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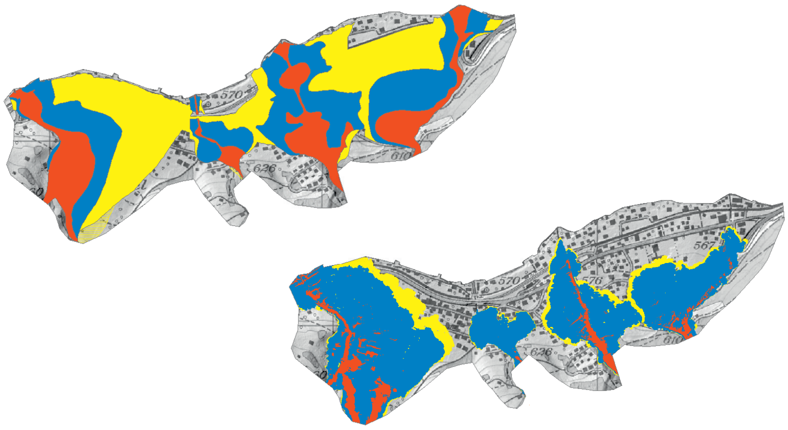
HAZARD MAPPING FOR DEBRIS-FLOWS

empirical, analytical techniques compared to numerical model simulations



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Abstract

Hazard maps are the link between land use planning with respect to natural hazards and process-based fundamental research. To avoid damage and protect the society from natural hazards an accurate assessment of the hazard potential is essential and a consistent mapping process is required. So far and for debris-flows in particular, hazard maps are based on quite subjective expert knowledge. The development of dynamic or kinematic runout models to simulate debris-flow behavior in the last decade complements hazard assessment by a more objective approach. Little investigation on the suitability of using model simulations for hazard mapping or the accuracy of model results in general has been carried out. The comparison of conventionally developed hazard maps and maps exclusively based on model simulations in this work is a further step towards a more transparent process of debris-flow hazard assessment and mapping. The study refers to the aspired objectivity of hazard maps due to their obligingness in terms of land use planning and building restrictions. By simulating 12 potential debris-flows in 3 study sites with the numerical model RAMMS, hazard maps based on the BAFU guidelines are developed. The modeling and the mapping process is described and difficulties and model limitations are discussed. The case studies suggest a quite adequate accordance with a slight underestimation of the model results compared to the official hazard map. A solid modeling in combination with field investigation constitutes a promising approach for a further hazard assessment. These discoveries lead to the confirmation of the importance of a revision of the debris-flow hazard mapping guidelines for Switzerland with respect to the possibilities of using model simulations.

Zusammenfassung

Gefahrenkarten sind das Verbindungsglied zwischen naturgefahrenberücksichtigender Raumplanung und prozessbezogener Grundlagenforschung. Um die Gesellschaft vor Naturgefahren zu schützen und Schäden zu vermeiden sind eine angemessene Gefahrenbeurteilung sowie eine einheitliche und strukturierte Kartierung unumgänglich. Bis anhin basieren Murgang-Gefahrenkarten auf ziemlich subjektivem Expertenwissen und Abschätzungen. Die in der letzten Dekade entwickelten dynamischen und kinematischen Modelle zur Simulation von Murgang-Fliessverhalten bereichern die Gefahrenbeurteilung um eine objektive Methode. Einige Arbeiten haben sich schon damit auseinandergesetzt, inwiefern sich Modellsimulationen zur Gefahrenkartierung eignen und wie Glaubwürdig deren Resultate im Allgemeinen sind. In dieser Arbeit wird durch den Vergleich von konventionell gefertigten Karten mit Karten, die ausschliesslich auf Simulationen beruhen ein weiterer Schritt hin zur adäquaten Gefahrenbeurteilung und Kartierung gemacht. Die erstrebenswerte Objektivität dieser Kartierungen beruht auf deren Verbindlichkeit für die Raumplanung und den damit verbundenen baulichen Einschränkungen. Die Simulation von 12 Murgängen in drei Untersuchungsgebieten mit dem Simulationsprogramm RAMMS ist Grundlage zur Erstellung von Gefahrenkarten, deren Klassierungen auf den BAFU Empfehlungen basieren. Die Prozesse der Modellierungen und die Kartierungen werden beschrieben sowie die Grenzen des Models und die Schwierigkeiten erläutert. Die Fallstudien zeigen eine ziemlich gute Übereinstimmung mit Tendenz zur Unterschätzung der modellierten Gefahr im Vergleich zur offiziellen Gefahrenkarte. Sorgfältiges Modellieren in Kombination mit Beurteilungen im Feld kann als vielversprechende Methode zur Gefahrenbeurteilung betrachtet werden. Diese Erkenntnis unterstreicht auch die Notwendigkeit der Überarbeitung der BAFU Richtlinien mit Rücksicht auf den Einsatz und die Möglichkeiten von Modelsimulationen zur Murgang-Beurteilung.

Table of Contents

Table of Figures

List of Tables

1 Introduction

Switzerland is a natural hazard prone country. 57% of its surface is mountainous terrain and precipitation reaches up to 2500 mm per year (Lateltin, 2005), therefore debris-flow activity is considerable. The densely populated and developed landscape in combination with the distinct topography gives rise to the importance of land-use planning and requires reasonable risk management to avoid preventable disasters.

Since enactment of the federal laws on forest and flood protection in the year 1991, hazard maps represent an essential precondition for land use planning concerning natural hazards (Lüthi, 2004). The cantons are therefore required to establish hazard maps to guarantee adequate hazard assessment and risk management. Meanwhile, 85% (2.5.2013) of the hazard prone areas in Switzerland are mapped and about 60% of the maps are authoritatively implemented in the use of zoning plans. (BAFU, 2013)

Focusing on debris-flows, hazard mapping has been predominantly based on empirical relations, historical events and expert knowledge. Due to developments in numerical modelling in the last decade, the appliances and therefore the requirements to generate hazard maps have obviously changed. This has led to a condition where maps are available which were generated using different approaches: empirical, analytical assessment on the one hand and numerically simulated model outputs on the other. While trying to ascertain the most appropriate method of hazard estimation it is essential to compare both approaches and highlight their benefits and disadvantages.

In the meantime, experts and engineers combine the two approaches to generate hazard maps. The absence of adequate guidelines and the uncertainties in modelling in general could lead to different assessments while mapping hazard prone areas and therefore to a different implementation in land use planning all over Switzerland. Therefore it is important to take a closer look; to question current practices and especially upcoming possibilities.

1.1 Motivation

Hazard mapping is a balance of process based, basic research in geomorphology and practical application, with benefits for the community.

The generation of hazard maps and their implementation in land use planning is an important step in preventing society from disasters, although many people regard this intervention as a disadvantage due to losses of money incurred by the rezoning of land and harsh restrictions while constructing or renovating buildings (Lüthi, 2004). Therefore, the accuracy of the results and their communication to the local population is an important aspect and aspired to be on its qualitatively best level.

It is an interesting phenomenon at least in my perception, that computer simulations have the pretention to be as accurate as possible and the appealing visualization of results suggests an arbitrary reliability. Compared to the approach of empirical, analytical determination of debris-flow behaviour based on generalised assumptions, subjective expert knowledge and seemingly archaic mapping of hazard zones, closer inspection is necessary. With respect to the uncertainties belonging to both approaches I am expecting to highlight some interesting issues concerning the hazard mapping process.

1.2 Goals

To compare the two mentioned approaches for debris-flow hazard mapping and to finally highlight the difficulties concerning the mapping process and the accuracy of the maps, a few goals have to be achieved.

- Understand the basic input parameters of the existing conventional hazard maps and the model simulations
- Recognize the advantages and disadvantages of different runout prediction methods
- Generate hazard maps based on model results for Gadmen and Leissigen using RAMMS
- Compare the Swiss communal hazard maps of Gadmen, Leissigen and Agarn (Meretschibach) with the modeled maps
- Discuss the results and provide recommendations

While focusing on these goals, a few steps are necessary to develop an adequate study with respect to the difficulties arising from different approaches and from regional to local scale natural processes which do not always conform with generalised assumptions and theories. The following structure of the thesis shows the steps which will lead to an efficient achievement of the defined goals.

1.3 Structure

As can be seen in Figure 1, this work starts with a treatise outlining the essential basics of debris-flows, hazard mapping in Switzerland, empirical and analytical techniques for debris-flow assessment and numerical model simulations. This leads to the main part of the thesis which is dominated by modelling the hazard potential in Gadmen and Leissigen, developing hazard maps based on the results and finally qualitatively comparing the maps with the official, conventionally developed hazard maps. The Gadmen case study can be seen as the exemplification while Leissigen is kept more straight forward in terms of the delineation of the input parameters and the omission of the sensitivity analysis. The Meretschibach is an additional case study modelled by Oggier (2011) to extend the informative value of this work. By discussing the results of the comparison, a few important aspects of hazard mapping for debris-flows in general and model limitations are illustrated.

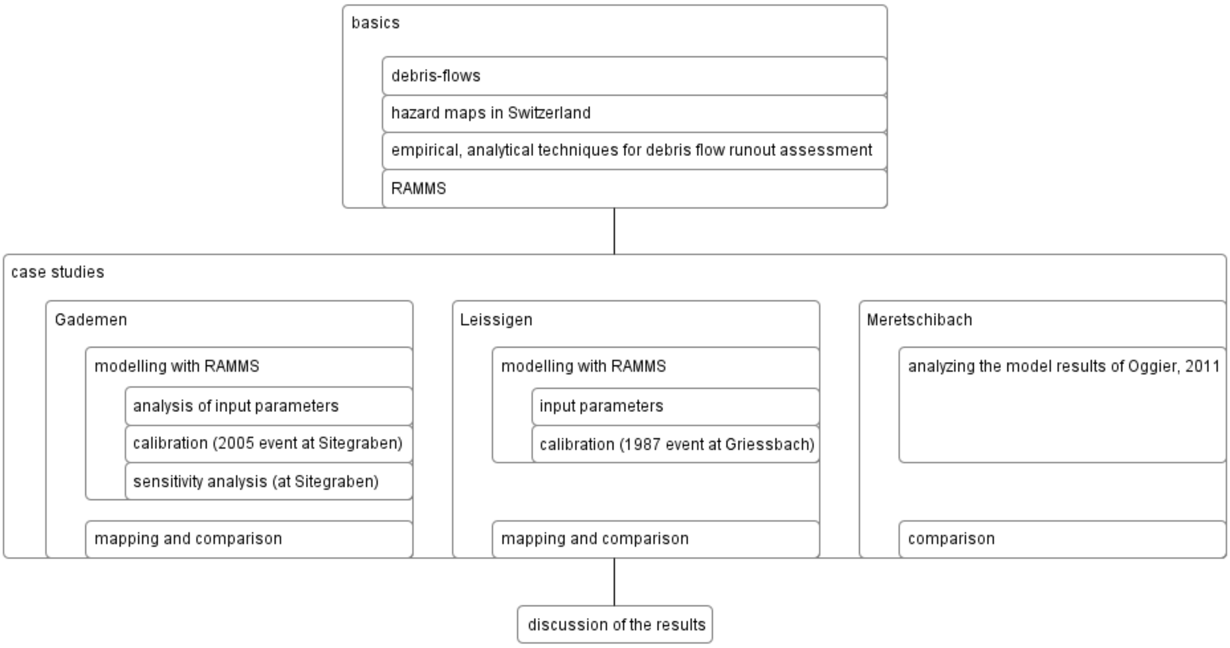


Figure 1: Workflow and structure of the study

2 Basics

This chapter provides a thorough introduction to the basic knowledge of debris-flow hazard mapping. Firstly, a definition is given and the debris-flow system and its leading factors are explained by using the concept of disposition (chapter 2.1.1). A general overview on debris-flow research is provided in chapter 2.1.2. The review of the geomorphological characteristics of debris-flows (2.2) and the influence of climate change on the system (2.3) completes the discussion about the debris-flow process. Further, an introduction to debris-flow modelling is given in chapter 2.5 and an overview about hazard mapping in Switzerland is provided in chapter 2.5.

2.1 Debris-flows

Debris-flows are a widespread geomorphologic phenomenon in mountain regions all over the world and probably one of the most efficient processes regarding mass transport and erosion in high mountain areas. Rickenmann (2005) defines the process as followed:

„A debris flow is a mixture of water, poorly sorted sediment and other debris, typically flowing rapidly, with one or more surges and a coarse-grained front, down steep mountain channels to a fan. Both solid and fluid forces strongly influence the motion, distinguishing debris flows from related phenomena such as rock avalanches and sediment-laden floods.

According to this definition three aspects have to be taken into account while engaging in debris-flows:

- The availability of debris
- The availability of water
- A distinct topography

Due to the dependency of these terms to different spatial and temporal variables, the following concept of disposition (2.1.1) developed by Kienholz (1995) is suitable to explain the interactions.

2.1.1 The concept of disposition

The concept of disposition (Kienholz, 1995) is an assistant way to illustrate the debris-flow system. The term disposition indicates the sensitivity of an area to debris-flow processes and describes therefore all the important variables, influencing the temporal and spatial distribution of debris-flows (Zimmermann, 1997). The following summary of the concept is based on Zimmermann et al. (1997).

The concept consists of three components:

- Trigger events
- Basic disposition
- Variable disposition

Trigger Events

The basic disposition in combination with the variable dispositions is devastated by episodic trigger events. In Switzerland mostly hydro-meteorological events, with a temporal variability from a few minutes to a few days are accountable. Trigger events in Switzerland are precipitation dependent, independent or a combination of both.

- Precipitation dependent
    - Heavy convective rainfall due to thunderstorms
    - Long continuous rainfall

- Precipitation independent
    - Intensive snow and ice melting
    - Lake outburst floods
    - Collapsing channel blockages

The intensity of a trigger event can be recognised as the stress on the system. A debris-flow is triggered by an event but the required intensity is defined by the disposition. Therefore an intense trigger event does not definitely lead to a debris-flow initiation (Figure 2).

Basic Disposition

The basic disposition describes the general sensitivity of the catchment for debris-flow activity regarding a long time scale. Durable or very slowly changing conditions define the spatial distribution of debris-flow and their potential magnitudes.

Relief

The relief potential is one of the key conditions. If there is no minimal relief energy, no debris-flow activity is observed. Exposition and height influences the availability of debris due to increased weathering or the nature of soil. Furthermore the permafrost is dependent on the topography. Due to variable long-term behaviour it belongs to the basic disposition but if we focus on the short-term variability induced by seasonal variations an attribution to the variable disposition is necessary.

Debris availability

The availability of debris is based on the conditions at the starting and erosion zone of the torrent. A concept applied by Stiny (1910) differentiates between two types of basins. If the channel erodes into unconsolidated quaternary sediments the basin is termed supply unlimited. This type of torrent is able to produce a debris-flow every time a critical hydroclimatic threshold is exceeded (Jakob, 2005).

Channels filled with coarse rockfall debris which are continuously supplied by weathering are termed supply limited. These types of channels have a high hydraulic conductivity and are therefore only triggered by exceptional climatic events and are completely scoured after a debris-flow. The occurrence of a future event depends on the time to recharge the channel. (Jakob, 2005)

Glacier dynamics and permafrost degradation

Due to the climatic changes as described in chapter 3, alterations in the basic disposition such as debris availability and relief factors are expected. In my opinion these changes are not attributed to the variable disposition due to the modification of outside influences which alter the equilibrium of earth systems in unknowable dimensions and time scales (chapter 2.3).

Variable Disposition

The variable disposition is characterised by fluctuations of debris-flow attendance due to the time-dependent variability. The changes of the conditions are mainly affected by cyclic variability. The following properties determine mainly the temporal distribution and the frequency-magnitude relationship.

Season

Debris-flow activity shows an obvious seasonal dependency. According to the mentioned trigger events the meteorological requirements are very important. Therefore the summer months are especially susceptible to events. In wintertime most of the precipitation above 1500m a.s.l. is falling as snow. In combination with the decreased mobilization potential while soil and debris is frozen, debris-flow activity in winter months is marginal.

Debris availability

As mentioned above the debris availability belongs to the basic disposition in general. If shorter time scales are considered, the availability of debris can be highly variable. Supply unlimited channels change from low to high debris-flow activity on a time scale of centuries. Due to the disturbance of a balanced system it is possible to start or restart a process chain which enhances the debris-flow activity for a certain period which can be followed by a long quiet phase.

A supply limited channel depends on the time required to recharge the channel with sediment after an event. This leads to a cyclic enhancement of disposition on a time scale of decades. (Jakob, 2005)

Hydrological material properties

While focusing on the variable properties of the material the most important aspect is the hydro-meteorological context. Snow melt or a specific hydrological history enhances the pore water pressure and therefore the short-term disposition in the system.

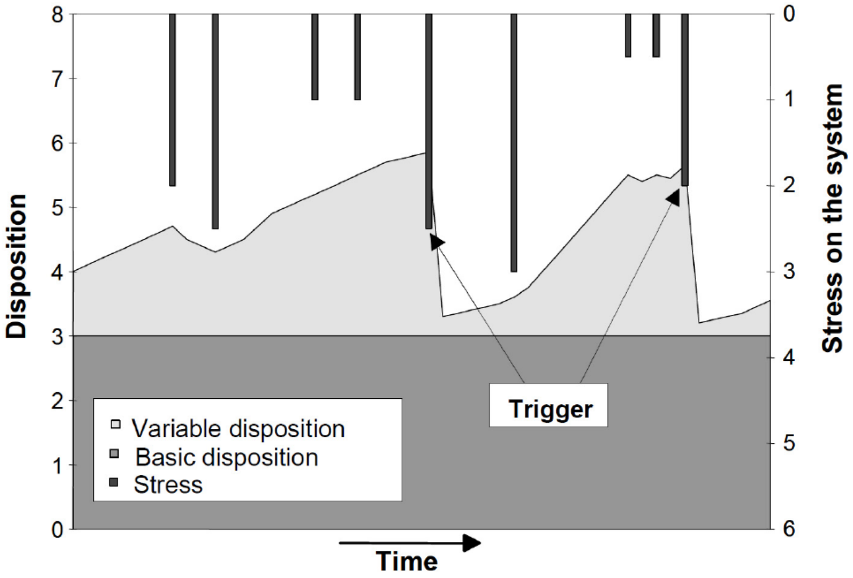


Figure 2: The disposition concept: basic and variable disposition in combination, forced by a sufficient trigger event resulting in a debris-flow. From Zimmermann et al. (1997)

2.1.2 Debris-flow research

The domain of debris-flow research lies in the European Alps, the U.S.A and Japan. In the European Alps, debris-flows have been observed for hundreds of years due to early settlement in the Alpine valleys. The villages were often built on fans as shelter from floods in the river planes and were therefore threatened occasionally by debris-flows.

The first scientific work on the subject is called “Die Muren”, and was written in 1910 by Stiny, an Austrian geologist. Montandon for instance had already documented numerous instances of debris-flow damages in the French Alps by 1933 (Jakob & Hungr, 2005). An established summary of the debris-flow process is given by Costa (1984).

Considerable adherence was given to the debris-flow process in the 1980’s, particularly in Switzerland. For instance, the catastrophic storm events in the summer of 1987 showed the hazardous potential of debris-flows and their future importance due to intensified use of Alpine regions (Zimmermann, 1997). An extensive analysis of the events is provided in Haeberli et al. (1991), VAW (1992) or Rickenmann & Zimmermann (1993).

According to Rickenmann et al. (2001) debris-flow research can be divided in three methodical aspects: field observations, laboratory experiments and model simulations. Sosio et al. (2007) provides a demonstrative work combining all the aspects for a debris-flow event in Valsassina in the Central Italian Alps.

Field observations

With specific case studies and the analysis of rheological and hydraulic parameters it is possible to gather fundamental knowledge about the dynamics of debris-flows. With only this basic understanding of the debris-flow system and the flow characteristics it makes sense to focus on laboratory experiments and especially numerical model simulations.

Examples of recent studies in Switzerland are Hürlimann et al. (2003), McArdell et al. (2007) and Berger et al. (2011) at Illgraben.

Compiling and investigating regional datasets e.g. the 1987 debris-flows in Switzerland enables to develop empirical relationships of debris-flow behavior based on semi-qualitative methods. In Rickenmann (1999) such runout prediction methods are suggested.

Laboratory experiments

In laboratory experiments it is possible to investigate material properties or rheological and hydrological parameters of a debris-flow independent of uncertainties caused by the environment. Therefore the results of such experiments are not linked to specific topography and local meteorological influences. Such an approach is used in WSL/LSC/LMS/VAW (1999) or Iverson et al. (2010) and Tognacca & Bezzola (1997).

Model simulations

As mentioned above, all model simulations are based on knowledge acquired by field observations and laboratory experiments. In the last decade a lot of effort has been made to develop numerical models to simulate debris-flow behaviour and to improve the associated hazard assessment. A detailed summary of the topic is provided in section 3.6.

While using this new approach for debris-flow assessment, the question of how to communicate and visualize results with respect to their accuracy in general is not yet answered. The hazard mapping process concerning these methods and their visualization are debatable and an important task for hazard prevention.

2.2 Geomorphological characteristics and debris-flow types

2.2.1 Flow-path classification

Catchment and initiation zone

According to Schatzmann (2005) debris-flows are initiated by two main mechanics. Either by **surface runoff** and conditional erosion or by **failure** which refers more to soil-mechanical processes.

The following classification of Zimmermann (1990) is a concept which indicates different aspects of debris-flow initiation. Four starting zones are specified and assigned to **slope** or **valley type**.

Slope type

The starting zones include high slope gradients and small catchment areas. The steeper the slope the less important is the channelised surface runoff.

1. **Regressive erosion** The starting zone is on steep and deep-seated slopes of soil or slightly consolidated debris. Slope angles between 25° and 38° are common. In many cases the erosion takes place in a retrogressive way and leads to quite large starting volumes. Active layers of permafrost areas are dedicated to this kind of initiation zone but result in more shallow slides.
   The initiation is mainly driven by the aforementioned soil-mechanical processes influenced by the properties of the sediment like cohesion, internal friction angle and pore-water pressure, and the surface runoff is less important than the saturation of the material.

2. **Contact zone rockwall – talus slope** The starting zone is in the contact zone of a steep rock cliff with an adjacent talus slope. Slope angles varying as well between 25° and 38°. The water is concentrated in gullies on the rock and seeps into the debris.

Valley type

The starting mechanism is a liquefaction of the torrent bed or the sudden outburst of a blockage of water and debris in the channel.

3. **Bed liquefaction** Debris-filled steep rock couloirs are eroded down to the bedrock basis. Slope gradients are found to be 24° and 35°. This starting zone is constrained by the surface runoff.
4. **Blockage** Parts of the debris-bed in steep channels are suddenly mobilised by breaking a retaining object. Slope gradients varying between 13° and 33°.

Transit zone

The transit zone is the section between the initiation zone and the fan apex. This section is normally defined by a recent channel or in talus slopes a new channel can be formed during the event. There is not only a transit of the mass. Depending on the characteristic of the channel notable erosion takes place at the channel bed and a specific form of deposition is observable at the margin of the channels. The levees are a result of the decreasing shear stress in combination with decreasing water content of the flowing material at the margin.

Travelling speeds depend on the composition of the debris-flow and the slope of the channel. According to Rickenmann (1999) velocities around 3.5 – 15 m/s where observed for Switzerland.

Cone

The debris-flow cone compared to a fluvial cone is much steeper and exhibits a rough surface. This issue is required by the Non-Newtonian nature of the debris-flow material. The shear strength of a material is the critical limit. If the shear stress goes below the shear strength due to decreasing inclination and reduced water saturation at the fan, a Non-Newtonian material stops its motion. The different runout distances of different surges and different events in combination with the previously mentioned levees develop a convex cone with a rough surface. The slope of a cone also depends on the lithology of the catchment. As a rule of thumb: The more weathering-resistant the material (e.g. genuine granite and gneiss), the more granular the debris-flows and the steeper the cones. On the other hand, the weaker the material (e.g. moraines or schist) the more viscous are the debris-flows and the shallower the cone.

2.2.2 Flow characteristics and flow types

For hazard assessment and especially for hazard mapping the runout distance and the velocity of a debris-flow summarised by the flow behaviour are most important factors. The two main parameters affecting the flow characteristics of debris-flows are the amount of water specified by the volumetric sediment concentration C_v (Bagnold, 1954) and the grain size distribution (Schatzmann, 2005). Concerning the possible variety of these parameters and the combinations with other factors like channel slope, particle shape, type of clay mineral etc. it becomes obvious why the assessment of debris-flow hazard is so difficult. The scheme of Davies (1988) visualises the variety and gives a hint to the further classification of debris-flows. A turbulent behaviour is given by a small sediment concentration whereas an increasing amount of sediment leads to a laminar flow and in combination with an increasing amount of fine material within the sediment tends to behave in a more Non-Newtonian manner.

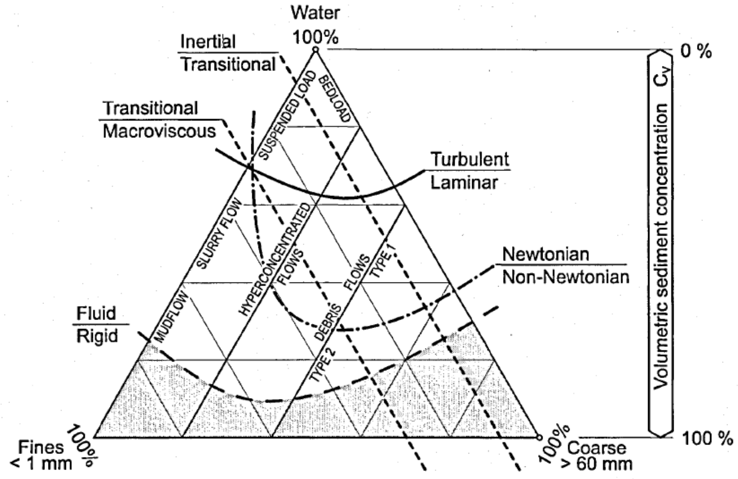


Figure 3: Flow characteristics and classification of debris-flows according to Davies (1988) in Schatzmann (2005).

In terms of determining runout distance and velocity a lot of effort has been made to describe debris-flow behaviour with physical concepts (chapter 2.4.1). Here we focus on a qualitative description embedded in a classification approach provided by Coussot & Meunier (1996). The classification also shows the delimitation of debris-flows to associated processes (Figure 4). Concerning all the different classifications that exist, this one seems to be accurate with respect to this work and in general.

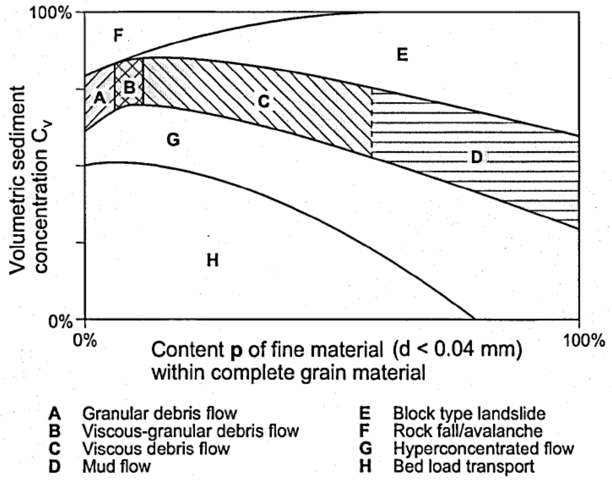


Figure 4: Classification of debris flows (A-D) and other mass movements (E-H). Coussot & Meunier (1996) and adapted by Schatzmann (2005).

Granular debris-flow

A granular debris flow is a composite of water, a large amount of coarse material and only a small amount of fine material. Usually the granular debris flow is divided into a fluid phase (pore fluid) constituted of water and the very fine material, and a solid phase constituted of the coarser material. The interactions between the coarser particles, such as collisions and friction as well as interactions of the pore fluid with the coarser particles are dominant. The runout distance is expected to be shorter and the long term deposits result in a steep cone. (Schatzmann, 2005)

Viscous-granular debris flow

This is a transition between the viscous and the granular type. These kinds of debris-flows are expected at the study site in Gadmen and Leissigen.

Viscous debris-flow

Viscous debris-flows behave more or less as one homogeneous viscous phase and the flow of the entire mixture is dominantly laminar. The sediment concentration C_v of the debris-flow is large and the content p of fine material within the complete grain material is high (> 10%). The grain material is usually poorly sorted. Due to the high amount of fine material, the coarse blocks are surrounded by the mixture of water and fine material. This leads to a more laminar flow and the appearance of a viscous phase because of the dampening in the space between the bigger blocks. (Schatzmann, 2005)

Mud flow

In comparison to a viscous debris-flow, a mudflow consists of an even larger amount of fine material and a smaller amount of coarser blocks. The fluid phase (mud), which is composed of water and finer sediments is separated from the solid phase of coarser particles. Depending on the content of coarser particles, interactions between them are quite negligible. Depending on the sediment concentration, the channel slope and the flow height laminar or turbulent flow can appear (Schatzmann, 2005). Much longer runout distances are expected and a stopped viscous debris-flow front can exhibit mudflow deposits in their extension.

2.3 Debris-flows in a changing climate

Climate change and the associated changes in temperature and precipitation are considerable (Trenberth et al., 2007) and an influence on debris-flow activity is obvious but not really describable quantitatively. As mentioned in chapter 2.1.1 the debris-flow sensitivity of a channel can be illustrated by the concept of disposition. To give a brief overview on the possible consequences caused by climate change this concept enables to understand the influences of climate change on different levels. This overview is supposed to denote that the debris-flow system and therefore hazard assessment and mapping are not static in time. The following explanation is a summary of chapter 6 of the Schlussbericht NFP31 (Zimmermann et al., 1997).

Sensitivity of trigger events

Most of the debris-flow triggers in Switzerland are precipitation dependent. Heavy convective rainfall due to thunderstorms and long continuous rainfall are common.

To get an idea of future precipitation patterns regional climate models and statistical downscaling methods are used (Frei & Schär, 2001; Schär & Frei 2005; Schmidli & Frei, 2005). Due to the complexity, the sensitivity and the small scale variability in the Alpine region the reliabilities of the predictions are questionable concerning the outcomes of debris-flow behaviour.

Snow melting in combination with heavy precipitation events is a mentionable factor of debris-flow initiation. This process is not coupled to the climate but the amount of snow is limited by the temperature-dependent snow line and therefore indirectly linked to changes in the climate system.

Sensitivity of the basic disposition

Relief

The relief is a quite stable factor regarding the climatic conditions. By considering a possible increase of frequency and magnitude of landslides due to climate change, the relief and therefore some debris-flow trajectories could be modified and influence the basic disposition.

Availability of debris

The availability of debris and its sensitivity to climate change is affected by three factors:

Due to the temperature-induced **glacier retreat** a lot of debris is released and moraine material becomes destabilised, especially the frontal moraines of small glaciers and the side moraines of big glaciers which provide depots of debris available for erosive processes. Retreating glaciers with a sediment bed often release debris-loaded couloirs which are also important starting zones for debris-flows.

The extent of a distinct **vegetation cover** is determined especially in the European Alps by temperature and precipitation. A warmer climate therefore supports an increase of vegetation coverage at otherwise erosion-susceptible areas and might stabilise the slopes.

The temperature dependent **permafrost degradation** and its impact on slope stability is a current research field (Haeberli & Beniston, 1998; Gruber et al., 2004; Noetzli et al,. 2007). There are two aspects to take a closer look at. While permafrost degradation is destabilising rockwalls, an increase of new debris in the system is provided by rockfalls and landslides. On the other hand a more long-term influence of permafrost degradation can be expected. Due to thawing of permafrost bodies in steep talus slopes in the periglacial belt slope stability decreases and the disposition for debris-flows therefore increases.

Sensitivity of the variable disposition

Season

Increasing temperatures are leading to a higher snow line in general. Therefore the debris-flow season can be longer. The possibility for debris-flow events is increasing due to the mentioned longer season and to the enlargement of the area containing exposed material at higher altitudes.

Availability of debris

This is a quite speculative topic especially when considering the uncertainties while predicting a future climate on a regional to local scale but it helps in recognising how complex the assessment of future debris-flow behaviour is.

As mentioned in chapter 2.1.1 the variable disposition of a debris-flow prone catchment is limited by the cyclic availability of debris and this in turn is influenced by the frequency of the triggering meteorological events and the material properties. The stability of a channel is dependent on the size of the erodible components and therefore defining its limiting factor. A small grain-dominated channel or failure zone for instance is more susceptible to debris-flow initiation and therefore smaller and more frequent events are expected. This character of a channel shows its dependency to a changing climate. For example, precipitation extreme events have a higher impact on the debris-flow magnitude of coarse-grained channels because the critical level of a small-grained channel is already reached when forced by a smaller runoff. On the other hand enhanced weathering and rockfall due to warmer temperatures has a larger influence on long term debris-flow frequency (for young deposited, small grain dependent channels) than the magnitude because of an increased debris supply.

2.4 Debris-flow assessment

As outlined above the debris-flow process is a complex and not completely understood phenomena. Regarding the hazard assessment process this complexity has to be reduced to evaluate possible debris-flow magnitudes and spatial behaviour. Models in general enable to reduce this complexity and it is possible to represent these characteristics in useful parameters. Especially in terms of hazard mapping, the simulation of debris-flows seems to be an interesting method due to its objective visualisation feature. A lot of effort has been made in the last 20 years to elaborate empirical relationships and to develop physically based models to get the most reliable prediction of debris-flow behaviour.

The comparison of two different approaches for hazard mapping is the main goal of this work. This requires a brief introduction into the conventional approach of hazard mapping by focusing on empirical and analytical techniques for debris-flow modelling (2.4.1). In chapter (2.4.2) the numerical model RAMMS used in this work is described.

2.4.1 Empirical, analytical techniques for debris-flow assessment

Empirical relationships

Empirical relationships are one of the most widely-used techniques to estimate the maximum runout distance of debris flows (Hürlimann, 2008). By analysing debris-flow datasets with statistical methods it is possible to determine the most important parameters of debris-flows and their relationships to each other. There are a few authors (e.g. Corominas, 1996 or Crosta et al., 2003) dealing with this topic. Empirical methods are easy to use, objective and reproducible, and are optimal where data, time, funding, or personnel are inadequate for application of more sophisticated methods. (Crosta et al., 2003)

This summary of empirical relationships is based on the publication of Rickenmann (1999) and is supposed to introduce the topic. It should be pointed out that these relations cannot provide a precise prediction of the spatial distribution of debris-flow deposits but they can suggest the order of magnitude in a quite accurate way.

Volume

The debris-flow volume M [m^3] is one of the most important parameters in terms of hazard evaluation. The volume depends on a few morphometric characteristics of the catchment as mentioned in chapter (2.1.1). It still has not been possible to find accurate empirical equations to determine the volume by these characteristics. Therefore it is recommended to use more geomorphologic assessments concerning the sediment potential of a starting zone. The precipitation is another very important parameter for debris-flow volume estimation. These are actually the two parameters of main impact for hazard mapping in the conventional way.

Peak Discharge

The evaluation of critical cross-sections and the conveyance capacity of a channel are defined by the peak discharge Q_p [m^3/s]. It has been shown that this parameter exhibits a quite distinct relation to the debris-flow volume M [m^3]. Rickenmann (1999) analysed a dataset of 145 debris-flows from around the world and came to the following equation:

$$Q_P = 0.1\,M^{0.833} \tag{2}$$

Mean Flow Velocity

The mean flow velocity is a difficult parameter to describe because of its dependency on the composition of debris-flow material and topography. Furthermore there are different velocities observable for a debris-flow surge. Here we focus on the cross sectional mean flow velocity v [m/s] which shows an empirical relation to the discharge Q [m^3/s] and the slope S.

$$v = 2.1\,Q^{0.33}S^{0.33} \tag{3}$$

Travel Distance

There is a dependency between the debris-flow volume and the mean flow path gradient H_e/L. The gradient is defined by the elevation difference of the starting point and the lowest point of the deposition H_e and the travel distance L of the debris-flow. This relation is expressed in the following equation:

$$L = 1.9M^{0.16}{H_e}^{0.83} \tag{4}$$

Runout Distance on Fan

The prediction of the runout distance on the fan would support a detailed assessment of the hazard potential. A relation between the runout distance on fan and the debris-flow volume has been found. But unfortunately the scatter is quite large between predicted and observed values and therefore not recommended to use for practical applications. (Rickenmann, 2005)

Deposition area

A semi-empirical relation between the deposition area and the debris-flow volume has been found by Iverson et al. (1998). The following equation explains the relation between the Volume M [m^3] and the denudated area A [m^2] influenced by an empirically derived dimensionless coefficient k which refers to the mobility of the process determined by water content and grain size of the flowing mass.

$$A = k\, M^{2/3} \tag{5}$$

An evaluation of the mobility coefficient k for granular debris-flows has been achieved by Crosta et al. (2003). Scheidl & Rickenmann (2010) enhanced the approach by examining the mobility coefficient k based on morphometric characteristics of the catchment. Best correlations have been found for the average fan slope S_f and the average channel slope S_c:

$$k_{slope} = 10 \cdot 3\, {S_f}^{-0.06} {S_c}^{-0.99} \tag{6}$$

Analytical approaches

Analytical approaches are based on theoretical physical assumptions. There are a few models describing the runout length of a debris-flow like the Hungr-Takahashi model (Hungr et al, 1984; Takahashi, 1991), the sliding block model by Sassa (1988) and the mass point model by Koerner (1980) and Perla (1980). The implementation of the rheology provides the main differences within the various models. Naef et al. (2006) presents an overview and comparison of the relations used for debris-flow modeling in general.

This work focuses on the single phase model of Voellmy (1955) modified by Salm (1993) which represents the basic assumptions for the model RAMMS, described in the following chapter.

The Voellmy-Salm model

To calculate the runout distances of snow avalanches Voellmy developed an analytical equation in 1955 which was modified by Salm in 1993. Due to the similar flow characteristics of snow avalanches and debris-flows, the equation is currently used for debris-flow modelling.

The equation consists of a dry-coulomb friction part with respect to the basal friction and an internal friction part which refers to the momentum decrease within the viscous material while flowing down a particular slope. The frictional resistance S [Pa] of the sliding block is determined by ρ the flow density, g the gravitational acceleration, φ the slope angle, h the flow height and v the flow velocity.

$$S = \mu \, \rho \, g \, h \, cos\varphi \, \frac{\rho \, g \, v^2}{\xi} \tag{7}$$

It is obvious that the frictional resistance of the flowing mass depends on the two friction coefficients µ and ξ, the slope angle and the flow velocity.

One reason the Voellmy-Salm model is useful for debris-flow modelling is that only µ and ξ are required to calibrate the model. The turbulent term (ξ) dominates the frictional behaviour when the flow is moving rapidly and the Coulomb term (µ) is dominant when the flow is moving slowly. Therefore one can control the flow velocity by adjusting ξ and the runout distance with µ.

The slope angle and therefore the flow velocity are the reason why a numerical solution for the equation is imperative. Due to a distinct topography in debris-flow prone areas the slope angle and the velocity change rapidly and therefore the values have to be calculated for every cell of the elevation model separately with respect to the neighbouring cells. A small introduction to how this equation is implemented in RAMMS is provided in the following chapter.

2.4.2 RAMMS

RAMMS (Rapid Mass Movements) is a software for two-dimensional modelling of rapid mass movements in three-dimensional terrain developed at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL).

The development of the version Avalanche started in 2005 and the model has found wide application for snow avalanche simulations (SLF, 2013). Due to the mentioned analogy of flow characteristics a few studies have been made using the avalanche module successfully for debris-flow assessments (Scheuner, 2007; Stricker, 2010; Oggier, 2011).

Since 2012 a special module for debris-flow has become available and is used in this study. The main improvement concerning debris-flows is the implementation of an input hydrograph (flow discharge as a function of time) which allows to model more realistic input conditions and a reduced calculation domain leads to shorter simulation times.

The model uses a single phase Voellmy fluid friction relation as mentioned above and it solves a depth-averaged shallow water equation for granular flows in two-dimensions using a finite volume scheme:

$$\delta_t\, H + \delta_x(HU_x) + \delta_y\left(HU_y\right) = 0 \tag{8}$$

$$\delta_t\left(HU_y\right) + \delta_x\left(HU_x{}^2 + g_z\,\frac{H^2}{2}\right) + \delta_y\left(HU_xU_y\right) = S_{gx} - S_{fx} \tag{9}$$

$$\delta_t\left(HU_y\right) + \delta_x\left(HU_xU_y\right) + \delta_y\left(HU_y{}^2 + g_z\,\frac{H^2}{2}\right) = S_{gy} - S_{fy} \tag{10}$$

Where H is the flow height and U is the velocity, g_z is the gravitational acceleration. S_g is the downslope gravitational acceleration of the flowing mass while S_f is the deceleration friction consisting of the internal flow resistance and the basal friction as explained for the Voellmy-Salm model (formula 7). The subscripts x and y indicate the quantities in the x and y directions. (Scheuner, 2011)

For further remarks and details about the implementation in RAMMS, Christen et al. (2010) provides an elaborated disquisition.

The input parameters and their influences will be explained in chapter 3.1.2.

2.5 Hazard maps in Switzerland

Due to the threat of natural hazards in Switzerland, a quite elaborate strategy is legally implemented (2.5.2) in the land use planning process. Land use planning therefore is the most effective procedure to minimize the damage potential in densely populated mountain regions. To realise an adequate mitigation of natural hazards, the hazard map is one of the most important instruments (BWW, 1997).

The hazard map combines the concept of hazard, based on magnitude and probability of an event, with empiric data out of registers and field analyses into a meaningful and descriptive principle of hazard mitigation (Figure 6). Once embedded in the use zoning plan, the hazard map and therefore an important step in risk management is authoritative.

According to BAFU (2013) a hazard map serves basically five objectives:

- Determination of hazard zones in the use zoning plan
- Formulation of construction requirements in the hazardous zones
- Planning of technical and organisational measures
- Basic principle for emergency planning
- Sensitise the community

Regarding the spatial planning purpose, synoptic hazard maps are used. A synoptic map combines all the process-specific hazard maps to a general map (Figure 5). In this case for example, the avalanche hazard potential in most places is higher than the potential for water related hazards and therefore the general hazard map is dominated by avalanche hazard zones. But it has to be pointed out that restrictions and requirements for buildings obviously depend on the kind of hazard and the diverging seasons where the danger takes place demands for a precise map for every hazard, especially in terms of emergency planning.

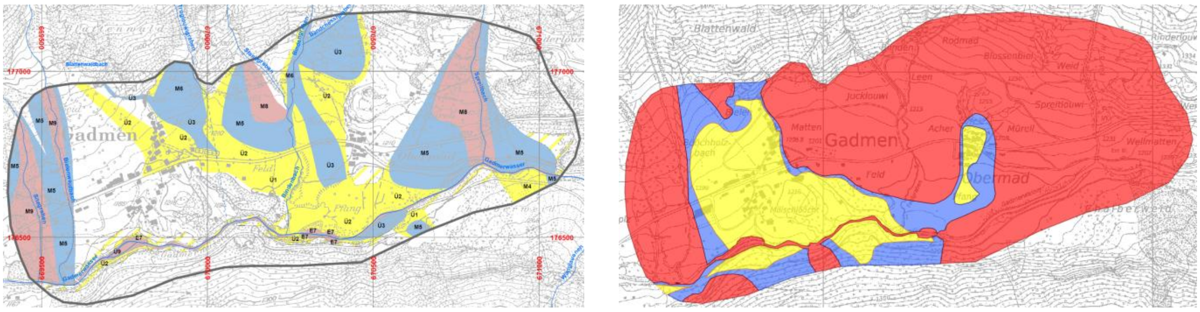


Figure 5: Hazard maps of Gadmen, (perimeter E). Left: water hazard map. (Geotest, 2007). Right: Synoptic hazard map dominated by avalanche hazard (Geoportal des Kanton Bern, 2013)

2.5.1 Definition and Parameters

A hazard map is an objective visualisation, based on scientific criteria, of the hazard potential with declaration of the threatening process, its intensity and its probability in a defined perimeter with a small scale resolution from 1: 2000 to 1: 10000 as illustrated in Figure 5. (BWW, 1997)

As seen in Figure 6, two major parameters are used to classify the hazard: the intensity and the probability (return period). The classification is visualised in four colours which are explained in Table 1. While this classification is used to dispose all kinds of natural hazards (snow avalanches, floods, landslides, etc.) in a homogenous and uniform way, the following description of the parameters focuses on debris-flows exclusively.

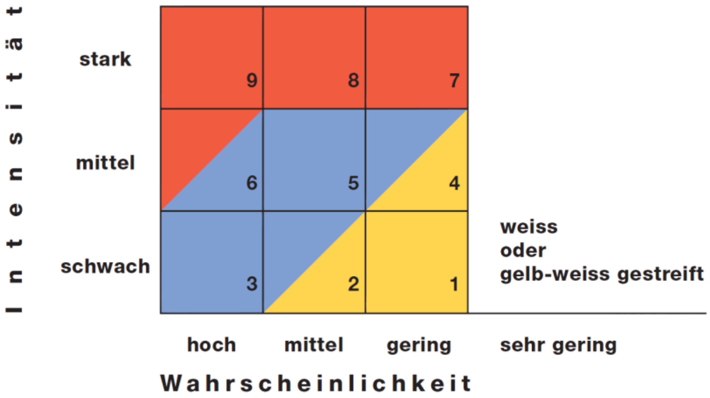


Figure 6: Hazard level diagram (BWW, 1997)

Table 1: Hazard level description (Raetzo, 2002)

RED: high hazard
People are at risk of injury both inside and outside of buildings. A rapid destruction of buildings is possible or: Events with a lower intensity, but a higher probability of occurrence. In this case, people are mainly at risk outside buildings, or buildings can no longer house people. The red zone mainly designates a prohibition domain (area where development is prohibited).
BLUE: moderate hazard
People are at risk of injury outside buildings. Risk is considerably lower inside buildings. Damage to buildings should be expected, but not a rapid destruction as long as the construction type has been adapted to the present conditions. The blue zone is mainly a regulation domain, in which severe damage can be reduced by means of appropriate protective measures (area with restrictive regulations).
YELLOW: low hazard
People are at slight risk of injury. Slight damage to buildings is possible. The yellow zone is mainly an alerting domain (area where people are notified of the possible hazard).
YELLOW-WHITE HATCHING: residual danger
Low probability of a high intensity event can be designated by yellow–white hatching. The yellow–white hatched zone is mainly an alerting domain, highlighting a residual danger
WHITE: No hazard
No danger or negligible danger, according to currently available information

Intensity

The intensity parameter in a first step is defined by a qualitative approach, describing the possible damage to property and people caused by a certain magnitude of an event. According to debris-flows a quantitative threshold of 1m deposition height and 1m/s flow velocity is determined to distinguish between high and moderate intensity. This qualitative description follows in Table 2.

For debris-flows, there is actually no classification for low hazards. According to the BAFU guidelines a low intensity doesn't exist for this kind of process. Due to this very simplified classification in general, this possibly outdated approach will be discussed in chapter 4.

Table 2 : Qualitative description and quantitative thresholds of Intensity for debris-flows (BWW, 1997 and Raetzo, 2002)

Qualitatively	Quantitatively
high intensity:	
people and animals are at risk of injury even inside buildings; heavy damage to buildings or even destruction of buildings is possible.	Deposition height > 1m **and** Flow velocity > 1
medium intensity:	
people and animals are at risk of injury outside buildings, but are at low risk inside buildings; lighter damage to buildings should be expected;	Deposition height < 1m **or** Flow velocity < 1
low intensity:	
people and animals are slightly threatened, even outside buildings, superficial damage to buildings should be expected.	-

Probability and Return Period

The probability of a debris-flow event and therefore the return period is a quite difficult and uncertain aspect to determine. It is to mention that for debris-flow hazard estimations no direct statistical principles are crucial. Due to the dependency on debris potential only expert knowledge determines the probability. A simple mathematical relation defines the probability with respect to the return period which leads to the classification in Table 3. (Raetzo, 2002)

$$p = 1 - (1 - \frac{1}{T})^{n} \tag{1}$$

The relation between the return period *T* and the probability *p* depends on the time period *n* which defines the duration of usage for a certain area. In Switzerland this period is set to 50 years. The return period is a statistically calculated value based on the precipitation history of the considered area. This leads obviously to highly uncertain assumptions regarding the frequency magnitude relationship of the debris-flow process discussed in 2.1.1. But the linkage of most debris-flow initiations to meteorological extreme events is obvious.

Table 3: Probability and return period classification (Raetzo, 2002)

Class	Probability for 50 years	Return period in years	Class
high	100 to 82%	1 t0 30	frequent
moderate	82 to 40%	30 to 100	moderate
low	40 to 15 %	100 to 300	rare

2.5.2 Legal requirements in Switzerland

The following summary of the legal requirements is based on the PLANAT report “Rechtliche Aspekte im Zusammenhang mit der Gefahrenkarte” by Lüthi (2004).

Land use planning is the most effective way to protect property and human lives from natural hazards. While respecting the guarantee of ownership (BV/SR 101, Art.26), the land owner has to be protected by imposing requirements which are mostly linked to bans or expensive construction restrictions. This leads to a conflict situation which needs to be clarified by the law. Concerning natural hazards in general the regulations (on all levels) are quite sectorial and inhomogeneous and regulation on confederational level is absent. This status is mainly based on the historically grown and punctually developed progression.

Focusing on debris-flows and other water hazards a clear structure is provided and the responsibility is defined.

The federal regulations on water engineering “Bundesgesetz über den Wasserbau (1991)” defines:

- the cantons as responsible institutions for flood prevention (WBG/SR 721.100, Art.2) using land-use planning and mitigation measures (WBG/SR 721.100, Art.3)
- the cantons denote the hazard areas and respect them in the land use planning (WBG/SR 721.100.1, Art.21)
- the cantons maintain an event cadastre, develop hazard maps and respect the guidelines for flood protection (WBG/SR 721.100.1, Art.27b, c, f)
- the confederation supplies with payments for hazard maps, event cadastres and mitigation measures (WBG/SR 721.100, Art.6)
- the confederation establishes guidelines for flood protection, hazard maps and cadastres (WBG/SR 721.100.1, Art.20a, b)

3 Modelled hazard maps compared to conventional maps

The development of hazard maps based only on model simulations is one of the main parts of this work. These maps enable us to take a closer look at conventional hazard maps and are therefore an important step towards high quality and more objective hazard assessments for debris-flows. It is fundamental to keep in mind that these maps do not have the pretention to be more correct than conventional ones. They have the aim to be exclusively modelled on the highest but still efficient level of quality. The aspects which are relativising the accuracy of such a modelled map are discussed in chapter 4.

With respect to the research question it is important to focus on typical sites for Switzerland with ordinary requirements in terms of debris-flow hazards. It wouldn’t make sense to investigate sites with special debris-flow magnitudes because most of the areas where hazard maps have to be acquired are quite ordinary. Furthermore at least four debris-flow channels with a few documented events have to be present in the perimeter. This considerations lead to the typical and not special study sites Gadmen and Leissigen in the canton of Bern (Figure 7).

The case study for Gadmen, from modelling and developing the hazard map to the comparison of the maps is provided in chapter 3.1. All important steps and information concerning the modelling and mapping process are explained in the case study Gadmen. It can be recognised as the main case. In chapter 3.2 a similar process is illustrated for the village of Leissigen. The Meretschibach (located in Agarn) case (3.3) has been modelled and mapped by Oggier (2011) in the context of a master thesis about using RAMMS for debris-flow modelling in general.

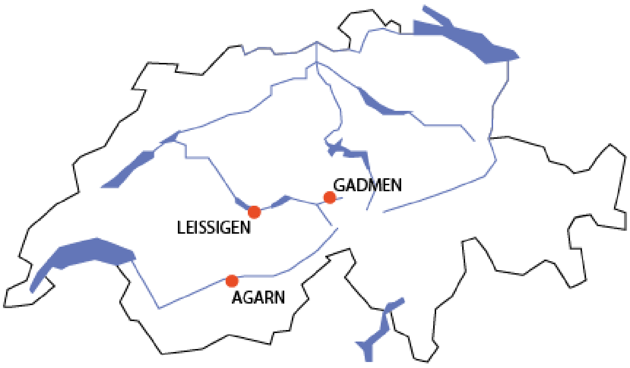


Figure 7: Location of the study sites Gadmen, Leissigen and Agarn (Meretschibach).

The structure of the case studies is as follows. First a closer look at the study site provides a basic understanding of the region. All important issues of the applied modelling process like input parameters, the model calibration and a sensitivity analysis (only for Gadmen) will be highlighted accordingly. Finally, the development of the hazard map from model outputs leads to the required comparison of the different maps.

3.1 Case study Gadmen

3.1.1 Study site

Gadmen is a small mountain village at the Sustenpass road in the Bernease Alps as shown in Figure 8. The elevation reaches from 1205m a.s.l at the village to 2970m a.s.l at the Mähren, the highest peak of the Wändenstöcke. The southerly exposed slope endangering the village holds a quite distinct debris-flow potential with magnitudes from 100m^3 to 10000m^3. The average slope of the rock walls is about 55°, in the channels about 30° to 40° and in the valley around 15° (Figure 9). Precipitation reaches 1500mm/year at about 135 day of the year (BVE Bern, 2012) and is therefore quite common for Switzerland.

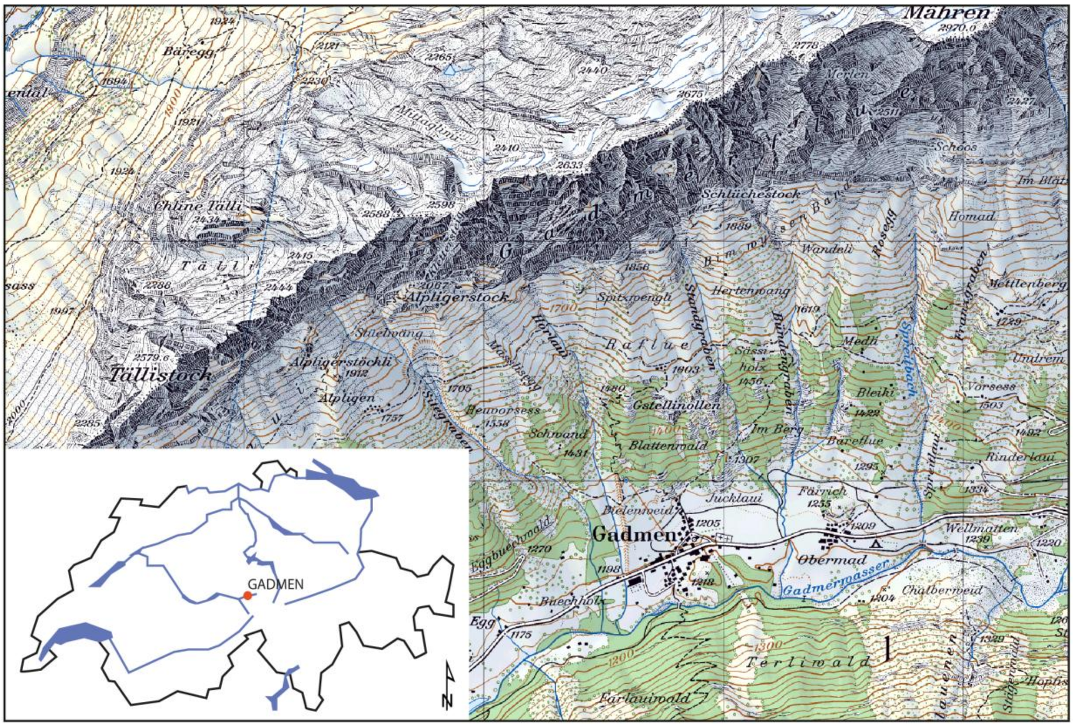


Figure 8: Swisstopo map (1:25’000) of the study site Gadmen.

An important aspect for Gadmen is the fact that avalanche hazards are very large and therefore appears to decrease the importance of the debris-flow hazard concerning the synoptic hazard map and land use planning at first impression. However, restrictions and requirements for buildings exposed to danger are different and the diverging seasons where the danger takes place demands for an accurate debris-flow hazard map.

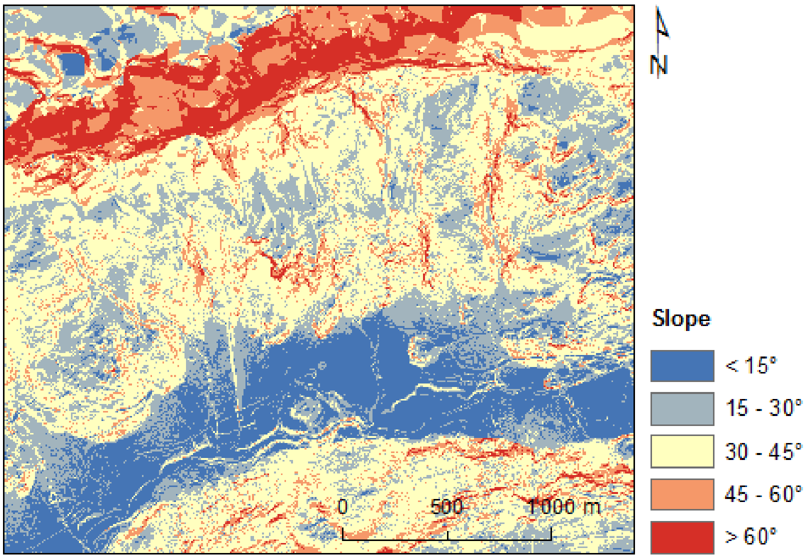


Figure 9: Slope angles of the study site Gadmen.

Geology and Geomorpology

The geology of Gadmen is dominated by two units. The steep lime stone rockwalls in the north consist of Malm and the Gneiss of the Aarmassif (Metagranitoide) in the south causes a smoother landscape.

The bulky lime stone walls of the Wendenstöcke provide the lower rock shoulders with a lot of debris. These accumulations of debris are starting zones for all debris-flows endangering Gadmen. The lower transit zone is dominated by torrents and avalanche gullies flowing through a forested zone of Gneiss bedrock. The valley bottom consists of debris-flow fans, and fine grained fluvial sediments of the torrents and the Gadmerwasser which is the main river in the valley. The fans are mostly around 15° with a smooth surface but previous traces of debris-flow activity like levees are observable.

In the event cadastre of Gadmen for debris-flows a few events are documented and a wide range of magnitudes are identifiable. As summarised in Table 4, 10 debris-flows and sediment loaded floods with magnitudes reaching from 50m^3 to 5000m^3 are noticed since 1955 for the relevant perimeter E.

Table 4: Documented events for Gadmen

Torrent	Date	Debris-flow volume [m^3]
Sitegraben	1955	500-600
	1970	500
	2005	3500
Horlaui/Bielenweid		
Troglauigraben	1950	flood
Standgraben		
Bindengraben	2011	300 (deposit)
	1955	50
	1955	200
	2010	1400 / 900 (deposit)
Bandchessigraben	2005	150
Spreitbach	1965	100
	2011	5000

3.1.2 Modelling the Gadmen debris-flows

While modelling the debris-flow intensities for different scenarios a few arrangements have to be made to improve the accuracy of the model results. First, a discussion of the input parameters, whose influences and uncertainties are provided. This leads to a previous examination by the following steps. The calibration of the model therefore guarantees an adequate appliance of the device and ensures that the results can at least be taken as a reliable reference. By conducting a sensitivity analysis the required accuracy and the associated impact of the different input parameters become apparent. The documentation of sensitivity analysis is only provided for the Gadmen debris-flows. The sensitivity for Leissigen is in the same range and therefore not documented in this work.

Input parameters

Table 5: Input parameters for RAMMS for all torrents in Gadmen. (Volume by Geotest)

Torrent	Scenario [yr]	ξ [m/s^2]	μ	Volume [m^3]	Q_{max} [m^3/s]
Sitegraben	30	800	0.15	5’000	121
	100	800	0.15	8’000	178
	300	800	0.15	10’000	215
Horloui	30	800	0.15	1’000	32
	100	800	0.15	1’600	47
	300	800	0.15	2’000	56
Troglouigraben	30	800	0.15	200	8
	100	800	0.15	200	8
	300	800	0.15	200	8
Standgraben	30	800	0.15	300	12
	100	800	0.15	600	21
	300	800	0.15	1’000	32
Bindenbach	30	800	0.15	100	5
	100	800	0.15	200	8

	300	800	0.15	400	15
Bandchessigraben	30	800	0.15	100	5
	100	800	0.15	100	5
	300	800	0.15	100	5
Spreitbach	30	800	0.15	3’000	79
	100	800	0.15	5’000	121
	300	800	0.15	8’000	178

Volume

The volume is the most important parameter because it generally defines the magnitude of the event. To get appropriate assumptions for the potential of a starting zone and the associated debris-flow volumes an accurate assessment of the mobilisable debris is fundamental. Field investigations and measurements as well as the analysis of aerial photos provide a basic determination of the parameter. In this work, no determinations have been made. To compare the conventional hazard map with a modelled one, it is necessary to work with the same input parameters. By taking the assumptions from a reliable and respected office like Geotest (Gadmen) or Geo7 (Leissigen), the accuracy is provided.

The volume of a debris-flow is not only defined by the mobilisable debris. The amount of water also affects the cubature and is essential for the flow characteristics of a debris-flow as mentioned in chapter 2.2.2.

Depending on the debris-flow type, different mixtures of water and solids are possible. A range between 40% and 60% for (Newtonian, laminar) debris-flows is probable (Schatzmann, 2005). Therefore the mean content of water is set to 50% for the modelled scenarios. That means that the debris-flow volumes are the double of the mobilisable debris potential. The ground erosion of the debris-flow is already included. It can be argued that the water just fills up the pore space within the debris and therefore the doubling of the debris-flow volume is not appropriate. However, the volumes of the debris-flows would be much too small in comparison with the historical events. Further statements are provided in the discussion. The difficulties concerning the flow height/deposition height problem are discussed in chapter 4 as well.

The following Table 5 summarises all torrents in perimeter E of Gadmen and their associated parameters which are used to generate the hazard map.

Hydrology

As mentioned above, the amount of water in a debris-flow is an important aspect in terms of flow characteristics and debris-flow volume. The conventional approach for hazard assessment focuses on flood analyses by precipitation-intensity-diagrams and the hydrological atlas of Switzerland to estimate the amount of water that accumulates within a catchment. To derive the peak discharges of the torrents, software like „HQx_meso_CH“ or „HAKESCH“ is used. These values enable to estimate the hazard potential.

For RAMMS the peak discharge $\boldsymbol{Q_P}$ of the debris-flow itself is important. Due to the amount of debris, the possibility of backwater, the oversaturation of soil material etc. the peak discharge of a debris-flow is up to 10 times higher than the peak runoff of the water without debris (McArdell, pers.

com.). It has been shown that empirical relationships can be established between the peak discharge of a debris-flow and its volume (Rickenmann, 1999). The relationship $Q_P=0.1\mathrm{M}^{0.833}$ is already mentioned in chapter 2.4.1 (Equation 2) and is the background for the calculated peak discharges in Tables 5 and 6.

Friction parameters ξ, μ (Xi, Mü)

As mentioned, the RAMMS model uses a single-phase model, so we cannot distinguish between fluid and solid phases and the material is modelled as a bulk flow which is just a simplification. The friction parameters are neither physically based nor fixed parameters. A lot of different conditions influence the parameters such as water content, grain size, grain shape and grain distribution. This leads to a wide range of possible parameters (Figure 10, area a for debris-flows). Therefore it is important to calibrate the flow properties of the model with real events. It is common that different events, even in the same torrent, show differences in composition. This fact makes the calibration of the friction parameters much more difficult and requires attention and expert knowledge about flow characteristics of debris-flows.

As explained in chapter 2.4.1 (Voellmy-Salm model) ξ is the so called turbulent (or viscous) friction coefficient which depends on the velocity of the debris-flow. It influences the results especially when the flow is rapid. The coefficient μ is the dry-Coulomb type friction and influences the basal friction which is more relevant for the slow moving parts.

The values used in this work and shown in Table 5 are 800 for ξ and 0.15 for μ. The calibration of the model at the Sitegraben is described afterwards and for the Griessbach in Leissigen in chapter 3.2.2.

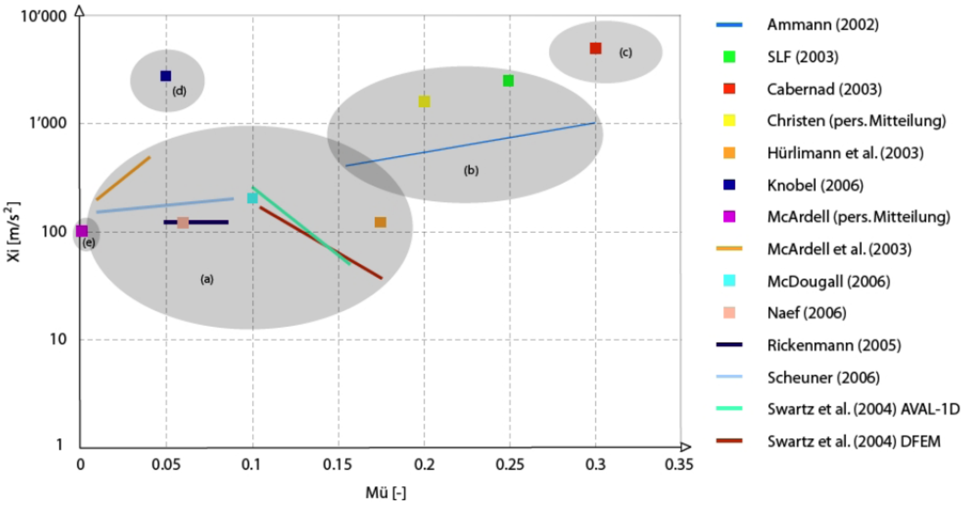


Figure 10: Range of ξ and μ for different mass movement processes: (a) debris flows, (b) avalanches, (c) rockfall, (d) ice avalanches and (e) floodwaves from Scheuner (2007).

Digital elevation model (DEM)

A study of Stolz & Huggel (2008) shows that the DEM grid resolution and the quality are crucial for hazard assessment and the mapping process. A fact which is not astonishing while all topographic information of the model is provided by the DEM.

The swissALTI^{3D} is a LIDAR based high-resolution grid with 2m cell size and accuracy in all dimensions of ± 0.5m (till 2000m a.s.l). There is actually no certainty that by using higher resolutions more accurate results can be achieved. That means that the cell size should be adjusted to the purpose of modelling. For this work the 2m resolution is optimal due to its attention to detail. By testing the 25m resolution no suitable results were achieved. The fact that the fans in Gadmen and Leissigen are not very active supports the decision for a high resolution grid; as it is likely to pretend an exaggerated accuracy by not using up to date high-resolution grids for very dynamic debris-flow channels and fans (Stolz & Huggel, 2008). A few more aspects concerning the topography for modelling purposes are provided in chapter 4.

There are several mitigation measures built in the study sites. In Gadmen just one debris retention dam is present (Standgraben) while in Leissigen all torrents are supplied with barriers. These dams are added to the DEM and therefore considered in the model results.

Flow Velocity

The flow velocity is a difficult parameter due to the same reasons as the friction coefficients. Different material compositions result in different flow velocities. The formula suggested by Rickenmann (1999) (Equation 3) represents an estimation for the flow velocity as a function of the peak discharge and the slope, and is used for the calibration of the model. By conducting a sensitivity analysis it turned out that the influence of the flow velocity between 4 and 10 m/s has no influence on the result because the model normalises its velocity within the increasing distance from the starting point of the simulation. This normalisation is forced by the basal and the internal friction of the moving mass. Therefore a realistic value of 6m/s is used for the following simulations.

Model calibration at Sitegraben

There are a few reasons to calibrate the model at Sitegraben. First there is a quite distinct debris-flow potential as designated in the hazard map of Geotest (Figure 21.3). Furthermore the runout of the Sitegraben is only limited by a bridge and no retention basins are influencing the flow. Most importantly, there is a well-documented event registered at the StorMe 2.0 event cadastre. The event numbered 2005-W-0350 occurred on 21.8.2005. A quite intense rainfall event with up to 60mm/h and a return period of more than 300 years triggered a debris-flow which ended with a blockage of the bridge and a deposit on the Susten road of about 100m with an overall thickness of 1m.

Out of this cadastre file the important parameters can be deduced or in the case of μ and ξ iteratively determined by simulating the debris-flow and compared with the extent of the real event (Figure 11).

- The **debris-flow volume M** is given by the StorMe file directly and reaches 3500m^3.
- According to Rickenmann (1999) the debris-flow volume M is correlated to the **peak discharge $\boldsymbol{Q_P}$** of an event as described in 3.4.1 (equation 2). This leads to a peak discharge Q_P of 90 m^3/s.
- To determine **μ** (dry-Coulomb type friction) which influences the basal friction, tan(α) where α is the slope angle of the fan is a good approximation to start with (RAMMS user manual v1.4, 2011). A slope angle of 13.5° results therefore in a μ value of 0.24. While testing the

value by simulating the flow path an overestimation is apparent. The output simulated by a more accurate value of 0.15 (iteratively generated) is illustrated in Figure 11. According to the range of values shown in Figure 10 this is plausible.

- ξ is the so-called turbulent (or viscous) friction coefficient which depends on the velocity of the debris-flow and therefore on the composition of the flowing material. The fine grained event suggests a high value concerning the more fluid-like behaviour. While testing different values 800 corresponds well to the mentioned μ value of 0.15 and is plausible concerning Figure 10. The fact that it is quite high agrees with the mentioned fine grain conditioned low viscosity.
- **The debris-flow velocity** is set to 6m/s. This value is based on the formula suggested by Rickenmann (1999) (Equation 3).

By using all the defined parameters in RAMMS Figure 11 shows the results.

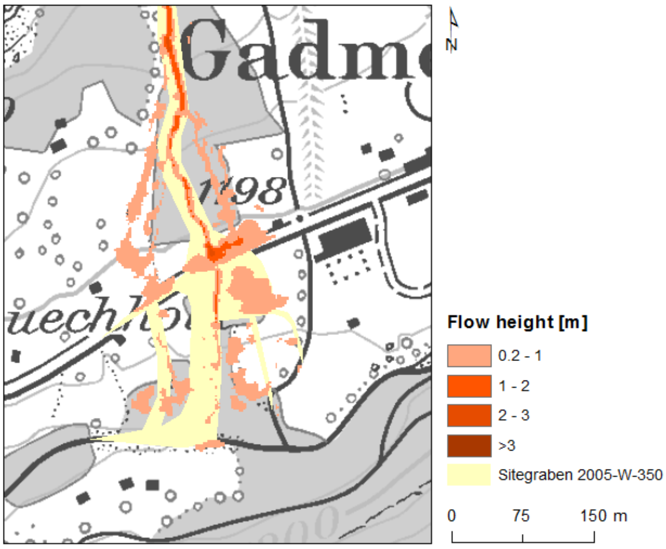


Figure 11: Model results of flow height compared to the debris-flow event of 2005 at Sitegraben.

For interpreting Figure 11 it is important to keep the physical background of the used model and the real appearance of the debris-flow deposition in mind (Figures 11 and 12). Therefore it is obvious that the model doesn't differentiate between real debris flow deposits and more flood-like sediments. This is the reason for not considering flow heights smaller than 0.2m as debris-flow deposits for the calibration. The absence of the (in this case) less important flow heights therefore leads to much more efficient visualisation. A further important aspect to mention is the fact that the RAMMS output shows the flow height and not the deposition height. This leads to a small overestimation of the simulations. But the overall thickness of 1m in the area of the road is well reproduced.

The key indicator for the calibration of the model is the runout distance which fits in this case quite well to the real event. Of course there is (as usual in mountain regions) a limiting object which forces a mass movement to stop but in this case, this issue just defines an upper limit which has to be reached.

The second clear issue which has to be represented by the model is the blockage at the bridge and the deposits on the road. This is clearly visible in the result in Figure 11.

The two breakouts on both sides of the channel which are not apparent for the real event are probably conditioned by the resolution of the digital elevation model and are, in this case, just to be recognised as a flow possibility.

Figures 12 and 13 illustrate the different perceptions of a debris flow deposit. The comparison with the displayed outline in Figure 11 shows the subjectivity of mapping the debris-flow deposit extent of an event.

Figure 12: Aerial photo of the event 2005 at Sitegraben. (Flotron AG, 23.08.2005)

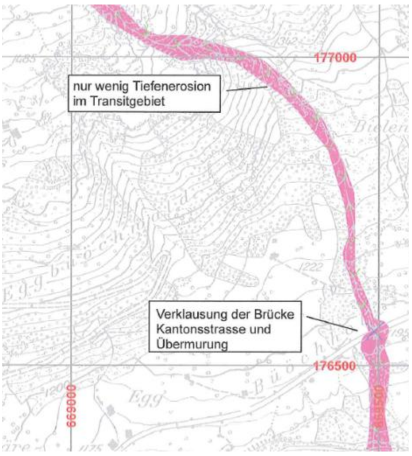


Figure 13: Map of the event 2005 at Sitegraben by Geotest

Sensitivity analysis at Sitegraben

Due the reasons mentioned above and the calibration itself it also makes sense to choose the Sitegraben torrent to conduct the sensitivity analysis. While investigating the different influences of the parameters it becomes evident that the following four parameters really affect the results.

Volume sensitivity

The dependency of the peak discharge to the debris-flow volume is mentioned before. In Figure 14 the extent of 5 potential debris-flows with the associated peak discharges (calculated with equation 2) are illustrated. The range of considered volumes cover 2625 m^3 to 4375 m^3 which is a ± 25% deviation of the documented event (3500m^3) already used above. The dependency is quite linear. This means that an increase of the volume by 25% results in an increase of the covered area by 34%. By decreasing the volume by 25% a decrease of the covered area by 27% is modelled. Hence for this order of volumes a deviation in debris-flow volume estimation leads to a variation of the covered area in the same percental magnitude.

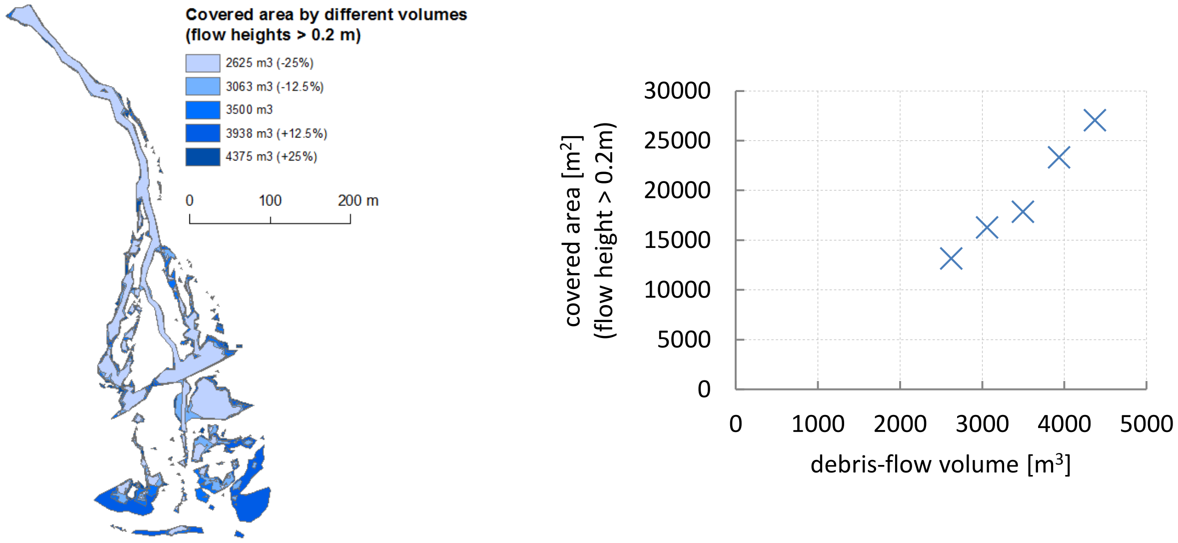


Figure 14: Visualised model sensitivity for volume/peak discharge. Covered area by different volumes/peak discharges (left) and a quite linear dependency between the different debris-flow volumes and the covered area (right).

Peak discharge sensitivity

The model is sensitive to changes of the peak discharge but not in a linear way and not profoundly. By keeping the volume and adjusting different peak discharges from 68 m^3/s (-25%) to 113 m^3/s (+25%) as model input the results of the covered area by flow heights higher than 0.2m reach a range between 3900m^2 while only the 102 m^3/s (+12.5%) is a significant outlier. An interesting phenomenon is that the results do not depend on the grade of the input parameter. It should be expected that higher peak discharges lead to more covered area than smaller discharges. But this expectation has not come true. As illustrated in Figure 15, the highest discharge for example results in the smallest affected area while the second highest discharge covers the largest area.

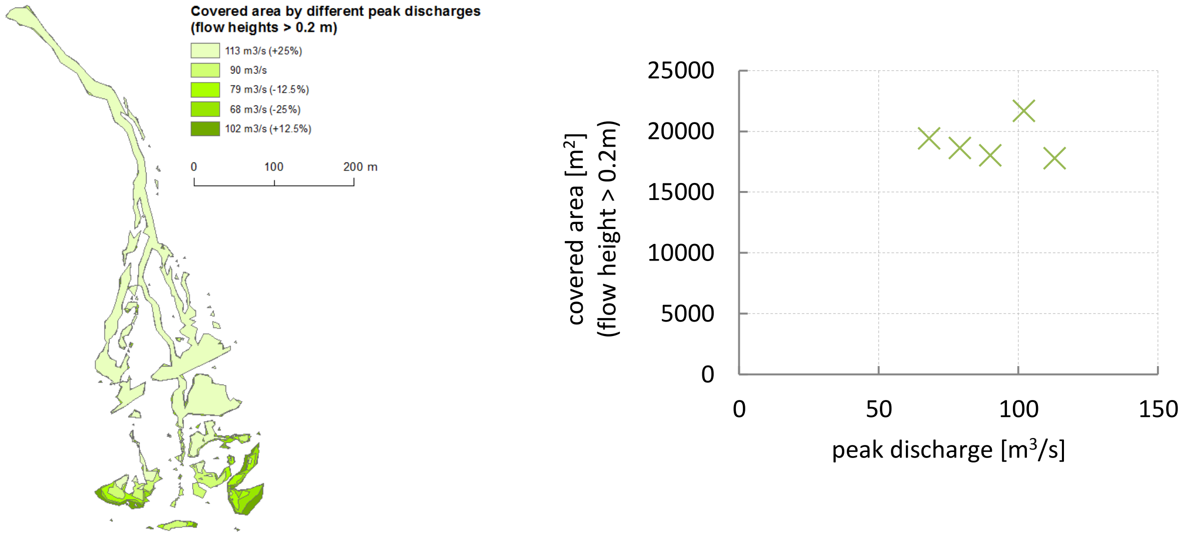


Figure 15: Visualised model sensitivity for peak discharge. Covered area by different peak discharges (left) and the dependency between the different peak discharges and the covered area (right).

ξ and μ sensitivity

The sensitivity for different Xi values with respect to the covered area is not mentionable between 200 to 1000. Therefore we only focus on Mu, the basal friction parameter. As aforementioned in the iteratively generated value fits to the range illustrated in figure 10 and the tangents of the slope angle. While testing different Mu's (with a constant Xi) it becomes apparent that the relative runout distance changes in a range of 200m for Mu values reaching from 0.1 to 0.2 (Figure 14). The runout distance and therefore the covered area is quite sensitive to the basal friction parameter Mu.

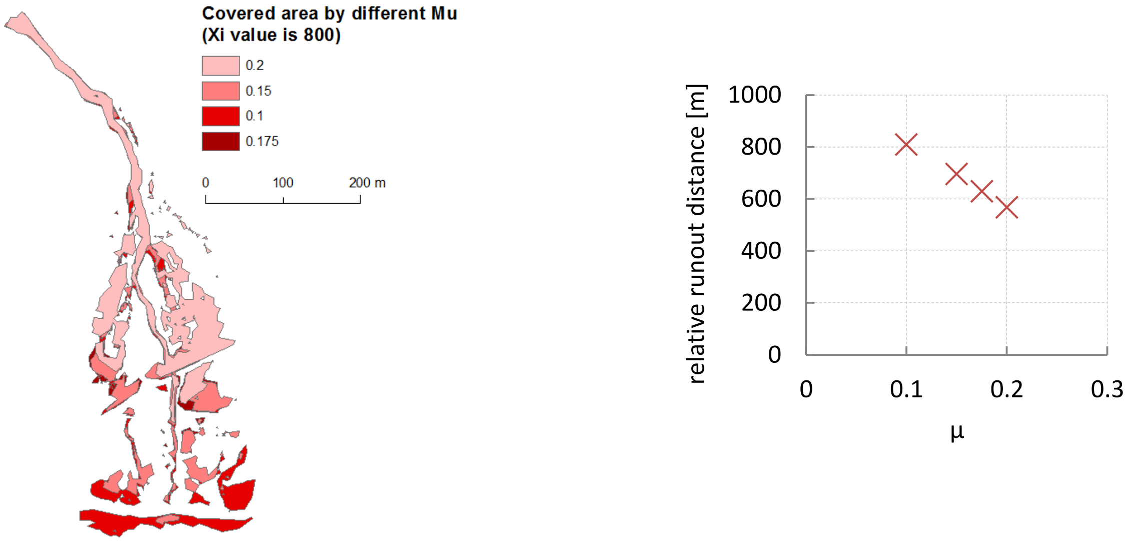


Figure 16: Visualised model sensitivity for Mu. Covered area by different Mu values (left) and a quite linear dependency for the relative runout distance (right).

3.1.3 Mapping and comparison

By simulating all potential debris-flows for three scenarios with RAMMS using the input parameters listed in Table 5 the base for the mapping process is given. This chapter documents the steps conducted to develop a hazard map which conforms to the BAFU intensity thresholds (BWW, 1997) mentioned in chapter 2.5 which are quite questionable. The discussion about the suitability of these thresholds in general can be discovered in chapter 4.

As mentioned in the introduction, hazard maps are produced using engineering judgment, empirical relations, historical information, and possibly simulation model results. The synthesis which is required to make a general hazard map is rarely described and no objective procedures are publically available (Bertoldi, 2012). The mapping process used in this work is based on a semi-automatic GIS model that converts the RAMMS outputs cell-by-cell into intensities and hazard levels similar to Schneider et al. (2012) or Hürlimann et al. (2006).

Hazard is the combination of intensity and probability of an event. According to the BAFU guidelines (BWW, 1997) the intensity is defined by the deposition height and the flow-velocity of the debris-flow. These terms are provided by the two RAMMS output files, the deposition height grid (flow height at the end) and the flow velocity grid. The discussion about flow height and deposition height will be conducted in chapter 4. The following diagram shows the workflow of combining the RAMMS outputs using a GIS model (Figure 17). With respect to the probability (small, medium and large scenarios) an intensity map and furthermore the hazard map is classified. A combination of these hazard classes represents the hazard map.

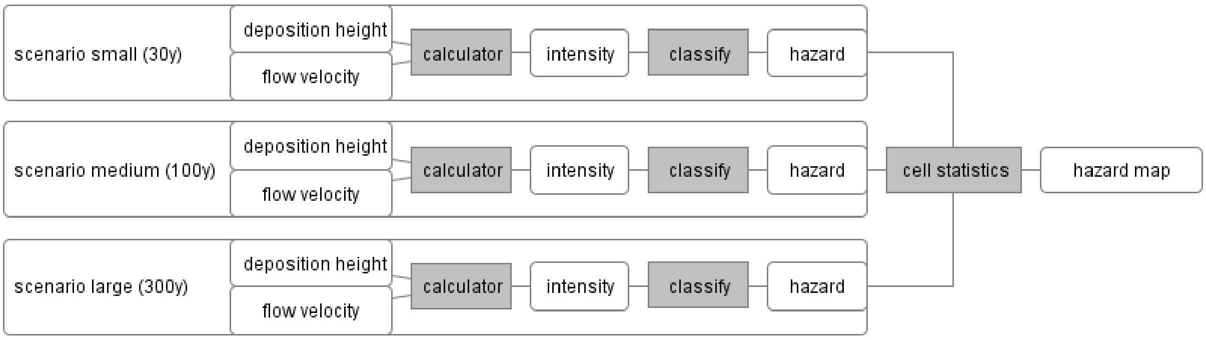
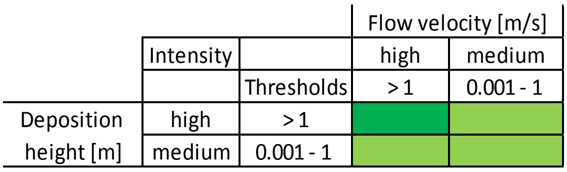


Figure 17: Workflow for combining the deposition height grids and the flow velocity grids of all scenarios to the hazard map.

The grey coloured box “calculator” contains the step of calculating the intensity by using the classification matrix in Figure 18. According to the BAFU guidelines, to require to the high intensity class, the deposition height **and** the flow velocities have to be higher than 1m respectively 1m/s. For the medium intensity class the term “**or**” determines the membership which is illustrated by the green colours.

By classifying these intensities with respect to their probabilities, the hazard level for each scenario is assigned as illustrated in Figure 19. The cell statistics tool in ArcGIS enables to combine the scenario dependent hazard to a hazard map by taking the maximum values of the generated grids into account.



			Flow velocity [m/s]	
	Intensity		high	medium
		Thresholds	> 1	0.001 - 1
Deposition height [m]	high	> 1	🟩	🟩
	medium	0.001 - 1	🟩	🟩

Figure 18: Intensity classification matrix

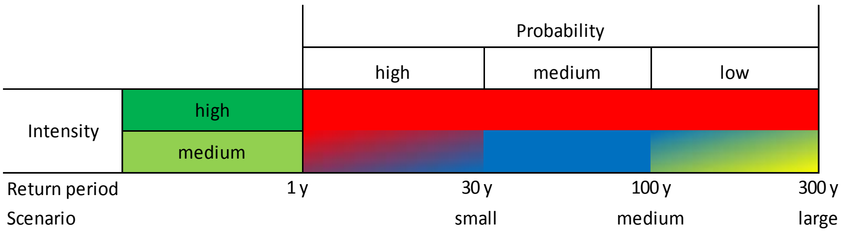


Figure 19: Hazard level diagram

As mentioned in chapter 2.5 and discussed in chapter 4, a classification of the debris-flow process especially while using numerical models needs more than the simplified and probably obsolete approach suggested in the BAFU guidelines from 1997. Corresponding to these guidelines, no yellow (low hazard) class is provided for debris-flows although a medium intensity / low probability event recommends this class. In practice, a third class is applied which at least takes the potential flow paths of the outflowing, sediment-laden water into account. This class has the pretention to be a hazard zone which belongs more to a flood-related phenomenon with respect to the question of how a debris-flow is defined in terms of the transitions of its flow characteristic. Nevertheless, the phenomenon refers to the debris-flow process and has to be considered.

Figure 20 shows the raw hazard map generated by using the explained method and classification. It is obvious that the topography derives the flow direction and it is therefore not remarkable that the simulations look quite realistic on a first impression. Very important parameters in terms of runout distance are the volume and the flow characteristics implemented as μ and ξ. As mentioned above the model simulates the flowing mass as a single phase viscous material. While not differentiating between variable phases, the water loaded with fine grained sediments outflowing of the coarse grained debris-flow deposits cannot be simulated. That means that the yellow areas (flood) are probably too small in terms of sediment deposition because the material would be less viscous than simulated and the runout more elongated as it is shown on the official map (Figure 21.3).

Due to the fact that a high hazard zone requires flow heights **and** flow velocities higher than 1 m respectively 1 m/s the red zone is almost restricted to the channels. Therefore a lot of the area remains blue because both conditions are not fulfilled even though the destructive power of a slow flowing mass with flow heights up to 1m is enormous.

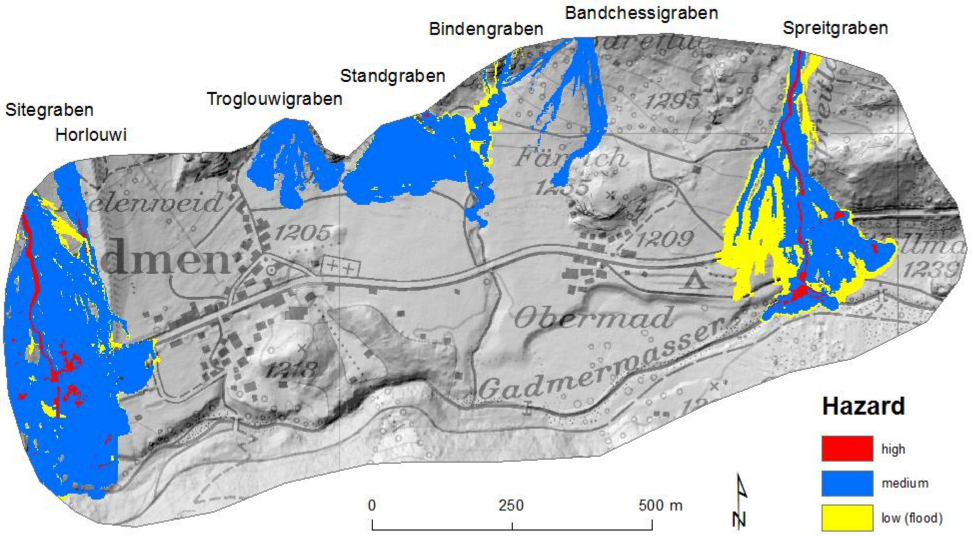
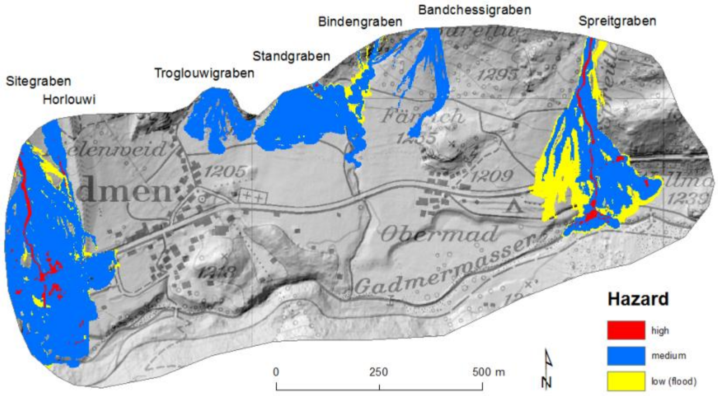


Figure 20: Classified model results (raw hazard map) of Gadmen.

Nevertheless the model results can be taken as reliable with respect to the model capability and the used input parameters. In Figure 21, map 1-3 the hazard maps which have to be compared are illustrated. The manually generalised map is based on the classified model results (map 1). This map has no pretention to be accurate, as it is just a subjective transformation of the model results to enhance the visual impact and no verification in the field has been executed. To get closer to an objective mapping process the step of generalisation has to be automated. This should be possible by implementing an adequate topography including algorithm in a GIS but this step exceeding the extent of this work.

While comparing the two hazard maps (Figures 21.2 and 21.3) it is apparent that the official map of Geotest slightly overestimates (or the modelled map underestimates) the hazard potential. By considering the map of the historical events (Figure 21.4) the influence of these registered events in the Geotest Map is obvious; especially the long runout of the Bindengraben could be explained by this speculation. Unfortunately it is not possible to distinguish between different flow heights and flow characteristics for the registered events. This could lead to a slightly overestimated Geotest Map, for instance, assessing the flood processes as debris-flows. The mentioned issue of overly-small yellow areas in the modelled map certainly underrates the inundated area. An interesting aspect is the underestimation of the blockage of the bridge of the Bielenweidbach in the Geotest map whilst all other cases are mapped quite generously. The cross-section under the bridge is inadequately small with $4.1m^2$ for a debris-flow volume of $2000m^3$ (300 year scenario). A second notable aspect is the breakout of the Spreitbach, which is in the Geotest map expected as a red zone while the modelled map suggests a medium hazard. The credibility of the Geotest map is probably higher in this case due to the geometry of the channel as checked in the field.

In general it is mentionable that the modelled map does quite well with respect to the disregard of the historical events and the field investigations. It might be too optimistic generally but the question if the Geotest map is slightly too pessimistic can’t be answered from my side.

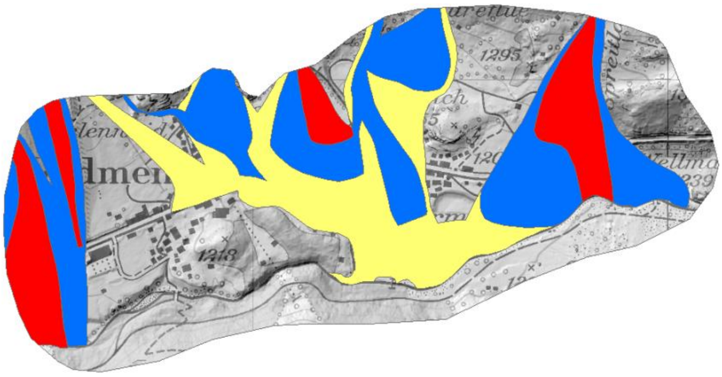


1 | Raw hazard map

Appropriate to the BAFU guidelines classified composite of all scenarios

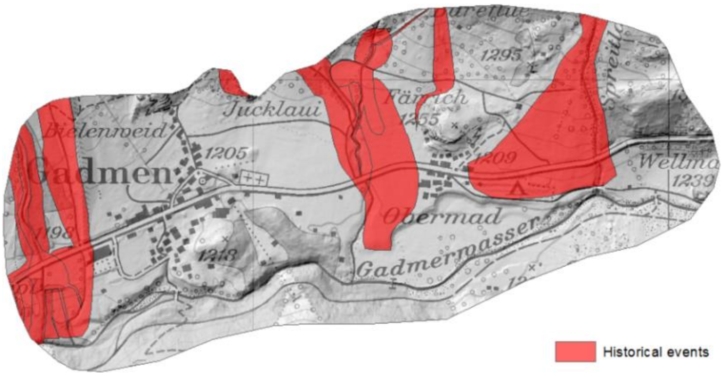
2 | Manually generalised map

Manually and subjectively generalised map derived from the raw hazard map.



3 | Official hazard map by Geotest

Official hazard map of Gadmen, developed by Geotest using conventional methods in the year 2007.



4 | Historical events

Composite of all registered debris-flow events since 1955 until 2013 as listed in Table 4.

Figure 21: Different debris-flow hazard maps for Gadmen (1-3) and a composite of all registered historical events (4).

3.2 Case study Leissigen

3.2.1 Study site

Leissigen is a small village on the southern shore of the Thunersee (Figure 22). The catchment areas of the 5 torrents reach from maximal 2249m a.s.l (Morgenberghorn) down to the lake on 560m a.s.l. In contrast to Gadmen, Leissigen is only endangered by water related hazards as debris-flows, floods and the high water of the Thunersee. There is more infrastructure such as buildings, railways and roads prone to debris-flows than in Gadmen. The north exposed channels with medium inclination of around 15 to 20° fade out to the populated debris flow cones with inclinations about 5 to 10° (Figure 23). The climatic conditions are determined by the location on the Alpine north side. Due to the hold up of humid air masses by the Därlig/Leissig ridge, convective precipitation is a common event with distinct effect on the debris-flow potential. (GEO7, 2008)

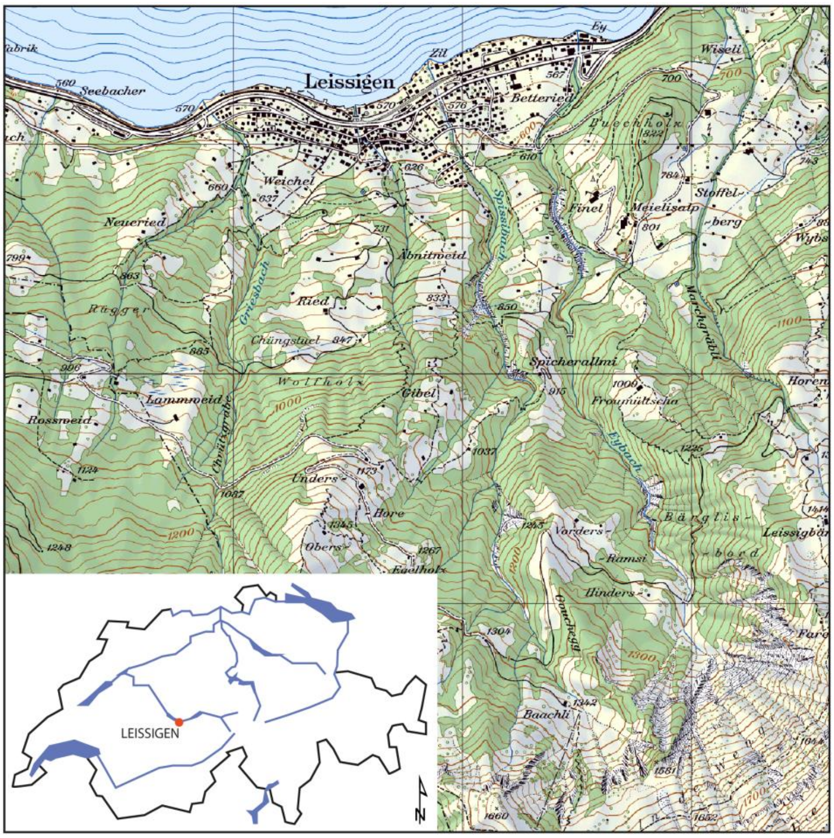


Figure 22: Swisstopo map (1:25’000) of the study site Leissigen.

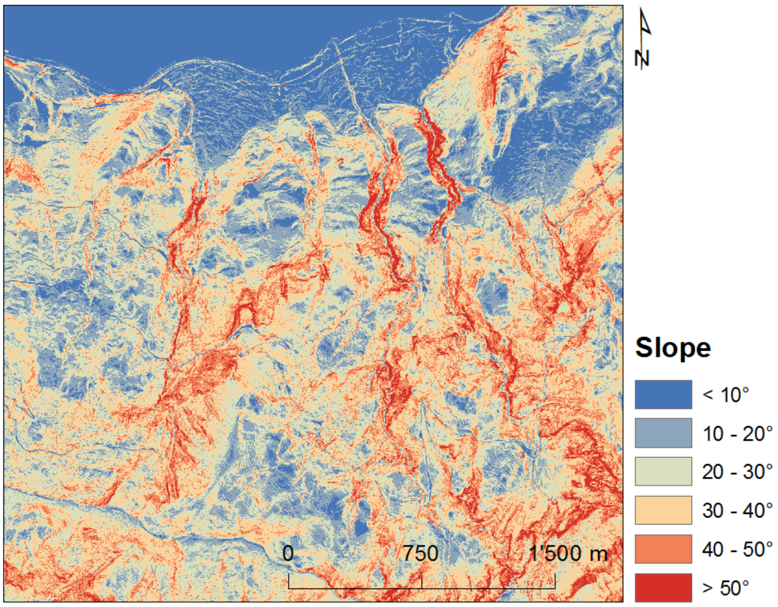


Figure 23: Slope angles of the study site Leissigen.

Geology and Geomorphology

The community Leissigen and in particular the slopes are geologically located in the Ultrahelvetikum. The Morgenberghorn belongs to the Wildhorndecke (Helvetikum) and therefore consists of quite resistant siliceous limestone. The lower part is dominated by Flysch which is, as becomes obvious upon regarding the deep incised channels, highly erodible. A few areas are dominated by quaternary sediments, especially the cones which consist of debris-flow and fluvial sediments. The formative landforms are the sub stable slope instabilities which are constricted to the Flysch areas while the Wildhorndecke only offers small scale slides. The steep faces of the Morgenberghorn and the Leissiggrat mainly comprise gravitational processes like rock-fall, rock-avalanches and landslides. (GEO7, 2008)

There are 10 historical events registered for the main perimeter, but unfortunately there is almost no specific information available for the estimated debris-flow magnitudes. For the Griessbach, where the calibration of the model takes place, an estimation of 6000m^3 for the debris-flow deposit is given. The assessment done by Geo7 shows the debris-flow potential reaching from quite small events about 2000m^3 at Riedbach up to highly destructive events at Griessbach reaching 60'000m^3.The mapped events are illustrated in Figure 27.4.

All torrents are meanwhile provided with barriers to shield from debris-flows. The barriers are between 5 and 6 meters high and hold a capacity between 1700m^{3}and 6400m^3. All barriers are implemented in the DEM and therefore considered in the simulations.

3.2.2 Modelling the Leissigen debris-flows

Modelling the debris-flows in Leissigen is a repetition concerning the input parameters in general and the sensitivity analysis of the model. So the focus is constrained to the used parameters and the model calibration at Griessbach.

Input parameters

The volume estimations are taken from the technical report of the hazard map of Leissigen developed by the geoscience office Geo7 in 2008. The assessment of the debris-flow magnitudes has been conducted by field investigations and analysing historical events. In contrast to the debris-flow volumes for Gadmen which were derived from estimations of the mobilisable debris potential in the starting zone, the assessment for Leissigen appraises the debris-flow volume directly. The used volumes and all other input parameters for the different scenarios are shown in Table 6. A special issue for Leissigen is the fact that the scenarios are not equivalent to the ones in Gadmen which are recommended in the BAFU guidelines. Geo 7 suggests scenarios with a return period of 100, 300 and an extreme case instead of the normal 30, 100 and 300 year periods. This issue has no influence to the comparison within the Leissigen maps but shows that different offices work with different criteria. For explanations and the derivation of the peak discharges, ξ , μ and the used DEM chapter 3.1.2 is commentarial.

Table 6: Input parameters for RAMMS for all torrents in Leissigen. (Volume by Geo7)

Torrent	Scenario [yr]	ξ [m/s^2]	μ	Volume [m^3]	Q_{max} [m^3/s]
Griesbach	100	600	0.15	20’000	383
	300	600	0.15	35’000	610
	ExDF	600	0.15	60’000	955
Riedbach	100	600	0.15	2’000	56
	300	600	0.15	3’000	79
	ExDF	600	0.15	4’000	100
Spissibach	100	600	0.15	18’000	350
	300	600	0.15	25’000	461
	ExDF	600	0.15	40’000	682
Eybach	100	600	0.15	13’000	267
	300	600	0.15	25’000	461
	ExDF	600	0.15	35’000	610

Model calibration at Griessbach

The calibration for the Leissigen debris-flow is more challenging than for Gadmen. In most of the event-cadastre files detailed information about the debris-flow magnitudes is missing. There is actually one event which comes with a magnitude estimation but unfortunately no map of the event extension is available. By analysing pictures (Figure 24), the dimension of the event can be reconstructed. There are no mitigation measures in the channel (not at this time) and the runout distance is defined by the lake.

The event occurred at the 6th of July in the year 1987 in the Griessbach and is registered at StorMe with the number 1987-W-0053. A heavy thunder storm forced a granular debris-flow with a volume of about 6000 m^3. According to the documentation, all three bridges (Krattigerstrasse, main road and Railways) had been blocked and distinct deposition took place on infrastructure (Figure 24).

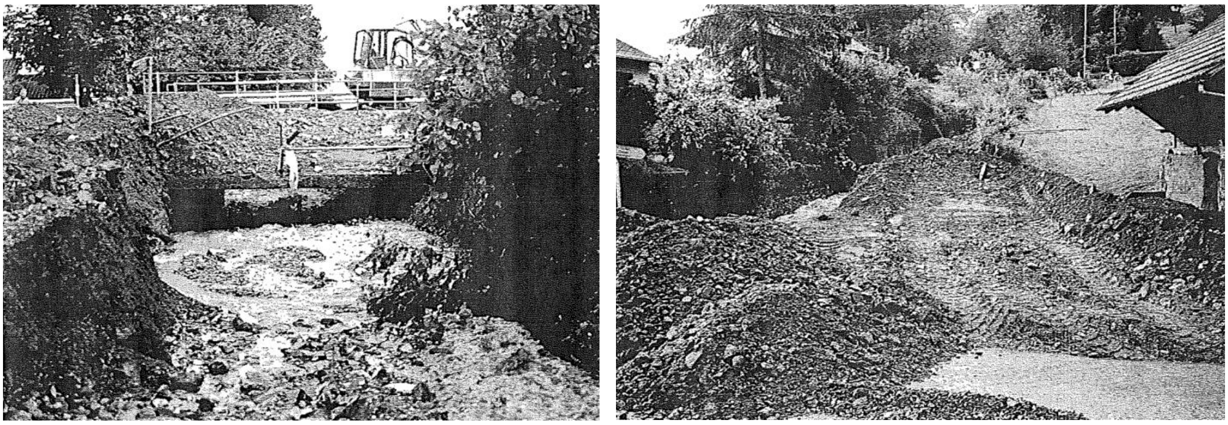


Figure 24: Downstream picture of the blocked and overflown main road bridge (left) and upstream picture of the debris-flow deposit remains between Krattigerstrasse and main road (right). (Event cadastre, 1987)

By using following parameters in RAMMS, the result is shown in Figure 25:

- The **debris-flow volume $\mathbf{M}$** is set to 6000m^3 as mentioned in the cadaster file.
- The **peak discharge Q_P** calculated as explained above reaches about 140m^3/s.
- The basal friction parameter **μ** is set to 0.15 which is the same value as in Gadmen.
- The turbulent friction coefficient **ξ** reaches with 600 a bit less than in Gadmen but as seen in Figure 10 this is an even more accurate value in comparison with others studies.
- The less important debris-flow **velocity** is set to 9 m/s

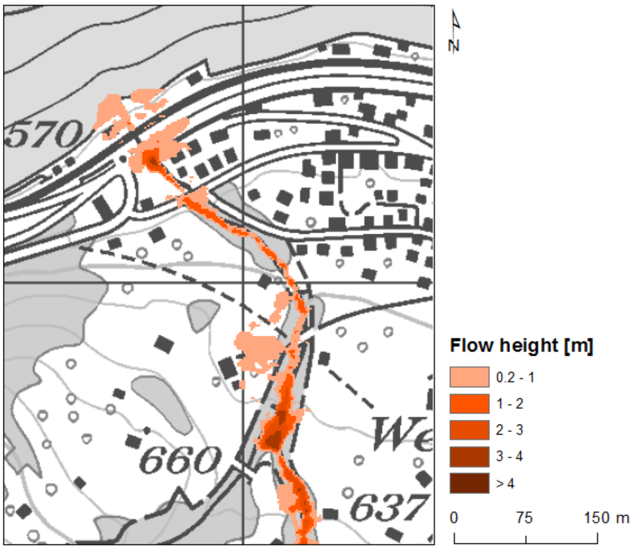


Figure 25: Model result for flow heights at Griessbach

The model result illustrated in Figure 25 shows the observed blockage of the bridges quite realistic. The flow heights of around 0.2 to 4 m seem to be suitable and the runout distance suggests an accurate calibration by using the friction parameters **μ** and **ξ** of 0.15 respectively 600 for the study site Leissigen.

3.2.3 Mapping and comparison

By using the input parameters listed in Table 6 with the modified DEM concerning the mitigation measures, Figure 26 is the result. The description about the mapping process is given in chapter 3.1.3.

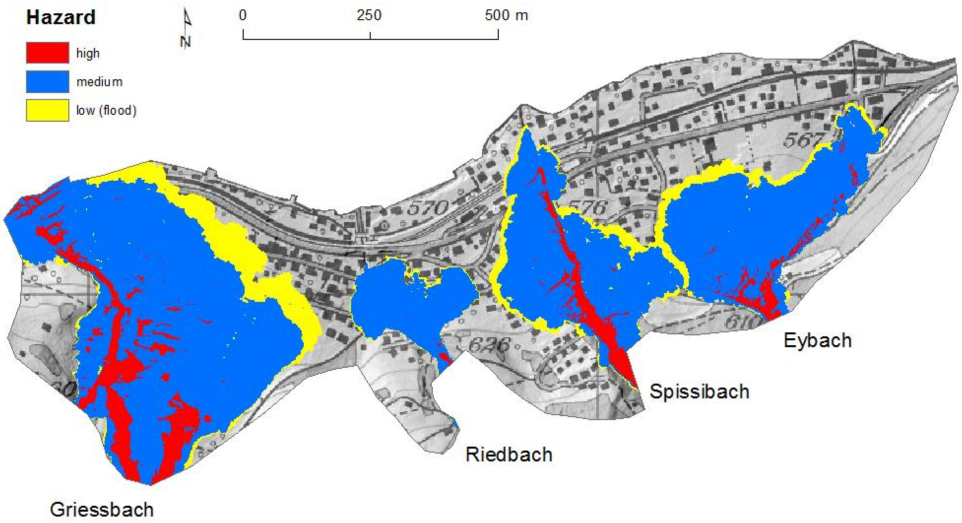


Figure 26: Classified model results (raw hazard map) of Leissigen.

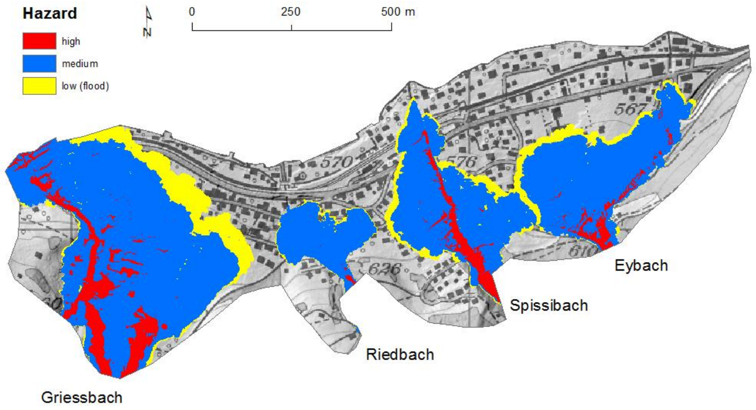
By comparing the modelled map (Figure 27.2) with the official hazard map (Figure 27.3) it is noticeable that the slight underestimation of the modelled map, as detected for the Gadmen case, is not that distinctive for Leissigen. The Griessbach for instance shows a larger red and blue zone. The first break out on the orographic right hand side is in the official map assigned to the residual risk while the model results suggest a clear red and blue hazard zone.

The differences between the Riedbach mappings is limited to the mentioned under / overestimation and the missing runout to the lake which is detectible for Spissibach and Eybach too. Spissibach in general is underrated and in particular the blockage at the main road bridge is missing in the model result. The similarity for the Eybach is eye catching for the blue and red zones, and the yellow area is underestimated for the modelled map in general concerning the model limitations explained in chapter 3.1.3. Due to the missing specifications of the flow characteristics for the historical events (Figure 27.4) it is difficult to take them into account in general. As detectible, the historical events probably didn’t have much influence to the official map in this case.

In summary, quite similar results were generated using different approaches, except for missing adaptations justified by field observations, for instance the discharge capacities of the bridges. The mentioned flood (yellow zone) underestimation in the modelled map is obvious and the missing runout to the lake for three torrents is questionable.

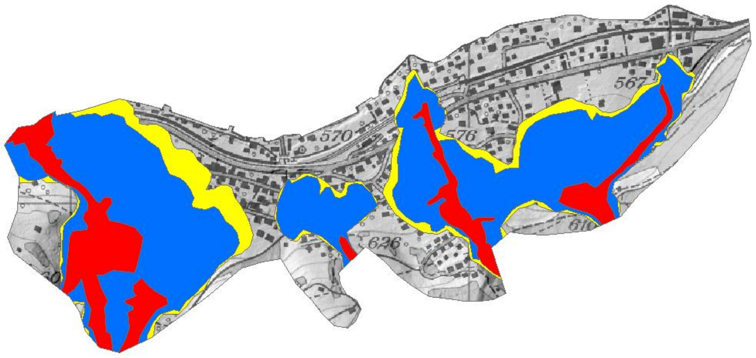
1 | Raw hazard map

Appropriate to the BAFU guidelines classified composite of all scenarios



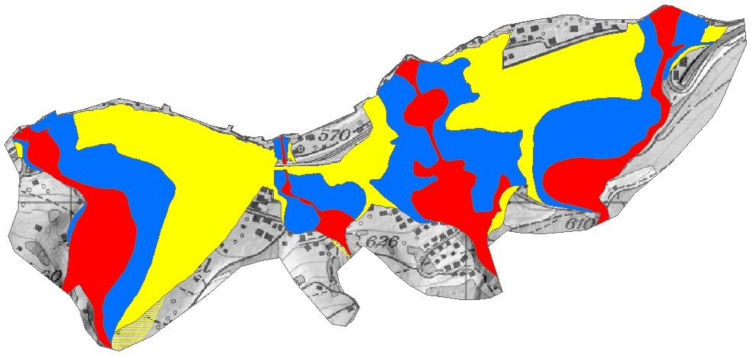
2 | Manually generalised map

Manually and subjectively generalised map derived from the raw hazard map.



3 | Official hazard map by Geo7

Official hazard map of Leissigen, developed by Geo7 using conventional methods in the year 2008.



4 | Historical events

Composite of all registered debris-flow events since 1930 until 2013

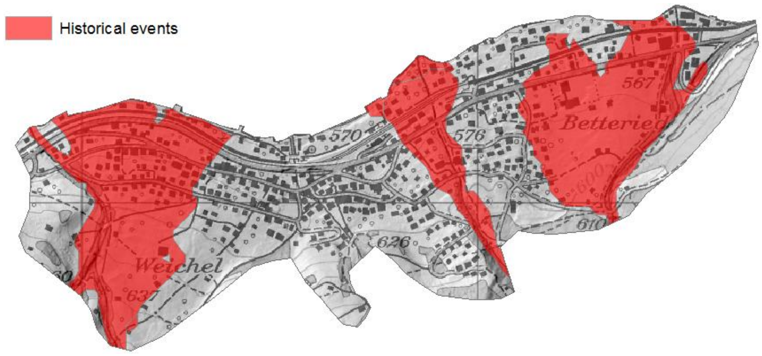


Figure 27: Different debris-flow hazard maps for Leissigen (1-3) and a composite of all registered historical events (4).

3.3 Case study Agarn (Meretschibach)

In the context of a master's thesis Nicole Oggier investigated the suitability using RAMMS for debris flow modelling in general. While focusing on the Meretschibach, the comparison of the model results with the hazard map was obvious. By using her results a third case study aspires to extend the informative value of this work. The following description of the study site and the hazard maps are based on the mentioned thesis of Oggier (2011).

3.3.1 Study site

The Meretschibach is a torrent with a distinct hazard potential to the village of Agarn. Agarn lies on a sediment cone on the southern side of the Rhonetal in the Canton of Valais (Figure 28). The torrent with a catchment area of 9.2km^2 covers an altitude range from 3025m a.s.l. (Bella Tolla) to 624m a.s.l. at the main road in the village. The slope angles are about 20 to 25° in the torrent and around 13° on the cone. The mean annual precipitation amounts 500 to 800 mm which reflects the dry climate in the Valais. The high hazard potential required for mitigation measures which were first built in the 1950s as a debris-flow barrier and from 2004 to 2009 as longitudinal dikes at Talmatten. In the simulations, interesting for the maps used in this comparison, only the barrier is considered. For having a comprehensive evaluation about the mitigation concept and the coherent simulations of the Meretschibach, Oggier (2011) is recommended.

Geology and Geomorpology

The upper catchment area is dominated by high Alpine environment. Steep rock faces consisting of metamorphic crystalline of the penninic deliver debris to the talus slopes and even a rock glacier is present. Two lakes and quaternary sediments are noticeable in the upper Meretschialp. The lower Meretschialp is dominated by Alpine meadows on moraine material. A distinct supply of debris to the torrent comes from the erosion area Bochtür which lies between 1‘600 and 2‘100m a.s.l. on the orographic left side of the Meretschibach. This area exhibits a high rock fall, landslide, avalanche potential and was identified to be an initiation zone for debris-flows. (Oggier, 2011)

3.3.2 Modelling

The hazard map is based on the combination of the simulation results using the input parameters as shown in Table 7. By the time the simulations by Oggier were done, RAMMS debris-flow was not ready to use. Therefore all the modelling has been done with the avalanche module of RAMMS which has the same input parameters except the peak discharge and the input hydrograph. The starting volume had to be defined by a block release area.

Table 7: Input parameters for RAMMS for Meretschibach. (Oggier, 2011)

Torrent	Scenario [yr]	ξ [m/s^2]	μ	Volume [m^3]
Meretschibach	30	300	0.12	15’000
	100	300	0.12	60’000
	300	300	0.12	120’000

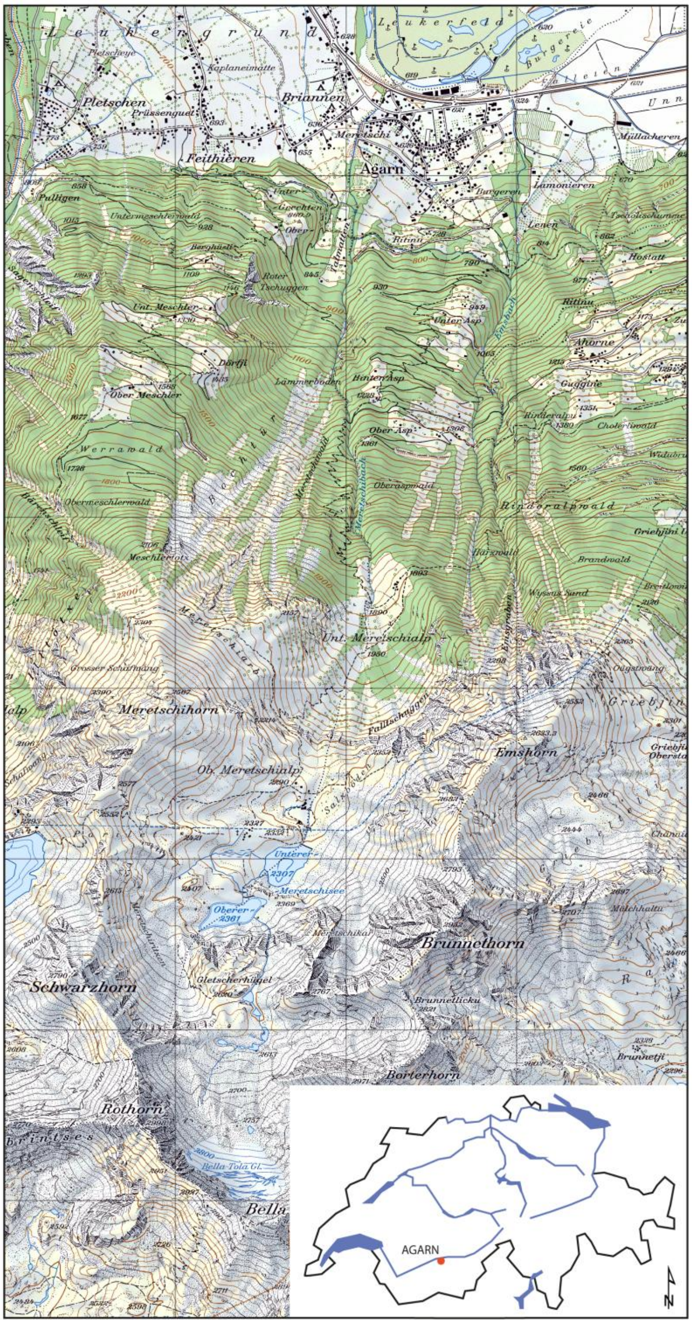


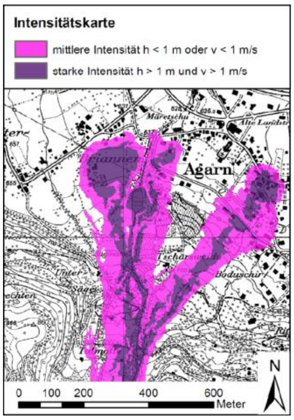
Figure 28: Swisstopo map (1:25’000) of the study site Agarn (Meretschibach).

3.3.3 Comparison

While comparing the different maps an interesting issue concerning the volume estimation have to be discussed. In the technical report of ARGE Geotest AG / T. & C. AG of the year 2001 the maximum debris-flow volume (main channel and Bochtür) was estimated to be about 46000m^3. The corresponding hazard map (Figure 27.3) appears similar to the modelled map (Figure 27.2), developed by Oggier (2012) which is based on a maximum volume estimation of 120000m^3. This adaptation of the maximum volume has been determined after a severe debris-flow event in the year 2000 with a volume around 27000m^3. The official hazard map was revised by Geotest AG / T. & C. AG and the volume estimations were set to the mentioned 120000m^3. It is not my task whether this adaptations of three times higher volumes are appropriate or not, but it is an important example how uncertain and variable in time an assessment can be. Further reasons for the different volume estimations and the implementation in the hazard map are probably the time invested for the assessment in general because the realization of the mitigation measures was close and the fact that the construction of the measures has been supported by different institutions whereat the measures are definitely appropriate. To mention is the fact that the official map of 2002 (Figure 27.4) includes the hazard potential of floods while the map of Oggier only simulates the debris-flow as mentioned in chapter 3.1.3 and no field investigations are considered.

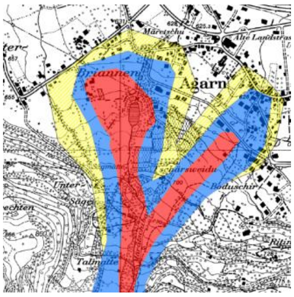
By summarising the findings with respect to the different input volumes and their estimations it is apparent that the map modelled by RAMMS (Figure 27.2) underestimates the hazard compared to the official map (Figure 27.3). But the overestimation of the official map in my opinion is obvious. It is therefore not possible to finally determine whether the accuracy of the modelled map is adequate or not.

This case study in general underlies the findings discussed in chapter 4 that an objective approach for debris-flow hazard assessment is essential and the disparities in the maps are almost negligible when considering the enormous volume uncertainties.



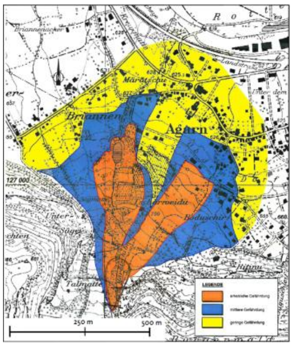
1 | Intensity map for the 300 year scenario (120’000m^3)

Appropriate to the BAFU guidelines classified 300 year scenario which corresponds with a raw hazard map.



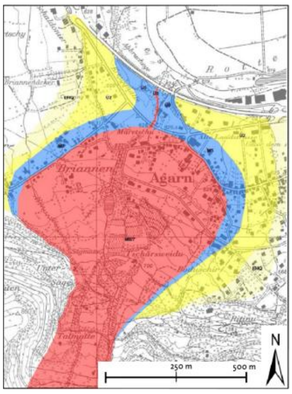
2 | Manually generalised hazard map by Oggier (2011)

The combination of the intensity maps of all scenarios with a maximum debris-flow volume estimation of 120’000m^3.



3 | Official hazard map by ARGE Geotest AG / T. & C. AG, 2001

This map was developed based on a maximum debris-flow volume estimation of 46’000m^3.



4 | Official hazard map by Geotest AG / T. & C. AG, 2002

This map was developed with support by a numerical 2D model (Flo2d) and is based on a maximum debris-flow volume estimation of 120’000m^3.

Figure 29: The 300 year intensity map (1) and different debris-flow hazard maps for Agarn (2, 3, and 4).

4 Discussion

As pointed out during the work, there are a few aspects which have to be discussed. Some of the following issues question the thematic of debris-flow mapping in general, while others focus on the modelling difficulties.

The accuracy of the model results for Gadmen and Leissigen compared to the conventional hazard maps are satisfying. The Agarn (Meretschibach) case study underlines mainly the volume estimation problem while the assessment of the accuracy is difficult. The results of this work have to be put in context by discussing the difficulties of debris-flow assessment in general and the model limitations.

The BAFU guidelines

It has been mentioned throughout the work that the BAFU guidelines of the year 1997 are insufficient for hazard mapping when numerical modelling is applied. A first reproach is the consideration of the deposition height instead of the flow height. It is obviously the moving mass and therefore the maximum flow height which harms an object and not the recommended deposition height. The discussion on the flow velocity as an accurate parameter for a hazard assessment is important and should be launched. The pressure is derived by the velocity and the flow height anyway but the destructive power and therefore the design of mitigation measures or constructional constraints are probably more driven by pressure than by velocity and it would make sense to map this parameter instead of velocity. But it should be pointed out that by applying an empirical approach for debris-flow hazard mapping the criticised parameters are quite appropriate. While the debris-flow volume corresponds to the distributed deposition heights and the flow velocity correlates more or less with the slope inclination the approach leads to the requested goals.

By aspiring to a more objective (not equivalent with more precise) method of hazard assessment, numerical modelling is essential. For this approach the classification scheme of the BAFU guidelines (Figure 6 and 19) is inappropriate and obsolete. For instance, a debris-flow with a flow height of 5 cm and a velocity of 0.1 m/s results in a medium hazard (blue) class for a 100 year scenario. Defining whether this mass movement could ever be a debris-flow and whether the hazard potential is appropriate to the blue zone at all indicates the deficiency of the classification while dealing with model results. With respect to the model limitations and the illusive precision of model results, a more appropriate classification is indispensable if the application of numerical models in practice will increase. The development of guidelines for hazard mapping based on model results and the revision of the classification scheme is required. A few modifications (Hürlimann, 2008 or Rickenmann, 2005b) have been done, but more specific research is required.

Debris flow volume

Considering that one of the most critical variables in debris-flow hazard assessment is the magnitude of the event, particular attention and effort have to be focused on volume estimations. As pointed out in Bertoldi et al. (2012) it is not realistic to produce precise model results when only crude volume estimates are available. The fact that for conventional methods the same volume estimations are fundamental relativises the small differences found between the modeled and the official hazard map. In particular when considering that no adaptations based on field observations had been done for the modeled map. In other words, one should give thought to the quite small disparity between modeled runout predictions compared to conventional approaches which are negligible when considering the difficulties and uncertainties of debris-flow volume estimations.

For this work, the volume estimations for Gadmen considering the model input need to be discussed further. As mentioned in chapter 3.1.2, the volumes of the debris-flows are composed from the mobilisable debris potential and the same amount of water with respect to the fact that a (Newtonian, laminar) debris flow consists of 50% water (chapter 2.2.2). But it can be argued that the water remains in the pore space and therefore no doubling of the volume is appropriate. This assumption is also linked to the following discussion about the flow height-deposition height relation. Due to the doubling of the debris potential, the debris-flow volume leads to increased flow heights, while the deposition height would probably corresponds to the mobilisable debris. Anyway, the model results suggest an accurate assumption.

Another aspect which underlines the immense impact of the volume estimation is the fact that the peak discharge, a quite important input parameter for RAMMS, is derived from the debris-flow volume. So it is an empirical equation (chapter 2.4.1) compared with expert knowledge and not a precipitation-related variable which determines the peak discharge. This aspect reveals the fact that no statistical probability is integrated in the model although the scenarios refer to return periods. It has to be mentioned that processes like debris-flows underlie a strong frequency magnitude relation (Jakob, 2005), which makes it almost impossible to consider this claim reasonable.

A further consideration which influences the debris-flow volume and therefore the runout distance is the surge behaviour of debris-flows (Coussot & Meunier, 1996). While volume estimations refer to the debris potential in the starting and transit zone, one worst-case debris-flow with a magnitude containing the total potential is expected. For real events, it could be expected that the debris potential is initiated in multiple surges. This would lead to smaller debris-flows with a shorter runout distance and a variation of the topography between the surges. This fact is not considered in the model and could lead to a general overestimation of the hazard.

Flow height vs. deposition height

It can be argued that the comparison in this work is inappropriate due to the fact that a conventional map refers to deposition heights while the RAMMS model results represent the flow height. This argument is correct in some aspects. The disparity between the two parameters depends on the slope inclination. The steeper the terrain, the more differences are to be expected. Due to the quite small inclinations on debris-flow cones where most of the predictions take place the argument is not crucial. But in general a slight overestimation of the model results exists because of the washout of fine material and the absence of the water in the deposition.

Historical events

Historical events are important while hazard mapping either for conventional approaches or for model simulations. Due to the calibration of the model parameters a well-documented event is indispensable. As mentioned in chapter 3.1.3 no specifications concerning the flow characteristics and the type of the deposits are indicated in the cadastre files. In particular, processes such as debris-flows with such a variety of forms require more information. While taking historical events into account for hazard mapping, the consideration of the mapped inundated area without specifications for the deposits can lead to misjudgement of the hazard potential. Therefore it is important to have documentary material, especially photos, to evaluate the characteristics of the deposition.

Model limitations

There are a few limitations while modelling debris-flows. As pointed out in chapter 3.1.3, the flowing mass is modelled as a single phase. There are no differentiations possible for flow characteristics. While using model simulations for hazard mapping this issue leads to an underestimation of the sediment-laden water in front of the main debris-flow deposits. Furthermore it has not been possible to implement bed erosion in RAMMS until now. Intentions with respect to this issue are in progress. The consideration of levee generation in the model is a further task which cannot be taken into account while modelling debris-flows. It is not yet understood why debris-flows generate their own channel on the cone in some cases while they start to spread out and deposit in other cases.

A further issue which limits the simulations is one of the main inputs. The topography determines the flow direction of the debris-flow, which is obviously a quite important parameter. To determine precise model results, the DHM has to be up to date and if we consider a high-resolution elevation model it is almost impossible to have current data to hand. Including buildings in the model is a further question which refers to the topography. Especially in highly cultivated areas the infrastructure influences the flow paths of debris-flows but it is questionable if the consideration makes sense with respect to the uncertainties of the input parameters. A last issue is the variability of the topography within an event or between surges. The aforementioned erosion and levee generation and the deposition in general influence the precondition on different time scales. Within two surges a few hours affect the topography while the actuality of the DHM can be devastated by years.

A few aspects of using model results for hazard mapping are discussed and the results of this work are critically evaluated. As pointed out, model simulations (in this case using RAMMS) compared to the conventional approach are appropriate for hazard mapping with respect to the absence of comprehensive field investigations and the difficulties of defining the input parameters in general. The knowledge of the expert about the applied model and the awareness of difficulties is a basic requirement for the implementation of the simulations in a hazard map. But the benefit of having an objective assessment of the hazard potential in my opinion exceeds the small differences detected for the hazard maps of the three study sites. It remains questionable how model limitations such as the absence of bed erosion, levee generation, topography changes and differentiations of phases within the flowing mass influence the assessment and if more sophisticated models would increase the accuracy with respect to the uncertainty of the input parameters and the complexity of the debris-flow process anyway. Models are approximations and the purpose and the available Input data determine the accuracy.

5 Conclusion

The runout prediction of debris-flows in literature and in practice is primarily based on empirical methods. The implementation of physically, analytical approaches in numerical models in the last decade supplements the debris-flow hazard assessment by a useful approach due to its objectivity. The plurality of such models and their basics imply the question which model is the most appropriate and how sophisticated they should be. For this study RAMMS serves its purpose sufficiently. The BAFU hazard classification scheme for debris-flows turned out to be inadequate when using model simulation for hazard mapping. The importance of updating the recommendations with respect to numerical models is required. To develop an appropriate classification scheme and to compose authoritative guidelines concerning numerical modelling further research is suggested.

However, the case study Gadmen and Leissigen show an adequate accordance considering the missing verification of the model simulations in the field and the deficient attention to the flood process. The case of Meretschibach is less coincident but emphasises the finding that the most difficult task of debris-flow hazard assessment is not the runout prediction; it is the estimation of the starting volume. The differences between the hazard maps developed by the two approaches are negligible concerning the volume estimation problem. An objective approach for debris-flow hazard mapping is highly desirable. The implementation of a topography respecting classification algorithm would lead to this goal and research in this thematic is required.

Nevertheless the assessment of debris-flow hazard depends on locality, is not static in time and process understanding is fundamental. Therefore whichever approach leads to the required goal, expert knowledge compared with extensive field investigations are indispensable. The suggested suitability using model simulations does not imply any degradation of empirical approaches. The only goal is to take a step further to a high quality hazard mapping process with respect to its objectivity.

6 Literature

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Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent, work. All external sources are explicitly acknowledged in the thesis.

Marco Walser