche deposition zones to get a correct 3D terrain model for the numerical modelling process.

The following data are available at NEA:

- Topographic map: _MDB & Raster format. Currently available 1:50,000 (digitised from 1980 data).
- Orthophoto res GSD 20cm & DTM Georgia_XYZ, Res: 5m; vertical accuracy ~1m. UAV aerial imagery is necessary to cover all possible gaps when NAPR (National Agency of Public Registry) data are not available for some areas vis-à-vis 2D & 3D representation.
- The orthophoto plans for 2016-2017 are produced within the project Maps for the Sustainable Development of Georgia project implemented with the support of the Government of Norway with the processing of aerial photography materials for 2016-2017.

- Orthophoto res GSD 25 cm & DEM Data 2014 res 15 m; vertical accuracy~4.0 m, covers partial western part of Georgia where snow avalanches seem not to occur.
- Snow cover data: according to the NEA, snow height information is available for every manual meteorological station and meteorological post and for eight automatic meteorological stations.
- Forest cover, density, (Format: Raster, polygon, point, xyz; Res.: 10-100 m) – the Copernicus Land Use project providing a 100 m grid land use worldwide and updated on a yearly basis can be acquired and assessed.

Historical avalanche events: an avalanche cadastre with a limited number of events is available and useful for back-calculation.

5.3.2. Climate Change Projection 2050

The projections for 2050 will be made in line with the SSP2 projections from the other meteorological hazards to be assessed. Avalanche activities are a consequence of heavy snowfalls over a number of days (normally, a 72-hour period) and thus depending on regional and national weather conditions. Projections into the future will be difficult due to the existing lack of snow accumulation data for 24 and 72 hours but in-depth considerations are necessary for all meteorologically based natural hazards. Projections based on IPCC scenarios and global climate models have to be done. Additionally, using EUWATCH might be an option for indications. Avalanche scenarios for 30-year, 100-year and 300-year return periods can be formulated in accordance with the 2050 projections. Such a detailed analysis could be performed on selected target areas with a detailed numerical avalanche modelling.

The climate projections will assist in determining how precipitation may increase which could result in increased snowfall and, therefore, an increase in avalanches. On the other hand, however, a reduction in avalanche activity might be expected due to warming. The GCM scenario selected must be in line with all other hazards.

06

Methodology for Snow Avalanche Modelling and Mapping

6.1 Introduction

As only limited data exist on snow and avalanches, the MSAMM defines conducting a nationwide large-scale hazard mapping process (LSHM) based on an automated GIS-based procedure as a first step. The LSHM will detect snow avalanche release areas combined with a dynamic avalanche modelling process which is based on the same physical and mechanical basics used in the software RAMMS for local detailed avalanche modelling.

Combining the results of the large-scale avalanche hazard mapping with other GIS layers (such as population, buildings, settlements, roads, railways, and other critical infrastructure, etc.) will lead to an indicative nation-wide avalanche risk map. Risk maps will be used for classifying avalanche prone zones in (local) areas at high, moderate, and low risks in order to be able to prioritise the subsequent dynamic avalanche modelling process in areas at risk.

To do a detailed local avalanche modelling process in areas at high avalanche risk, RAMMS software will be used. The results of this step are to be used many-fold – e.g., for land-use planning maps and technical avalanche prevention and protection measures, etc.

6.2 Large Scale Hazard Mapping for Avalanches

6.2.1 Deterministic Large-scale Avalanche Hazard Mapping (LSHM)

Although large-scale indicative hazard maps are less detailed than regular local hazard maps, they can provide an initial broad overview of avalanches based on numerical simulations spanning large areas and are thus often the only spatial planning tool available. This is especially useful for places which, as is the case in most areas of Georgia, have only sparse records available regarding relevant events. The SLF has developed an algorithm to identify potential avalanche starting zones based on terrain

parameters (Christen et al., 2013, Bühler et al., 2018). To produce meaningful and cost-effective avalanche hazard indication maps over large regions (regional to national scales), automated release area delineation must be combined with volume estimations and state-of-the-art numerical avalanche simulations. Potential release area delineation algorithms are based on digital terrain models and their derivatives such as slope angle, aspect, roughness, and curvature. In combination with an automatic procedure to estimate the average release depth (d_0), defining the avalanche release volume, the SLF algorithm enables the numerical simulation of ten thousand avalanches over large regions and for different avalanche scenarios (return periods, etc.).

Once the starting zones have been identified and the related snow avalanche fracture depths have been defined, a dynamic avalanche simulation is performed for each of the relevant release area terrain polygons and parameters used for the characterisation of the avalanches (mainly friction parameters) which are determined based on back calculations of some well documented real avalanches all over the country. This validation is very helpful and leads to better results.

The procedure should be applied for a variety of scenarios such as a return period of five-30 years (frequent) or 100-300 years (extreme). This allows dynamic avalanche simulations to be performed efficiently and automatically, not only for individual avalanche paths but also in the context of large-scale applications at regional and national levels. This approach can also be used to assess the capacities of protection forests to avoid the occurrence of avalanches. While limited in specific details, the approach provides a prerequisite dataset for the priority setting of the subsequent dynamic modelling of local avalanche tracks using the SLF RAMMS software.

No licensable software exists for large-scale hazard mapping. The NEA will have to rely on the up-to-date SLF software for that purpose.

The software used consists of two modules. The first module automatically identifies the avalanche release areas using a new object-based image analysis approach. The second module combines the release area determination with an automatic procedure to estimate the average release depth (d_0), defining the avalanche release volume, and a dynamic avalanche simulation model which follows the same physical and mechanical basics as used in the RAMMS software which is licensed by the SLF. The model is based on Voellmy-Salm depth averaged fluid flow equations applying a dry friction parameter μ and an internal viscous friction parameter ζ dependent on the avalanche flow velocity (Bartelt, et al., 1999). The model requires an understanding of potential release volumes which are set by the fracture depth d_0 and the release area wherein the most critical factor is the measurement of three-day snow falls. The model also requires an understanding of the internal mechanics of avalanches including frictional processes (Bartelt, et al., 2007 and 2010) and internal pressures (Buser, et al., 2011) in addition to the entrainment of snow along the transition path (Vera Valero, et al., 2015) and the influence of forest cover detrainning snow (Feistel, et al., 2014).

The application of the RAMMS avalanche flow model on a large scale requires a number of model assumptions to parameterise the avalanche flow friction parameters (μ and ζ) and the release depth scenarios providing a d_0 . If possible, the selection of the model parameters μ and ζ must be based on the validation of the RAMMS model with some detailed avalanche case studies in the respective re-

gion. Back calculations based on well-recorded avalanches in Georgia will allow the determination of these friction parameters.

If only limited data will be available and back calculations hardly possible, it is recommended to select a proxy parameter set from well calibrated parameter sets for an avalanche region with similar characteristics. Well calibrated avalanche parameter sets are, e.g., available for Switzerland and could be applied to Georgia.

This LSHM modelling approach produces results compatible with a GIS- environment (Christen, et al., 2012) thus providing avalanche prone areas at a large scale.

The selection of d_0 requires detailed annual snow fall records wherein annual snow depth measurements are available which hold three-day new snow accumulation records. This is critical in defining the maximum depth of d_0 releasable in snow avalanche prone areas. For Georgia, and assuming that only limited field data of past avalanches exist, a proxy parameter set must be selected from well calibrated parameter sets for an avalanche region with similar characteristics. Well calibrated avalanche parameter sets are, e.g., available for Switzerland. Table 7 lists some possible values for the avalanche release depth d_0 for several avalanche return periods which could be used for the LSHM for Georgia.

Table 7. Scenario Based d_0 Selection for a Starting Zone at 2,500 m on a 35° Slope. The d_0 values are typical examples taken from case studies in Switzerland (L. Stoffel, SLF Davos, 2018).

Fracture dept d_0	T=10y	T=30y	T=100y	T=300y
d_0 : typical value for starting zone at 2500 m, 35°	0.80 m	1.00 m	1.20 m	1.35 m

The inclusion of forests in avalanche simulation is essential because the braking effect of forest cover on the dynamics of avalanches has a strong influence on the runout distance and the damage potential of avalanches (Feistel et al., 2014). Moreover, forests can act to prevent the release of avalanches (Feistel et al., 2015). In this respect, forests can be considered as an asset in avalanche areas and are also a viable protection solution when managing avalanche threats.

Steps Needed for Large-scale Numerical Avalanche Hazard Modelling and Mapping

To do a large-scale hazard mapping, several steps must be done, and a broad set of data must be available (Figure 8). The avalanche mitigation work is split into three phases with a total of eight steps. Steps 1 – 4 are achieved in a close cooperation with the SLF in Davos. The main goal is a large-scale hazard mapping covering all regions in Georgia which are affected by heavy snowfalls. Frequent and extreme snow conditions will be analysed, i.e., conditions with return periods of ten, 30, 100 and 300 years. The output of Steps 1 – 4 will enable the NEA to come up with a large-scale risk map (Step 5 in Phase 2). Phase 3, again under the full leadership of the NEA, is focused on local avalanche hazard mapping (Step 6) and the design of adequate mitigation measures (Step 7). The risk-based approach at a large scale (Step 5) will also provide the opportunity to do cost-benefit analyses, respectively cost-risk reduction analyses (Step 8) and evaluate the optimal mitigation measure in Step 7.

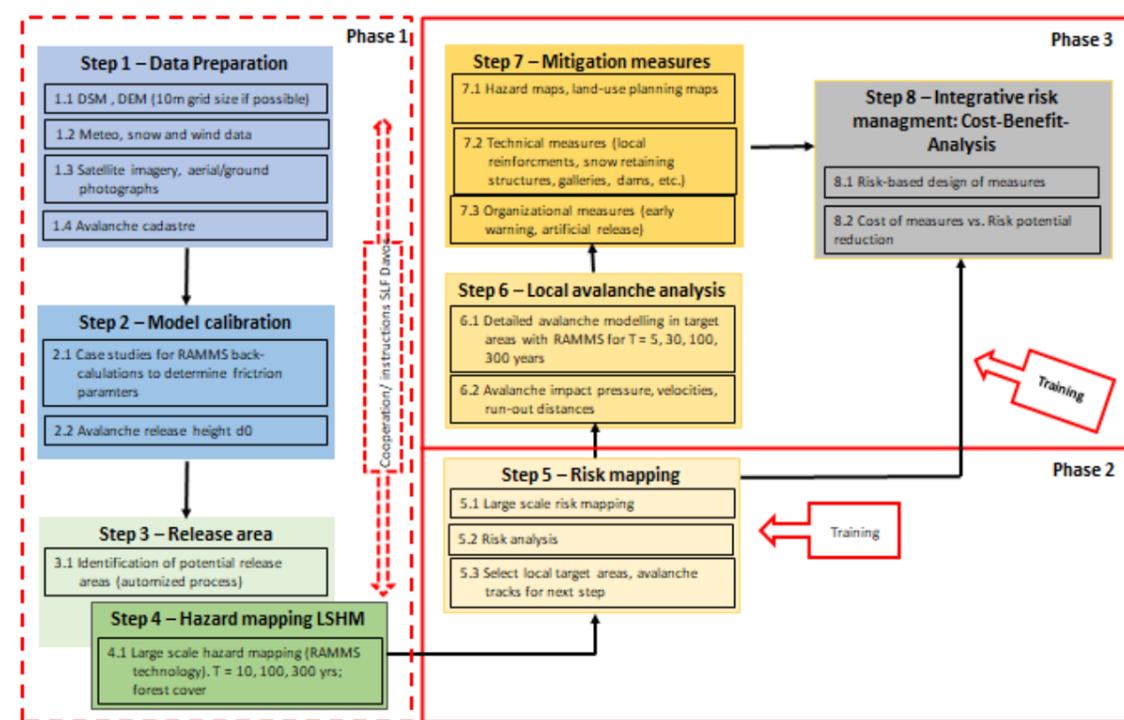


Figure 8. Workflow of a Large-scale Hazard Mapping Process (Step 1 – 4), Impact on Local Hazard and Risk Analysis (Step 5 – 7) and Cost-benefit Analysis for the Prioritisation of Avalanche Mitigation Measures (Step 8). For Phase 1 (red dashed line box), a close cooperation with the SLF Davos and its LSHM software has to be foreseen with instructions on how to use the LSHM results by the NEA for the risk mapping in Step 5 (Phase 2). Phase 3 (red box) and Steps 6 – 8 are under the NEA's leadership. Some training will be necessary to use the licensed software RAMMS by SLF experts (GRF own graph).

Step 1: Data Preparation

The potential for snow avalanches is influenced by several factors such as terrain parameters as well as meteorological conditions and snow characteristics. The more data available, the more accurate hazard mapping can be performed. Some parameters (data) are only important for early warning. A slope angle of $>28 - 30^\circ$ is usually required for dry snow slab avalanches. At slope angles of $>50^\circ$, the snow is hardly stable and is constantly released so that no large avalanches can occur. For large (catastrophic) snow avalanches, precipitation of more than 1 m of fresh fallen snow within three consecutive days is necessary or an unstable snow layer of 40-50 cm is critical for naturally released avalanches in general. Meteorological conditions such as temperature and wind (speed and direction) are important parameters. Wind causes snow drift and accumulation in lee zones and is often considered the most active contributing factor to avalanches. Air and snow temperature affect snow stability in various ways. Wind, air temperature, snowfall and the radiation budget ruled by the orientation of the slopes determine the snow cover stratigraphy and its stability. Rainfall can additionally affect snow cover stability. The orientation of slopes (aspect) with respect to the sun has a strong influence on the day-to-day stability

of the snowpack. To determine avalanche release areas, terrain parameters such as ground surface roughness, ground shape, curvature, vegetation (trees, bushes, etc.) and altitude are important.

For the evaluation of potential avalanche release areas and for the numerical simulation of avalanches, a good terrain model is essential. A 5 m DTM is an ideal resolution to perform detailed three-dimensional avalanche simulations. The caveat of applying a coarser grid is that the quality of avalanche release area detection and avalanche simulation is substantially reduced. However, for large-scale avalanche hazard mapping it is necessary to resample the DTM resolution in order to avoid excessive computational times and permit the automation of the simulations that come with such a large area dataset (for example, for the 5 m DTM dataset, the calculation of avalanche release areas might be performed on a 10 by 10-meter grid and the final avalanche simulations up to a 20 by 20-meter grid size).

The following datasets are available according to the NEA:

- Topographic Map: _MDB & Raster format. Currently available 1:50'000 (digitised from 1980-1990 data). 1:50,000 scale topographic maps are raster and vector format data produced by geo-referencing topographic analogue (paper version) topographic maps of the Soviet period. High-resolution (300 dpi) scanning of topographic maps was performed to obtain a digital (scanned) version of the Soviet time: 50,000 scale topographic maps.
- Orthophoto resolution GSD 20cm & DEM Georgia_XYZ, resolution 5 m; vertical accuracy ~ 1 m. The orthophoto plans for 2016-2017 are produced within the Maps for the Sustainable Development of Georgia project implemented with the support of the Government of Norway with the processing of aerial photography materials for 2016-2017. The total area covered by orthophotos is 40,000 square kilometres which is about 58% of the territory of Georgia and the time period covered by the resource is two years (2016-2017). On-board data (GNSS-INSS) are provided for the further processing of aerial images. During the work process, ground control points (GCP) were identified through which aerotriangulation was performed in a special software environment. Subsequently, a Digital Elevation Model (DEM) was developed on the basis of which orthophoto plans are produced. Orthophoto plans based on aerial photography are updated at appropriate intervals according to the planned national strategy and action plan. Orthophoto plans are protected by the State Fund of Geodesy and Cartography of the National Agency of Public Registry.
- Orthophoto resolution GSD 25 cm & DEM Data 2014 resolution 15 m; vertical accuracy ~ 4.0 m. Orthophoto plans of Western Georgia are raster format data created by processing aerial photography materials in 2014. The GSD of aerial images is 25 cm. The total area covered by orthophotos is 8,800 km² which is about 12.6% of the territory of Georgia and the time period covered by the resource is one year (2014). On-board data (GNSS-INSS) are provided for the further processing of aerial images. During the work process, ground control points (GCP) were identified through which aerotriangulation was performed in a special software environment. Subsequently, a Digital Elevation Model (DEM) was developed based on which orthophoto plans are produced. The mosaic is made according to the orthophoto plans obtained as a result of aerial photography carried out in the same year (product owner: LEPL - National Agency of Public Registry).

- The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) as 1 arc-second (approximately 30 m resolution) DEMs are available for Georgia. Currently used SRTM data at a downscaled grid size of 20x20 m.
- Aerial LIDAR data available only for floodplains but not for potential snow avalanche areas.
- Forest cover, density, (format: polygon, shp Res.: 100 m, Copernicus Land Use project).

Step 2:**Model Calibration RAMMS and Model Parameter Selection**

Calibrating the RAMMS avalanche model parameters involves collating all available snow and avalanche data and information of historical and well documented avalanches. Information on avalanche release areas, snow heights, avalanche deposition areas, deposition heights, damages to buildings and infrastructure, etc., will be helpful as well as information on damages caused by avalanches in the past. The aim is to define the likely characteristics of avalanche release zones and their dynamic flow properties and runout distances with which suitable model parameters can be selected in order to characterise avalanche behaviour (friction parameters, snow release heights, return periods). A comprehensive list of the required data for a full model calibration is given in the avalanche desk study report. They are a mix of both qualitative and quantitative data describing snow properties, release volumes, runout areas and damage reports. Furthermore, in order to be able to perform a robust analysis based on event magnitudes of a given return period (T), the calibration should be based on historic avalanche data that cover decades of avalanche events. All available data sources should be screened to ensure that the best possible parameter selection will be made. Back calculations of some few but well documented historical avalanche events with the software RAMMS will enable the evaluation of the necessary friction parameters for future analyses in the LSHM procedure.

For the calibration process, it is necessary to select a few well documented avalanche events all over Georgia and do the back calculations with the RAMMS software. As a result, the friction parameters should be available to be fed into the LSHM process.

The back calculations might also serve to gain a better insight into the snow release heights and their periodicity in the avalanche starting zone. This would enable the RAMMS modelling to be based on locally observed snow heights and not only on the d0 values.

Step 3:**Identify Avalanche Release Areas**

Bühler et al. (2013, 2018) present a method to automatically detect avalanche release areas by using a slope, curvature, ruggedness derived from the terrain model, exposition, etc. The algorithm should operate on a 5-10 m grid resolution, and it detects all possible release areas on the terrain. A key pa-

rameter in the identification of the release zones is the ruggedness of the terrain. For example, break points in the terrain, such as rocky outcrops, are common initiation points for avalanches and hence a relatively high-resolution terrain model is a prerequisite. It might also be possible to use a more detailed approach depending on data availability. The method proposed by Veitinger et al. (2014) not only uses the digital terrain model but also information on regional snow accumulation and the prevailing winds. The additional parameters account for the effects of terrain roughness, terrain smoothing through snow accumulation, which is included in the roughness parameter, and snow loading due to snow drift from wind in a wind shelter parameter.

From a study in 2011 for Georgia, a DEM (ASTER GDEM) seems available, and satellite data sets from MODIS were used to map snow-cover distribution. Land cover information was used from existing topographic maps, cadastral maps, and aerial images (e.g., forest cover from Landsat satellite images, etc.). To analyse and assess the effectiveness of the forest cover, it will be necessary to do the LSHM simulations with and without the existing forest cover.

Step 4:**Large-scale Hazard Mapping LSHM**

The large-scale hazard mapping task requires that the analysis of avalanche hazards is focused along areas that are affected by substantial snowfalls. Not only areas that receive snowfall are of interest but also those areas where the snowfall should be sufficient to induce an avalanche. Moreover, for these analyses, the amount of snowfall should be sufficient to generate a depth of snowpack that is conducive to a 100-300-year avalanche hazard scenario. In areas with limited terrestrial snow data, snow cover from satellite data might help. However, it should be noted that this dataset does not contain data of snow depth and, as such, all zones with snow are marked as areas for potential avalanches. This leads to a conservative selection of likely avalanche areas as it is not possible to indicate an intensity level according to snow depth.

The detail of snow and weather data required to perform a rigorous parameter selection for a nationwide large-scale avalanche hazard mapping is extensive. To be able to perform this mapping in greater detail, it is necessary that data for snowfall are available daily throughout the year for many consecutive years and with a broad spatial coverage over Georgia.

An option to get more information on snow-pack depth also exists in using the General Climate Model (GCM) dataset to generate snow water equivalents (SWE) based on the assumption that snowfalls when there is precipitation and a (freezing) temperature $<0^{\circ}\text{C}$ at a given location in the GCM. It is important to note that SWE measurements do not give a direct measure of snow height. The conversion of SWE to a snow height can be made by assuming a nominal snow density. In the case of the examination of the modelled SWE values, a bulk snow density ρ_s of 300 kg m^{-3} could be assumed to equate snow height HS (Jonas et al., 2009).

The Georgian snow avalanche study in 2011⁴ concluded that 10% of Georgia's territory appeared to be in the high hazard zone for snow avalanches, 22% in a moderate zone and 6% in a low-risk zone. Consequently, 62% of the areas of Georgia are not at risk of snow avalanche hazards. This means that approximately 25,000 – 30,000 km² of the whole country are prone to avalanches (including some areas in the semi-arid zones of Georgia).

The resulting map was done manually and later digitised. It represents polygons on areas where snow avalanche may happen. The scale of the map is 1:2,000,000. It has to be mentioned that the study was focused on the detection of potential release areas only and did not contain any avalanche runout calculations. It is, therefore, not known if the map and the numbers mentioned above are only focused on the release areas or if some qualitative expert judgement was done to estimate the area of the runout zones. Consequently, the map represents some avalanche hazards but not the resulting risks.

Step 5:

Avalanche Risk Mapping

Linking the results of this large-scale avalanche **hazard** mapping with other GIS layers (population, buildings, settlements, roads, railways, and other critical infrastructure, etc.) results in a nation-wide avalanche **risk map**. The risk, therefore, is a mathematical construct as a multiplication of the avalanche hazard, the assets/values which are exposed to the avalanche hazard and the respective vulnerabilities of these assets. The risk map can be used for classifying the avalanche prone zones in (local) areas, e.g., in zones at high, moderate, and low risks; thus, there is the ability to prioritise the subsequent dynamic and more detailed avalanche modelling process in areas at risk at a local scale. This step is based on the outcomes of Phase 1 in combination with the economic risk analysis procedure and can be done independently of the SLF software used in Phase 1. Phase 2 is only partially addressed hereafter as the provision of the GIS based layers with information on the various assets exposed to avalanche hazards are not covered by this methodology. However, the LSHM methodology recommended hereafter is fundamental for the risk approach. The risk-based approach – in particular, the presentation of the results at the risk level – has to be the same for all hazards. The three risk levels must be agreed in order for all hazards to be considered. Only a risk-based approach guarantees the appropriate priority setting for the various methods to be taken in order to cope with hazards.

Step 6:

Local Avalanche Hazard Mapping

Step 6, local avalanche hazard modelling, is based on the RAMMS software and is explained in more detail in the subsequent sections.

⁴ Lasha Sukhishvili and Irakli Megrelidze. Snow Avalanche Risk Assessment. 21 December 2011.

Step 7:

Mitigation Measures

To mitigate avalanche risks, several different types of measures are possible and include:

- a. **Preventive measures** designed at preventing avalanche formation in the release zone:
 - Par-avalanche constructions (steel snow fences and nets, stone walls, wooden fences).
 - Snow drift fences and wind deviation constructions.
 - Reforestation and forest regeneration management (combined with temporary technical support structures).
- b. **Protection measures** designed at stopping or deflecting avalanche flow:
 - Earth/concrete dams.
 - Concrete galleries (protect roads and tunnel portholes).
 - Tunnels (avalanche avoidance).
 - Single house protection.
- c. **Organisational measures:**
 - Snow and avalanche observation activities.
 - Automatic snow and weather stations.
 - Avalanche (early) warning services.
 - Artificial release of avalanches of a manageable volume.
 - Temporary closing of roads.
 - Evacuation of settlements, etc.
- d. **Mitigation measures:**
 - Land-use planning based on avalanche hazard mapping implemented at preventing settlements to be built in avalanche prone areas.

In most cases, the evaluation, design, and implementation of an adequate measure relies on numerical modelling as described above. Risk modelling as described in Step 5, combined with a cost-benefit analysis as described in Step 8, are prerequisites for a cost-effective avalanche risk reduction.

6.3 Integrative Risk Management: Cost-benefit Analysis

The planning of measures serves to identify and assess measures that are necessary and appropriate in order to reach risk reduction goals. The main function of the planning of integrated measures is to achieve the intended level of safety within the agreed limits in the most cost-effective way. Protection with organisational, technical, and biological measures has to be planned, checked for effectiveness,

and undertaken in concert while keeping in mind that prevention, intervention, and reconstruction are all equally valid risk-management measures.

Further criteria, such as the acceptability, feasibility, and the reliability of solutions, have to be kept in mind as well. All solutions have to fulfil the criterion of sustainability, i.e., a sustainable way in risk-reduction management has to be a socially, economically, and environmentally equilibrated approach. A periodic survey as a risk audit is necessary in order to reveal gaps and support priority setting. To easily memorise the different steps of integral risk management, we can use the '5S concept' which implies that stakeholders, strategy, standards, sustainability, and survey are important issues to be followed (Ammann 2006 and 2008).

Safety measures usually have side effects which also have to be considered in a cost-effectiveness analysis. The most obvious among these are the financial or economic aspects. But aspects of ecology, landscape protection or land use planning can be of equal importance. For an optimal coordination of all measures, all relevant aspects have to be considered. As long as the side effects are an inherent part of the safety measures, all costs have to be allocated to the issue of safety. But if safety measures, as an example, also further economic growth, then the resulting costs should be split between economics and safety while providing full transparency.

Integral risk management shows how the overlying objectives can be reached with corresponding technically, economically, societal, and environmentally justifiable risk-reduction measures. It applies the required measures within the framework of the risk dialogue. Integral risk management, therefore, makes it possible to address different risks, including those originating from natural hazards, in a uniform and transparent way and based on the risk concept and within a comprehensive risk culture.

Administrative Procedure to Have Access to the LSHM at the SLF Davos

The software used for the automatic detection of all of the potential avalanche release zones throughout Georgia, as well as the highly sophisticated software used to analyse the many thousands of potential avalanches, are not publicly available but can be made accessible by the WSL Institute for Snow and Avalanche Research, (SLF) in Davos, Switzerland in close interaction and cooperation with the NEA. While the SLF will do all of the numerical simulations on its high-performance computer, the NEA will have to provide the data, in particular, in the form of a high-resolution DTM/DEM and, if possible, snow and avalanche data, including historical avalanche events, throughout Georgia. The historical data are used to calibrate adequate friction parameters in the numerical modelling and the fracture depths in the release areas. The model calibration (Step 2) will have to be done by the SLF based on a few well documented avalanche events. The calibration is focused on the friction parameters. The SLF will inform the NEA which events might be best suited for calibration purposes. The results of this model calibration in Step 2 will serve as basic input parameters for Step 4 (LSHM) and for Step 6 (local avalanche analyses).

The selection of adequate fracture depths for the various avalanche return periods will be determined based on a joint analysis of available snow height data in the potential avalanche release areas. If no reliable data are available, a similarity study will allow the identification of corresponding snow heights

in the release areas (see also Table 1). In addition to these snow heights, the LSHM simulation needs some friction parameters resulting from Step 2 (see section on model calibration). These calibration tests are based on the RAMMS software needed for Step 6 (local hazard mapping) and can serve as a first training for NEA experts to become familiar with the RAMMS software under the supervision of SLF experts.

Based on these calibration tests, the SLF Davos will run the LSHM simulations in close cooperation with the NEA and provide country-wide GIS based results for further use by the NEA such as the:

- Exact extent of the avalanche release areas.
- Runout contour lines of the avalanches.
- Avalanche pressure contour lines (e.g., 3 kN/m², 30 kN/m², 100 kN/m²).
- Avalanche deposition heights (contour lines).
- Avalanche velocities along the avalanche trajectories.

The large-scale avalanche hazard modelling (LSHM simulations) will be done for:

- Frequent avalanches with a return period of about ten years.
- A return period of 100 years.
- Extreme avalanches with a return period of 300 years.

It is recommended to do the LSHM simulations with and without the forest cover (to assess the capacity of the forest to limit the release of avalanches in forested areas).

These simulations will allow to get an overview on the various regions with low, medium, and high intensities and, by combining the results with the various asset layers leading to a country-wide avalanche risk mapping, enabling setting priorities on where and when to start with the local avalanche hazard analyses with the RAMMS software.

The simulations with forest cover can serve as a first and preliminary analysis of the importance of forest cover and its protection capacity in the various areas. For example, the protection capacity of the forest might be categorised in areas with low respectively high importance which provides some first indications where it might be useful to do silvicultural measures.

6.4 From LSHM to Risk Maps to Local Hazard Maps

As schematically shown in Figure 9, risk can be expressed as a mathematical product of the (e.g., 100-year period of avalanches) hazard, the assets and values that are exposed to the hazard (people, livestock, housing, public buildings, schools, hospitals, commercial and industrial buildings, roads, farmland, power supply lines, water reservoirs, etc.) and the vulnerabilities of all of the values impacted by the avalanches (hazard). Based on the outcomes of the large-scale hazard mapping, a loss analysis on available data has to be undertaken in a GIS database. With hazard maps of avalanche runout paths which include, for example, flow pressures f_p for the 100-year return period |T| scenario performed

in the large-scale hazard mapping, the likely damages to exposed assets, livelihoods and lives can be analysed. The nominal force required to damage buildings and infrastructure can be mapped from the simulation results. Vulnerable assets and values can be identified from the hazard maps. In this way, it will be possible to summarise the total assets and values that are likely to be exposed to an avalanche of a certain intensity (represented by the annuity of the avalanche, e.g., a 100-year return period).

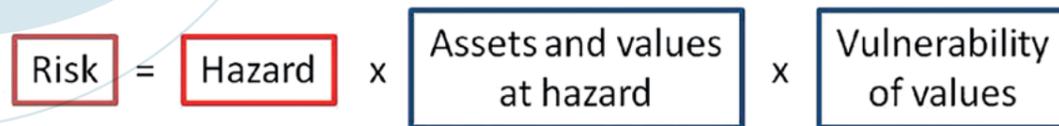


Figure 9. Risk is a Mathematical Construct, i.e., the multiplication of the avalanche hazard, the assets exposed to the hazard, and their vulnerability. The total risk results by adding each asset's risk to an overall total in a specific area (GRF own graph).

Linking and overlaying the results of this large-scale avalanche hazard mapping with other GIS layers (population, buildings, settlements, roads, railways, and other critical infrastructure, etc.) will provide an indicative nation-wide avalanche risk map (Step 5). The risk map is used for classifying the avalanche prone zones in (local) areas at high, moderate, and low risks in order to be able to prioritise the subsequent dynamic avalanche modelling process in areas at risk (Step 6). Step 5 is only partially addressed hereafter as the provision of the GIS based layers with the various assets exposed to avalanche hazards, and leading to the risk maps, is not part of the MSAMM objective.

Hereafter, only some snow avalanche specific aspects are addressed in more detail. The various assets which might be impacted by avalanches, and thus be a target for avalanches, can be divided into:

- a. **Stationary (static) targets** such as buildings, settlements, agricultural areas, livestock shelters, etc. They are addressed in some specific GIS layers which use geographically allocated information.
- b. **Moving (dynamic) targets**, such as people walking outside and, in particular, vehicles or trains which might be subjected to avalanches. These moving targets are only exposed for a very limited time to a specific avalanche. Modelling needs some specific information on the moving velocity of these targets and the potential number per time defined of these moving targets.

Risk Analysis for Moving Targets

The risk definition represented by Figure 9 implies that the assets/values are exposed to an avalanche hazard. People travelling by train or by car become “moving targets” which makes risk analysis time dependent. The velocity of a car must be considered when it crosses an avalanche track as well as the segment length of the road exposed to an avalanche. Table 8 shows some mortality rates for passengers sitting in different types of vehicles and which are hit by an avalanche with an impact pressure of >3kN/m².

Table 8. Mortality in the Case of an Avalanche Accident on a Road (GRF Davos own graph).

Vehicle Type	Mortality
Trucks	0.1
Bus	0.05
Cars	0.1
Motorcycles	0.3

For a single avalanche track overflowing a road, the risk of death for the moving targets is then calculated according to the following equation:

For an individual avalanche track, the resulting risk R is (deaths/year):

$$R = (1/T_i) \cdot \frac{g_i \cdot DTV}{v_i \cdot 24h} P(A) \cdot n \left[\frac{Deaths}{year} \right]$$

With the parameters:

- Avalanche return period: T_i (years)
- Segment length of the avalanche track at the road level: g_i (km)
- Average vehicle velocity across the avalanche track: v_i (km/h)
- Average daily traffic number: DTV (Number of vehicles/24 hours)
- Vehicle splitting (% of cars, trucks, buses, motorcycles)
- Probability of death (mortality, see Table 4) due to impact by an avalanche at a given location $P(A)$ (% of incidents) – depending on the type of vehicle
- Average occupancy of each vehicle type: n (Number of people/vehicle)

Vulnerability Levels

Large-scale avalanche hazard analysis can provide maps which delineate the runout areas of avalanches. LSHM simulation provides the possibility of receiving results in a raster format containing layers of avalanche pressure displayed in kN/m² (resp. kPa). Pressure values can be directly linked to vulnerabilities and thus to risks; respectively, damages to structures and for engineering purposes where avalanche mitigation structures and buildings must be designed to withstand avalanches. A list of known damages to structures due to avalanche pressure and the according pressure are given in Table 9. The impact pressure is defined perpendicularly to the flow direction. By intersecting the different exposure datasets with the according pressure zones, the extent of damages caused by avalanches can be visualised.

Table 9. Avalanche Impact Pressures Perpendicular to Flow Direction and Respective Damages to Structures (L. Stoffel and S. Margreth, SLF Davos, personal communication 2019)

Approximate Average Impact Pressure and Potential Damage	
Impact Pressure (kPa)	Potential Damage
2.0 – 4.0	Windows get broken
3.0 - 6.0	Doors pushed in, damages to roofs and walls
10.0	Wood-framed structures damaged
20.0	Wooden houses destroyed, damages to cemented brick-walls
30.0	Cemented brick-walls and concrete buildings destroyed

6.5 Hazard Mapping and Territorial Planning at Local Scale (Step 6)

An avalanche hazard map is meant to help ensure that all activities that have an impact on the land-use (issuing and approbation of directional plans and land-use plans, concepts, sector plans and the necessary basics, the planning and the construction of buildings and infrastructure of any type, granting licences and concessions, issuing subsidies, etc.) of a governmental body at the national, regional or community levels take avalanche danger into consideration. For already existing endangered buildings, the avalanche hazard map is the basis for required protective construction or for measures of communal avalanche service (evacuation, closures of roads, etc.). For the drafting of avalanche hazard maps, the avalanche hazard should be assessed and considered with the same criteria and standards for the whole of the country. To achieve this, adequate legal regulations and technical guidelines might have to be developed.

The resulting products of such an avalanche hazard analysis process are:

- **Avalanche cadastral map:** The avalanche cadastral map (scale 1:25,000 or 1:10,000) contains the date, the impact area, and the damage of each observed avalanche.
- **Avalanche hazard map:** The avalanche hazard map (scale 1:10,000 down to 1:2,000, equidistance 10 m) depicts the hazard areas based on the periodicity and the avalanche pressure. The hazard areas are separated in zones with different hazard levels. The borders of these zones are formed by lines of equal avalanche hazard. The avalanche hazard map is a document (without legal implications) which aims at depicting the avalanche danger with objective criteria.
- **Land-use planning:** The avalanche hazard maps are used as a base for the hazard zoning vis-à-vis the land-use planning process. Land-use plans (scale 1:2,000 or 1:5,000) contain, for example, both the building and the hazard zones. One can also see them as modified and interpreted avalanche hazard maps. It specifies limitations such as construction prohibition, regulations on building enforcements or operational measures such as evacuation. Unlike the avalanche hazard map, it is a legally binding document.

6.6 Local Hazard Mapping

The creation of an avalanche hazard map – be it at a regional large-scale or at the local level – must exclusively follow scientific criteria. The following basic information is helpful:

- Avalanche cadastral map as historical data about past events. According to the NEA, only a limited amount of historic avalanche information is available. For this reason, it is important to start collecting various parameters in order to characterise historic avalanche events.
- Local terrain assessment based on local topographic maps and aerial photography.
- Physical on-site terrain survey and observation upon inspection (e.g., assessment of existing avalanche tracks, investigation of avalanche traces in the field, broken tree branches, extent of deforested area, heavy stones moved, etc.).
- Local weather and climatic conditions over past years (long-term observations on daily snow precipitation, total height of the snow cover in an area, air temperature wind speed and direction, etc.).

Local avalanche hazard maps are generated for inhabited areas which show signs of avalanche danger or for critical infrastructure and the many other assets which might be exposed to avalanches. It is obvious that the LSHM simulation will reveal thousands of potentially hazardous avalanches. For the decision on which areas to choose for local hazard mapping, it is recommended to proceed along the following lines:

- To start with those areas where destructive avalanches have occurred in the past and have led to substantial damage (people, assets). In these areas, the local hazard mapping will prevent new buildings from being built in an avalanche prone area and provide information on design parameters (local pressures) for strengthening existing buildings and infrastructure.
- Based on Step 5, the resulting avalanche risk map will depict all areas with a corresponding avalanche risk. It is recommended to distinguish between a low, medium and a high avalanche risk which enables the NEA to first concentrate on the high-risk areas for the local hazard mapping process. It is further recommended to do the local hazard mapping process community by community, although it will be seen that not all avalanche tracks represent a high risk within one and the same community. Nevertheless, it will also be more efficient to integrate the medium- and low-risk avalanches into the whole mapping process at a community level. The results will be more consistent by doing all of the mapping within the same process at the same time.

As a measure for the hazard level, it is recommended to use the periodicity (frequency) and the pressure (intensity) of an avalanche. The frequency of an avalanche with a certain dimension is specified by the periodicity. The periodicity is the reciprocal value of the frequency and corresponds with the mean time interval in which the event occurs at least once in a defined time period, e.g., the 100-year period avalanche which means that an avalanche occurs at least once in 100 years.

The avalanche pressure is defined as the impact force level which acts onto a large plane obstacle which is perpendicular to the direction of the avalanche flow. The avalanche pressure is proportional

to the density of the snow and the squared velocity ($p_n = \rho v^2$; $\rho_{\text{dense flow avalanche}} = 300 \text{ kg/m}^3$). For hazard mapping, the snow density is considered as a constant value at 300 kg/m^3 .

The fracture depth, the avalanche velocity and the avalanche pressure are coupled with the issue of periodicity. In general, the periodicity depends on the slope angle. With a low slope gradient ($\Psi \approx 30^\circ$), avalanches are rather rare but if they happen, they occur in large dimensions (destructive avalanches). On the other hand, steep slopes ($\Psi \approx 50^\circ$) will discharge the snow at already modest snow depths. Therefore, steep slopes show a lower periodicity/higher frequency than those less steep.

6.7 Levels of an Avalanche Hazard Map

The avalanche hazard map distinguishes between four degrees of hazard (see Figure 10). They are distinguished by colours (red, blue, yellow, and white). The following criteria and conditions are based on Swiss standards transformed to Georgian use.

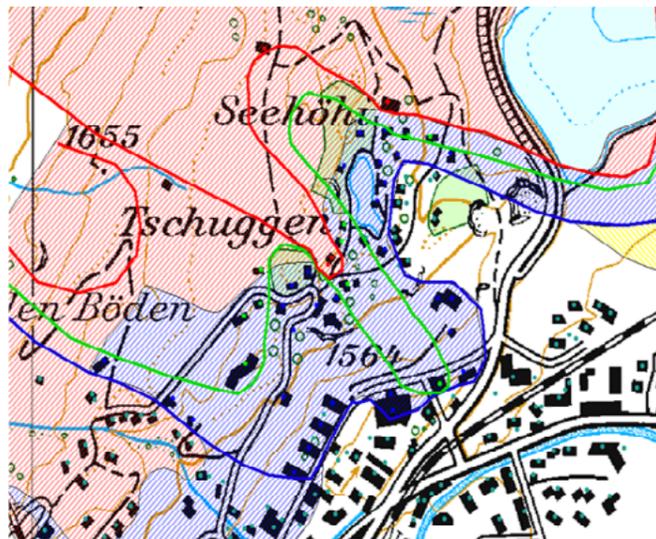


Figure 10. Example of an Avalanche Hazard Map (Avalanche Hazard Map Extract of Davos, Switzerland).

RED ZONE

Criteria: Considerably endangered area; there is no doubt about the existence of an avalanche hazard.

An area is attributed to the red zone if the following criteria apply:

- 3) $p_n \geq 30 \text{ [kN/m}^2\text{]}$ and if $T \leq 300$ years return period
- 4) $0 \leq p_n \leq 30 \text{ [kN/m}^2\text{]}$ if $T \leq 30$ years return period

Each of the conditions 1) or 2) by itself is sufficient for an attribution to the red zone.

If buildings within the red zone are hit by an avalanche, they are expected to fail. Therefore, people's lives are in danger, including within buildings (condition 1). Smaller but more frequent avalanches mainly threaten people outside of buildings (condition 2).

BLUE ZONE

Criteria: Areas which will only be reached by avalanches with low intensity in rare cases, or there might be doubts as to the existence of an avalanche hazard.

An area is attributed to the blue zone if the following conditions apply:

- 3) $p_n < 30 \text{ [kN/m}^2\text{]}$ if $30 < T \leq 300$ years
- 4) $p_n < 3 \text{ [kN/m}^2\text{]}$ if $T < 30$ years (only applies for powder snow avalanches)

Destruction of buildings during their typical lifetime (50-70 years) is hardly not expected if certain construction standards and additional building regulations (strengthening of walls, windows, etc.) are considered. A certain hazard exists outside of buildings which is acceptable (if certain construction measures are followed).

YELLOW ZONE

Areas with very low avalanche hazard.

The definition of a yellow zone is optional. An area is attributed to the yellow zone if the following conditions apply:

- 3) $p_n \leq 3 \text{ [kN/m}^2\text{]}$ if $T \geq 30$ years (only applies for powder snow avalanches)
- 4) p_n unknown; $T > 300$ years (applies for statistically not detectable dense flow avalanches)

Damage to buildings in this area is very unlikely with the risk for people only in limitation to access.

WHITE ZONE

It is very unlikely that avalanches will occur in this area.

6.8 Practical Procedure for the Development of a Local Hazard Map

6.8.1 Analysis of the Avalanche Cadastral Register

The existing avalanche cadastral maps provide some limited information on the periodicity of an avalanche of a certain (damaging) size (see also section 2.4.2). In general, the resulting extent of the hazard zones based on these cadastral maps will not be the maximum as potential extreme avalanches can often not be included due to the rather short observation time. Therefore, to represent potential large avalanches, the avalanche hazard map is generated using a return period of 300 years.

6.8.2 Detailed Assessment of the Terrain

For a detailed assessment of the terrain, maps and aerial photos are valuable tools to complement an on-site visit by avalanche experts.

Examination of “indirect avalanche witnesses”

Indirect witnesses can be found on an on-site field inspection and include, for example, the condition of the forest, the age of the trees and visible damages. Additionally, tree ring analysis sometimes provides useful data on the occurrence of damaging avalanches at a specific site. Entrained material, originating from avalanche depositions (e.g., tree trunks) and scraping marks on the ground are additional hints about former avalanche activities.

6.8.3 Definition of Starting Zones

A visual inspection on-site helps to determine the size of a potential avalanche starting zone. A realistic starting zone is often not identical with the total potential catchment area as local vegetation, surface roughness, ridges, etc., influence the surroundings of a starting zone. Dominant wind directions also must be taken into consideration as large volumes of snow can be transported by the wind from the luv to the lee side where huge volumes of drifted snow might accumulate and enlarge a potential starting zone.

6.8.4 Determination of the Fracture Depth d_0 for $T=10, 30$ and 300 Years

The determination of the fracture depth is very important as the runout distance is almost proportional to it. Further, the fracture depth is linked with the periodicity which renders the runout distance to a statistical dimension with a certain probability of occurrence.

The main influencing factors for the snow height d_0 in the release area are:

- **New fresh fallen snow:** This considers the climatically possible maximum amount of snow for three consecutive days. The consideration of precipitation periods longer than three days has shown to be irrelevant. Thus, it can be assumed that large avalanches – unlike the so-called skiers-avalanches – are always caused by snowfall and that basically only the new snow is released. Studies have confirmed this despite the occasional fracture within the old snow cover. The periodicity of the new snow growth is assumed to be identical to the one of the respective avalanches (unfavourable assumption).

- **Slope angle:** The shear strength limits the amount of new snow that can be deposited on a slope. Thus, the snow will slide off before the climatically possible maximum amount of snow is deposited. The strength is linked to the Mohr-Coulomb law known in geotechnics and is increasing with heavier snowfall as well. Otherwise, the fracture depth for equal slope angles would – assuming similar strength – always be the same, independent of the periodicity.
- **Snow drift:** On the lee side of mountain ridges, the new snow accumulation and, therefore, the fracture depth is locally larger (considering the prevailing wind direction during snowfall).

The determination of the fracture depth needs some further considerations. The mean fracture depth d_0 perpendicular to the slope is defined as:

$$d_0 = d_0^* \cdot F(\psi)$$

Where:

d_0^* = base value depending on the local climate (potential snow accumulation in three days) and on the periodicity T [years]. An example is given for Switzerland in Table 4 below.

$f(\Psi)$ = gradient factor, determined by the snow strength

Table 10. Recommended Base Values d_0^* for $\Psi=28^\circ$ (example taken from Switzerland)

Periodicity T	base value d_0^* for $\Psi_{om}=28^\circ$ Climatically possible snow accumulation for three days	
	small [m]	Large [m]
Years		
30	0.88	1.50
100	1.06	1.81
300	1.23	2.10

The recommended base values are valid for an altitude of 2,000 m.a.s.l. For higher or lower starting zones, 5 cm per 100 m of altitude must be subtracted or added. In high areas, the wind influence is dominant and the added value for the altitude only has a secondary influence. For snow drift, the base values for d_0^* should be enlarged by 0.3 to 0.5 m. The base value d_0^* is used along the whole starting zone. It is also interesting to see that the base values for the climatically possible snow accumulation within three days for the 300 respectively the 30-year periodicity remains almost constant.

$$\frac{d_0^*(T=300)}{d_0^*(T=30)} \cong 1.4$$

This means that the 300-year periodicity snow depth is only 40% higher than the one for the 30-year return period.

The dependence of the fracture depth and the slope angle can be expressed by the following factor (Table 11):

$$f(\psi) = \frac{0.291}{\sin \psi - 0.202 \cdot \cos \psi} \quad (6.3)$$

Table 11. Slope Angle Factors $f(\Psi)$. The angle Ψ describes the mean slope angle in the fracture zone.

Gradient Ψ_{om} [°]	$f(\Psi)$ [-]	Periodicity T [years]
28.0	1.00	Rather large
30.0	0.90	
32.5	0.79	
35.0	0.71	
37.5	0.65	
40.0	0.60	
45.0	0.52	
50.0	0.46	Rather small

Example

Wanted: fracture depth d_0 of a snow slope with an angle of 35° for a 300-year avalanche

Solution: $T = 300$, $d_0^* = 2.10$ m

$\Psi = 35^\circ \Rightarrow f(\Psi) = 0.71$

Resulting fracture depth: $d_0 = 2.10 \cdot 0.71 = 1.49$ m

The numerical simulation of avalanche paths is recommended to be done with the RAMMS software from the SLF Davos. This 3D numerical approach allows the analysis of the avalanche flow from the starting zone to the deposition zone, including avalanche velocities, pressure, flow heights, the lateral distribution of the avalanche in the runout zone, etc.

6.8.5 Minimum Requirements for the Different Hazard Zones

The following minimum requirements apply for settlements and are only briefly described. For other purposes, such as communication lines, roads, tourist infrastructure, etc., they must be adapted.

RED ZONE

In the red zones of an avalanche hazard map, no buildings are allowed. This is also the case if an existing building has been damaged or destroyed by an avalanche. Reconstruction is not possible. New buildings or the reconstruction of buildings for people and the sheltering – even if it is only of a temporary

nature – are only permitted if they do require exactly that particular location due to forestry or agricultural reasons. The same applies for infrastructure (water catchment, sewage plant, etc.). In these cases, experts must be consulted in order to guarantee the highest possible security.

BLUE ZONE

In the blue zones of the avalanche hazard map, building zones should be defined very conservatively. If there are still existing land reserves in these areas which are not at risk, they should be used with priority. New buildings and reconstruction are permitted with certain limitations but, in general, building activities should be restrained. Buildings and infrastructure, which gather large numbers of people (e.g., schools, hotels, restaurants, sports facilities etc.), should be avoided. The conversions and the changes of purpose of buildings are only permissible if the number of people at risk does not increase considerably.

YELLOW ZONE

There are no special building regulations.

WHITE ZONE

Areas which are marked as white zones on the avalanche hazard map do not require any particular safety measures.

Organisational Measures and Access to Zones

For people living in the red or blue zones, an early warning and alert system must be installed in order to ensure people are evacuated from the red zone while not leaving their houses in the blue and yellow zones.

Areas which can only be accessed by passing through a higher avalanche hazard zone are treated as areas with this higher hazard level. For example, an area belonging to the blue zone, but which can only be accessed by travelling through a red zone must be treated as red zone as well.

6.9 RAMMS Software as a Dynamic Modelling Tool

The software recommended for the local hazard mapping (LHM) process is RAMMS which is a software package developed, maintained, and managed by the Swiss Federal Institute for Snow and Avalanche Research SLF in Davos. RAMMS is a reliable numerical simulation tool yielding runout distance, flow heights, flow velocities and impact pressure of dense flow snow avalanches, hillslope landslides and debris flows.

RAMMS has the advantage that other natural hazard processes, such as debris flow, landslides, or rock-fall, can also be modelled and analysed with this same software so that NEA experts can use the same input and output procedures. The mechanics and dynamics behind the various processes and the physical modelling process are kept as close as possible which also facilitates the trainings for the users. For example, the debris flow modelling is very similar to the snow avalanche modelling. For avalanches, in particular, RAMMS is the leading software world-wide and thus highly recommended for use.

RAMMS offers a number of features such as:

- Calculation and animation of runout distance, flow height, velocity, and impact pressure.
- Advanced 3D visualisation interface for digital elevation models, aerial imagery, topographic maps, simulation results and additional georeferenced datasets. Topographic map and aerial imagery.
- GIS tools such as slope angle, curvature, contour, and friction parameter calculation.
- Manual release area and forest editing tools.
- Exports the results to Google Earth, ArcGIS, and other tools.

RAMMS for LHM is an internet version and is provided to clients based on an annual license fee agreement. The SLF will provide specific training courses for applying the software. SLF experts are ready to integrate NEA experts in the whole modelling process and enable them to use the results of these simulations for further evaluation procedures such as for the detailed local risk assessment and the design of technical measures, etc.

6.9.1 IT-System Requirements

The following IT-system requirements are required:

- Operating System: Windows 7/8/10 (64-bit)
- RAM (Memory): 4 GB (more recommended)
- CPU: min. 2.6 GHz (dual core or more recommended)
- Graphic Card: OpenGL support recommended.
- Disk space: ~ 200 MB

6.9.2 Recommended User Skills

The following user skills are required:

- Process know-how (avalanche, debris flow or rock-fall)
- Hazard mapping understanding
- AVAL-1D experience (for avalanche module) – understanding the Voellmy-Salm basic snow avalanche model
- Experience using geo-data such as digital elevation models (DEM)

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