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Multi-Hazard Risk Analyses: a Concept and its Implementation

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Preface

The present study is a cumulative dissertation which unites work published in several journal articles and conference proceeding contributions. It consists of a monographic part, the main text, and the published or submitted articles in the appendix. Thereby, the monographic part is structured according to a set of hypotheses and objectives, implementing concepts, approaches, procedures and performed studies outlined in the articles. This implies that many details are not presented in the monographic part, nevertheless, clear reference is given to the respective articles in which extensive information is available. Moreover, several paragraphs are repeated verbatim from the articles. These text passages are indicated by footnotes and reference is given to the publication they are taken from. Although the articles were written by several authors, it should be noted, that these paragraphs were written solely by the author of this thesis.

Many persons supported and encouraged me during my PhD thesis and I want to express my gratitude for all the ideas and input, conversations and help.
First of all, I want to sincerely thank Thomas Glade who gave me the chance to write a PhD-thesis in the multi-hazard field and his assisstance and advice during my research. Moreover, I want to thank Margreth Keiler for many discussions, support, ideas, and an always open door and open ear.
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Mein ganz besonderer Dank gilt meinen Eltern und meiner Schwester, die mir ein Zuhause sind wo auch immer ich mich befinde. Ein ganz großer Dank geht auch an Jeanne und Laura, danke für eure unerschöpfliche Geduld und Unterstützung.
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1. Why Consider Multi-Hazard Risk?

The term *multi-hazard* is closely related to the international political context with one of the first references in the United Nations' Agenda 21. In this document, focused on the integration of environment and development concerns, "complete multi-hazard research" for sustainable human settlement development is called for (UNEP, 1992, paragraph 7.61). In the field of sustainable development (Johannesburg Plan) the term reappears in the following statement: "[a]n integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world" (UN, 2002, p. 20). In the Hyogo Framework for Action again, the ideas presented in the Johannesburg plan were further specified to the risk reduction focus: "[a]n integrated, multi-hazard approach to disaster risk reduction should be factored into policies, planning and programming related to sustainable development, relief, rehabilitation, and recovery activities in post-disaster and post-conflict situations in disaster-prone countries" (UN-ISDR, 2005, p. 4). This illustrates that the term *multi-hazard* was primarily used in the broader context of risk reduction and it is strongly characterised by the practical objective of risk reduction. In the following, the connection between the threat natural hazards pose, measures to reduce the risk and the need for a joint multi-hazard risk consideration is outlined.

Background for these calls for a safer world is the assumption and notion of increasing confrontation between humans and the natural environment with the result of severe consequences for human life, wellbeing and economic productivity. Events such as the Wenchuan-Earthquake in China (2008), the earthquake in Haiti (2010), the heavy floods in Pakistan (2010), the earthquakes in New Zealand (2010 & 2011) or the combination of earthquake and tsunami in Japan (2011) cause high damage and severe losses. Due to the worldwide acting media these high-magnitude events with serious impacts are the most noted examples of the threat posed by natural hazards[1]. However, also the high level of overall damages and losses is alarming. Statistics derived from disaster databases of Munich Re, Swiss Re, the Emergency Disaster Data Base (EM-DAT) and others show two recurring trends, although the specific numbers differ due to distinct selection criteria[2] for

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[1] Especially in a multi-hazard context the clear definition of key terms poses a challenge. Therefore, detailed definitions will be presented in chapter 2. Preliminarily, *natural hazard* refers to a "[n]atural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UN-ISDR, 2009b, p. 9).

[2] For each database, criteria are defined according to which a damaging event is considered a disaster and

the events which are included and the unequal quality of the loss assessments (Fuchs, 2009a): losses of live are decreasing while the direct economic damage is still increasing (Munich Re, 2000; White *et al.*, 2001; Arnold *et al.*, 2006; EM-DAT, 2009). According to statistics derived from the Munich Re disaster database MRNatCat this rise of economic damages is notable. An increase is indicated from about €27 billion (US$ 38.5 billion) in the decade 1950-1959 to about €375 billion (US$ 535.8 billion) in the decade 1990-1999 (Munich Re, 2000). An upward trend is also mentioned for indirect losses (PLANAT, 2004; Arnold *et al.*, 2006; The World Bank, 2010), but verification on basis of detailed longterm statistics is still not possible since indirect losses are very difficult to quantify and are not included in the majority of the databases. However, Arnold *et al.* (2006, p. xiii) state that "the number of those affected in terms of disruptions to daily life, loss of livelihoods, and deepening poverty continues to increase" and the The World Bank (2010) identifies a general trend of an overproportional rise of indirect losses with increasing direct losses. Munich Re (2000, p. 70) highlights different factors causing these high and still increasing economic damages including "the global increase in population and other related developments like urbanization, the utilization of highly exposed regions, and alterations in the environment". Nevertheless, the identified upward trends need careful interpretation and consideration of the influence of inflation, increased reporting activity of damages and losses and time-varying socio-economic factors (Barredo, 2009; Fuchs, 2009a). In summary, it can be stated that, even though the previously estimated increase of damages may turn out to be lower or even non-existent after a normalisation procedure, the level of damages due to natural hazards does still not show a clearly decreasing trend.

White *et al.* (2001) pose the question how this is possible although scientific knowledge about natural hazards has been increasing continuously as the large number of articles and books they reviewed indicate. Should not play knowledge and understanding of the causes of the losses a key role in their reduction (White *et al.*, 2001)? To be able to assess the role of scientific knowledge for the reduction of risks[3], it is necessary to examine the overall framework of efforts in this field, subsumed under the term *risk management*. Risk management is composed of the risk analysis, assessment and all "strategies and specific actions to control, reduce and transfer risks" (UN-ISDR, 2009b, p. 11). It can be structured in the four interlinked components of risk assessment, prevention, event management and regeneration (Figure 1.1). That implies, risk management should ideally start with risk assessment, composed of risk analysis and valuation, to supply important information

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inserted as record. In the case of EM-DAT this refers to: ≥10 people are reported killed or ≥100 are reported affected or a state of emergency is declared or international assistance is called for (CRED, 2009). By contrast, criteria for Sigma from Swiss Re for the year 2010 are: ≥20 casualties or ≥50 dead or missing or ≥2,000 homeless or total economic losses ≥US$86.5million or ≥US$17.4 million for maritime disasters or ≥US$34.8 for aviation or ≥US$43.3 in case of other losses (Swiss Re, 2011)

[3] The term *risk* is defined as the "[e]xpected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period" (WMO, 1999, p. 2).

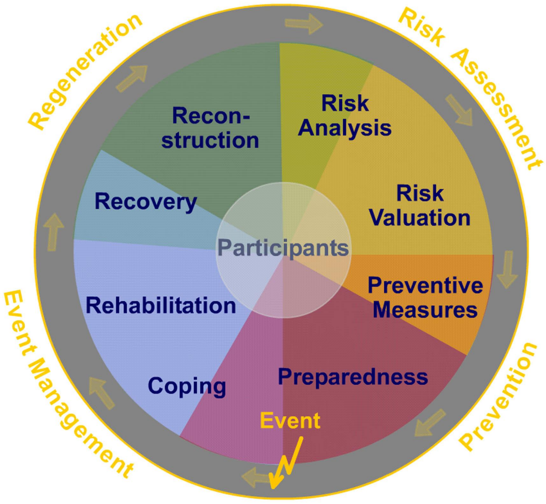

Figure 1.1.: Risk management cycle according to Swiss Virtual Campus (2008)

for all further steps (Kienholz *et al.*, 2004). Thereby, the risk analysis provides information on the potential effects of interaction between nature and society. Thus, the potential consequence natural hazards can have on the human sphere is studied to identify "[w]hat could happen ?" (Kienholz *et al.*, 2004, p. 9). The subsequent risk valuation serves to determine "[w]hat is allowed to happen ?" (Kienholz *et al.*, 2004, p. 9) and where risk reduction measures have to be applied. The valuation is therefore a fundamental step for decision-making if and where measures and activities have to be performed (please refer to Figure 1.1 for the sequence of risk management steps explained in the following). For instance, in the prevention phase the central issue is the elimination or reduction of risks by means of active measures such as dykes or avalanche defense structures, or passive measures such as land use regulation (Kienholz *et al.*, 2004). Thereby, the information provided by risk assessments facilitates the identification of those locations with the highest risk levels and supports the determination of adequate risk reduction measures. In contrast to prevention, preparedness deals rather with the potential damages than with the hazard and includes for instance the preparation of resources required during an event, training initiatives or the establishment of an early warning system (Kienholz, 2003; Kienholz *et al.*, 2004). Again, risk assessments provide important information e.g. for the design of early warning systems or the identification of resource requirements. Also in the case of an event, risk information is highly valuable for the coordination of the emergency management, in particular for evacuation purposes. Moreover, the recovery and reconstruction following a hazard event should be based on risk information and accompanied "by efforts to learn from recent experience" (Kienholz *et al.*, 2004, p. 1). This refers especially to the choice of the reconstruction location for buildings or infrastructure and the determination of building codes. Based on risk assessments which are amplified by recent experience, sustainable planning and redevelopment should be the first priority

to reduce risks. Finally, the newly gained experience from the incidence shall support the improvement of the risk assessment and prevention activities to turn "the risk management cycle into an ascendant [...] spiral" (KIENHOLZ *et al.*, 2004, p. 1).
However, the reduction of risks cannot only be based on better knowledge about natural hazards, "technical assessment and the optimisation of the risks as quantified entities" since risks have also "social and psychological dimensions, and are shaped by values, beliefs, political systems and cultural factors" (ASSMUTH *et al.*, 2010, p. 3943; refer also to KASPERSON *et al.*, 1988; FELT *et al.*, 2007). With a wider participation of stakeholders in the risk reduction efforts, especially the general public, and communication between all actors, these social and psychological aspects can be better considered. However, while the risk management concept does not account for these issues in depth, the still rather young concept of risk governance shows a broader and more interlinked view of dealing with risks and clearly emphasises participation and communication. According to a description of the IRGC (2005, p. 4) risk governance "includes the totality of actors, rules, conventions, processes and mechanisms and is concerned with how relevant risk information is collected, analysed and communicated, and how management decisions are taken". In short, DE MARCHI (2003, p. 171) describes it as a combination of "sound science" with democratic participation. The components it consists of are (1) risk assessment and (2) risk management which are embedded in (3) risk communication. Communication refers in this context not only to the transfer of information on risk or risk management decisions but to "establishing the two-way dialog needed at all stages of the risk handling process" (IRGC, 2005, p. 6) within a "diverse yet interdependent set of actors organised as part of a network" (WALKER *et al.*, 2010, p. 8). Expected advantages of this approach are increasing public awareness, change of attitude towards the risks as well as more trust and less conflict between different stakeholders (WANCZURA, 2006; DE MARCHI, 2003; IRGC, 2010).

Thus, referring again to the question of WHITE *et al.* (2001) how losses can still rise although scientific knowledge is increasing: knowledge about hazards and risks is obviously indispensable for the performance of risk assessments which are "a required step for the adoption of adequate and successful disaster reduction policies and measures" (UN, 1994, p. 5). Despite the differences between risk management and risk governance, the components and structure of both concepts indicate that risk analysis has an important part in terms of providing the basis for further strategies and actions in the context of risk reduction. Though, this does not mean that risks will directly decrease on basis of knowledge about risks and the information obtained by profound risk analyses, but it indicates the importance of this step. It is thus reasonable to investigate the role increasing scientific knowledge plays in a framework of non-decreasing levels of economic losses. WHITE *et al.* (2001) examine several possible explanations, amongst them the possibilities that although much is already known still much knowledge is lacking, knowledge is not used or knowledge is used ineffectively. In the following, they reject the first explication stating that especially in developed countries "a lack of knowledge is not a major contributory factor to the growth of disaster losses" while the second and third possibility may apply (White *et al.*, 2001, p. 89). With respect to the first explication, White *et al.* are probably right regarding knowledge about single hazards and approaches to analyse them. Already extensive knowledge about the processes and a huge variety of models to analyse the hazard and risk they pose is available. The detailed review of the state of the art for meteorological, hydrological, volcanic and seismic hazards of the WMO (1999) give a good overview of the multitude of methods and models, although there is always potential for further improvements. However, many regions of the world are not only subject to a single hazard but to multiple hazardous processes, such as mountain regions, coastal zones or volcano vicinities. For instance, the Principality of Andorra is a small country (470 km^2) entirely situated in the Pyrenees that suffers from a combination of different landslide types, snow avalanches and floods (Corominas *et al.*, 2003; Cascini *et al.*, 2005; Planas, 2007). Another example is Mount Cameroon, an active volcano around which about 450,000 people live or work although the area is prone to volcanic eruptions with lava flows and lapilli ejection, slope instabilities and earthquakes (Thierry *et al.*, 2008). The risk analysis of such areas cannot be restricted to single processes since this would lead to a misestimation of the overall risk and the risk patterns but has to consider all relevant[4] perils in a multi-hazard approach (Greiving *et al.*, 2006). This indicates, that the necessity for a multi-hazard approach in the risk reduction context emerges from the spatial aspect: risk reduction measures are the task of administrative bodies and units that are responsible for "territorial entities (e.g. administrative area)" such as municipalities, federal states, the complete country etc. (Carpignano *et al.*, 2009, p. 514). To effectively reduce the overall risk in a defined area, risk assessment and management cannot be restricted to one or few single hazards, on the contrary, "a spatially oriented [approach] has to take into account all risks that are related to a specific area" (Greiving *et al.*, 2006, p. 1). In other words, "[m]ulti-hazard cases can be described as settings where a multitude of hazards need to be included in the risk management of a certain area" (Olfert *et al.*, 2006, p. 128) and Hewitt & Burton (1971, p. 5) refer to a "all-hazards-at-a-place" approach. For instance, the structure of the risk management framework in France is a clear example of the relation between the spatial aspect of risk reduction and multi-hazard consideration. There, risk management tasks are clearly allotted to the different administrative levels. The Prefect of a *Département* is responsible to decide, based on the particular natural hazard situation, which municipalities have to develop risk prevention plans (Fleischhauer *et al.*, 2006). Thereupon, the assigned municipalities perform the necessary analyses for the relevant natural hazards and the final risk prevention plan has

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[4] The definition of *relevant* depends on the knowledge about hazards, risk perception and in case of risk analyses on the objective of such a study. This topic will be discussed in more detail later in this chapter.

to be approved by the Prefect (FLEISCHHAUER *et al.*, 2006).

In the description of a spatial approach to risk reduction discussed above, the terms *multi-hazard*, *a multitude of hazards*, *all risks* or *relevant hazards* were used. Thereby, the question arises, as to the processes that these descriptors refer to. The selection of the hazards to be considered in a multi-hazard approach is in the first place related to the characteristics of the specific region for which risk analyses, management and finally risk reduction is required. That implies, the environmental setting gives rise to a range of natural hazards that pose a threat on that area. To identify those hazards, a multitude of methods is in use such as the examination of different maps, aerial photos, field surveys, measurements carried out in the past and inventories, but also interviews with contemporary witnesses, the review of newspaper articles etc. (KIENHOLZ & KRUMMENACHER, 1995; LOAT & PETRASCHECK, 1997; CAMENZIND-WILDI *et al.*, 2005). However, it is important to keep in mind, that the resulting list of hazards will always be restricted to the *known* perils (HEWITT & BURTON, 1971; CAMENZIND-WILDI *et al.*, 2005). Thereby, for instance extremely rare events or *new* perils emerging with changes of the socio-environmental setting may be neglected. Nevertheless, the simple listing of all identifiable and identified hazards gives no indication about their *relevance.* Not all hazards active in a certain area may be relevant in the specific context and related to the objective and responsibilities of the stakeholders. For instance, in the spatial planning context, GREIVING *et al.* (2006, p. 4) restrict the set to spatially relevant hazards. This refers to "hazards that are closely tied to certain areas that are especially prone to a particular hazard" and exclude the ubiquitous risks such as meteorite impacts since they show no spatially differentiated patterns. Another example for the specification of relevance are the parameters of the EUROPEAN COMMISSION (2011, p. 24) for the determination of *all significant hazards* for risk assessments at a national level: threats with an annual probability of at least 1% and "significant potential impacts, i.e.: number of affected people greater than 50, economic and environmental costs about €100 million, and political/social impact considered significant or very serious [...]. Where the likely impacts exceed a threshold of 0.6% of gross national income (GNI) also less likely hazards or risk scenarios should be considered (e.g. volcanic eruptions, tsunamis)". In Switzerland, those processes posing *no relevant damage* to humans, buildings, infrastructure, livestock, agricultural areas, protection forest, parks or cultural assets can be excluded from the multi-hazard risk analysis (BORTER, 1999). Moreover, HEWITT & BURTON (1971) mention a strong dependence on the extent of the area to be covered with the analysis. The larger the area under consideration, the higher the *cut-off point* of the related damages, that implies, the higher the threshold of damages and losses above which hazards are considered relevant at this scale. Consequently, the set of hazards finally taken into account in a multi-hazard approach consists of those processes present in a certain area that are known and considered relevant for the specific objective of the study.

In summary, a first definition for the term *multi-hazard* in a risk reduction context could read as follows: *the totality of relevant hazards in a defined area*, whereby *relevant* has to be clearly defined according to the specific situation and setting. Another expression appearing in this context is that of *all-hazards*. *All-hazards* as used by FEMA (1996), Britton (2002), Ritchey (2006), Rural Alaska Mitigation Planning (2009), Tate *et al.* (2010), European Commission (2011) indicates an equivalence with *multi-hazard* according to the proposed definitions given above.

In a wider sense, *multi-hazard* could also be defined as *more-than-one-hazard*, as for example the multi-hazard sessions of the European Geoscience Union Meetings suggest (sessions bringing together >1 hazard; EGU, 2011). While in the scientific sector only few studies deal with *all relevant hazards* present in an area, many studies fall under the definition of *more-than-one-hazard*. The strict separation of disciplines in science does not really facilitate the joint consideration of many, and especially not of very different, hazards (cf. WMO, 1999). However, in various contexts it is not possible to restrict the analyses to only one process. This refers for example to the triggering of one hazard by another as in the case of landslides being triggered by earthquakes (e.g. Bommer & Rodríguez, 2002; Keefer, 2002; Lin *et al.*, 2006; Chang *et al.*, 2007; Lee *et al.*, 2008; Miles & Keefer, 2009). Although the focus of this type of study might not be equally on both processes, they can, with this wider definition, be considered as multi-hazard studies. In other cases one event might cause several different threats which are considered jointly as in the case of a volcanic eruption with ash and lapilli fallout, lava flows, lahars etc. (e.g. Zuccaro *et al.*, 2008; Thierry *et al.*, 2008). Likewise, certain research topics, for example the examination of the complete sediment cascade including soil erosion, rock falls, full-depth avalanches, shallow landslides and debris flows (Wichmann *et al.*, 2009) or the modelling of rapid mass movements (RAMMS) comprising snow avalanches, debris flows and rock fall (Christen *et al.*, 2007), lead to the joint consideration of several hazards. This means the hazard combination is primarily not determined spatially, as in the framework of risk reduction, but thematically. This may result in the consideration of only very few hazards, nevertheless these studies offer a great know-how and knowledge potential.

However, the joint examination and quantification of multiple hazards is a difficult task since hazards exhibit a wide range of characteristics and are analysed by strongly differing models (WMO, 1999). Thereby, contrasting hazard characteristics refer to their time of onset, duration, extent, intensity and return period and parameters of influence on the built environment and humans (Tyagunov *et al.*, 2005; Carpignano *et al.*, 2009; Kappes *et al.*, 2010). These contrasts are reflected in the modelling approaches. Delmonaco *et al.* (2006b) undertook a comparison of modelling methods for different hazard types at distinct scales and identified huge distinctions in the approaches. For instance, statistical analyses are generally used for landslide susceptibility analyses at a *national* scale while for volcanic hazards deterministic methods are common. Moreover, not for each hazard models are available at each scale, e.g. no models exist for local level forest fire analyses. Furthermore, separate analyses will most probably apply "disparate procedures and time-space resolutions" and thus "it is difficult, if not impossible, to compare the risk of different origins" (MARZOCCHI *et al.*, 2009, p. 7). That implies, emphasis is still primarily on the constant improvement of single hazard approaches, however, there is a great need for multi-hazard approaches to consider the challenges outlined above. This situation has already been identified by HEWITT & BURTON in 1971. HEWITT & BURTON (1971, p. 5) noticed on basis of a quick literature review, that "most work has been done on single hazards, whereas the expanded concern demands a more systematic cross-hazard approach". Obviously rather little has changed since then in the scientific sector. Also in practice, the joint analysis of multiple hazards is still rare and instead separate computation of single-hazards is commonly performed. The survey and management of the natural environment including the assessment and management of natural hazards is in many countries traditionally subdivided according to the disciplines (i.e. hydrology, geology, meteorology etc.) and assigned to the institution responsible for respective discipline (geological surveys, institutes for meteorology or hydrology). This is a hindering aspect for jointly considering multiple hazards since the combination of threats will transverse a range of disciplines, departments, laws etc. For example, in Germany, risk assessment and management activities refer primarily to the fields of planning processes, building permissions and/or emergency response, and several sectoral planning divisions are in charge (FLEISCHHAUER *et al.*, 2006). While the task of the Geological Survey is landslide assessment, the water management authorities of the different federal states are responsible for river floods, and forest fires fall into the field of duties of the Federal Agency for Agriculture and Food (Bundesanstalt für Landwirtschaft und Ernährung). This situation does not only affect the risk assessment but in further consequence the management and effective reduction of risks.

In summary, the joint consideration of multiple hazards to achieve risk reduction is a necessity since many regions are prone to different types of threats. However, this is neither simple and straightforward nor commonly undertaken at present since different natural hazards are usually analysed and managed by different institutions.

This situation gives rise to the first hypothesis examined in this thesis:

I) Multi-hazard (risk) analyses are not just the sum of single-hazard (risk) analyses.

Three objectives issue from this hypothesis:

1. **To investigate aspects and challenges emerging in the multi-hazard risk environment.**
2. **To review the recent approaches used to cope with the identified challenges.**
3. **To develop an analysis scheme considering the knowledge gained in the previous two steps.**

The analysis of risks is usually carried out as a three-part procedure consisting of (1) the hazard analysis, (2) the appraisal of the vulnerability and value of elements at risk, and (3) the computation of risk as combination of hazard, vulnerability and value of elements at risk (VARNES, 1984, refer to the definition of *total risk* as proposed by). Furthermore, each step requires data preparation and computation of intermediate products. For multi-hazard risk analyses, these three steps, including all single operations, multiply with the number of hazards taken into account. That implies, already in case of three processes nine steps are necessary to analyse the risk they pose, not yet including preparative and intermediate steps. This makes multi-hazard risk analyses rather time-consuming, error-prone and unwieldy. Moreover, a risk analysis should not be a one-time issue because hazards, vulnerabilities, values of elements at risk and thus risks change over time. Especially in the context of global environmental change hazard levels are not static but dynamic. Shifts in temperature, precipitation patterns, glacier cover or permafrost due to climate change cause effects on landslides, floods, avalanches etc. (KEILER *et al.*, 2010), and land use changes, such as removal of the vegetation cover, lead among other effects to erosion and slope destabilisation (SLAYMAKER & EMBLETON-HAMANN, 2009). Likewise, vulnerabilities and values of elements at risk are subject to changes: long-term shifts due to socio-economic development as well as short-term changes resulting from seasonal or diurnal variability, especially of mobile values or intangible assets (FUCHS *et al.*, 2005; KEILER *et al.*, 2005; ZISCHG *et al.*, 2005; FUCHS & KEILER, 2006). Thus, an occasional or even periodical repetition of the analysis procedure is needed to be informed about the current risk level and projections of future risk as a consequence of global environmental change, socio-economic variation, and different management strategies are recommendable to support provident and sustainable decision-making.

An aspect closely linked to the fast, user-friendly and repeatable analysis of multiple haz-

ards is the subsequent visualisation. To support decision-making effectively and communicate the results of a multi-hazard risk analysis comprehensibly, the clear representation of the modelling output is very important. However, without profound experience with Geographic Information Systems (GIS) and knowledge of cartographic rules, the clear and intelligible display of multiple hazards and risks is very challenging (KUNZ & HURNI, 2011a). Not only the single-hazard and -risk patterns have to be shown but also their joint distribution and overlapping etc. while an overloading of the maps has to be avoided (KUNZ & HURNI, 2011a).
These considerations lead to the second hypothesis of this thesis:

II) A software platform provides practical advantages for reproducible multi-hazard risk modelling and visualisation.

Two objectives originate from this hypothesis:

1. **To implement the developed analysis scheme into a modelling tool.**
2. **To develop a visualisation tool to present the modelling results.**

According to the previously presented hypotheses and objectives, the present study is structured as follows: Chapter 2 provides a review of the current situation in the multi-hazard risk analysis field as foundation for all following steps. Therein, particular issues and challenges emerging in this sector are compiled and prevailing approaches to cope with these challenges are presented (hypothesis I, objectives 1 and 2). In chapter 3 the methodology is outlined by means of which an analysis and visualisation scheme is developed (hypothesis I, objective 3) and implemented in a modelling software (hypothesis II, objective 1 & 2). Chapter 4 presents the completed concepts and the finished analysis and visualisation tools. In chapter 5 a case study is performed in the Barcelonnette basin to test the usefulness of the developed concepts as well as the applicability and user-friendliness of the software. Chapter 6 discusses the hypotheses in the light of the developed methodology, the elaborated software tools and the experiences gained in the case study and chapter 7 provides an outlook on future challenges.
Those articles written by the author of the present study, cited in the text and forming part of this PhD-thesis are attached as appendix.

2. Challenges and Current Approaches in the Multi-Hazard Field

The fundamental aim of this work is the identification of challenges and difficulties arising in the multi-hazard risk analysis field and current approaches to solution as basis for all subsequent steps (hypothesis I, objectives 1 & 2). On that account, a detailed literature review has been carried out to get an overview of the current state of the art. Thereby, all studies falling under the multi-hazard definition *more-than-one-hazard* have been involved. Despite the fact, that the present study is rather approaching the topic from the definition *totality of relevant hazards in a defined area*, studies with a wider multi-hazard definition provide very interesting ideas and methods especially on specific hazard combinations and challenges. A detailed review is presented in Kappes *et al.* (subm.b, A.1) of which the principal findings are presented in this chapter.

This review is structured according to the three main pillars of general risk analyses (according to the definition of risk after Varnes, 1984): the hazard (section 2.1) and vulnerability of elements at risk (section 2.2) analyses and their combination to risk (section 2.3). These three issues are complemented by a fourth item which is composed by several additional and rather practical aspects arising in the multi-hazard context (section 2.4). The emphasis is clearly put on the hazard step, since at this stage the challenges originate primarily and exert their influence on the further steps.

The first challenge any scientific study faces is the clear use of terms to transmit the content as explicit as possible. Already between scientists of one discipline, different understandings and descriptions are applied, and in a multi-hazard context this difficulty is even more pronounced due to the combination of multiple disciplines (Huttenlau & Stötter, 2011). Therefore, definitions and explanations for the most important terms are introduced before presenting the review (the definitions and descriptions presented in the following are in large parts repeated from the article Kappes *et al.* (subm.a, A.4).

Natural hazard	describes a “[n]atural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage” (UN-ISDR, 2009b, p. 9). However, in a technical context hazard refers usually to quantitative information on the “likely frequency of occurrence of different intensities for different areas, as determined from historical data or scientific analysis” (UN-ISDR, 2009b, p. 7). In the field of multi-hazard both definitions of hazard are useful: *hazard* according to a wider definition is suitable when generally referring to one or several processes and *hazard* according to the technical definition is required to describe the level of information available for a certain process (in contrast to susceptibility). To enable the distinction between the two meanings, in the present study the term ***Full-Hazard*** will be used to indicate the second (technical) definition. The term *threat* is synonymously used to *hazard* according to the first definition.
Hazard relations	Any kind of connection, mutual influence, or spatial or temporal coincidence between hazards. The terms *hazard relationships* and *hazard interrelations* are used synonymously.
Susceptibility	offers in first place spatial information on a hazard, i.e. indications on “[t]he propensity of an area to undergo” for instance landsliding (Glade *et al.*, 2005, p. 791) or “the probability that any given region will be affected” (Guzzetti *et al.*, 2005, p. 277). This implies that susceptibility offers spatial information on a hazard and lacks, in contrast to full-hazard, information on magnitude-frequency relationships or intensity distributions.
Exposure	refers to “[p]eople, property, systems, or other elements present in hazard zones that are thereby subject to potential losses” (UN-ISDR, 2009b, p. 6). In this study the definition includes not only the presence of elements in hazard (i.e. full-hazard) but also in susceptibility zones.
Vulnerability	relates to the “” In this study, the emphasis is on physical vulnerability, in other words, in first place the characteristics describing the resistance of the physical environment to the impact of natural hazards are considered.

Elements at risk	"means the population, properties, economic activities, including public services, etc., at risk in a given area" (Varnes, 1984, p. 10)
Risk	is defined as the "[e]xpected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period" (WMO, 1999, p. 2).

2.1. Multi-Hazard Analyses

According to Delmonaco *et al.* (2006b, p. 15), the performance of multi-hazard analysis refers to the "[i]mplementation of methodologies and approaches aimed at assessing and mapping the potential occurrence of different types of natural hazards in a given area. Analytical methods and mapping have to take into account the characteristics of the single hazardous events [...] as well as their mutual interactions and interrelations". This description indicates two important issues giving rise to difficulties in multi-hazard analysis procedures: (1) differing hazard characteristics and their effect on the comparability of hazards, and (2) hazard relations and interactions. In the following sections these issues are described in detail and the principal current approaches to solutions are presented (refer also to Kappes *et al.*, subm.b, A.1).

2.1.1. Comparability of Hazards

One of the major objectives of multi-hazard analysis is the comparison of hazards and hazard intensities, respectively. However, comparability is difficult to achieve since hazards differ widely "by their nature, intensity, return periods, and by the effects they may have on exposed elements" (Carpignano *et al.*, 2009, p. 515). The problems at the hazard analysis stage, without proceeding to risk, emerge in the first place due to disparities concerning the impact indicators and impact metrics used to study the effects of hazards on humans and assets (Delmonaco *et al.*, 2006b; Papathoma-Köhle *et al.*, 2011). For instance in the case of floods, impact indicator and metric relate usually to the inundation depth in [m], for rock falls to the impact pressure in [MPa] and for earthquakes to the peak ground acceleration in [m/s^2]. Since neither impact indicators nor impact measures are directly comparable, an additional step to accomplish comparability is necessary.

According to Kappes *et al.* (subm.b, A.1) standardisation of hazards is a commonly applied approach to solve this problem. Two standardisation methods are in wide-spread use, (a) classification and (b) index schemes.
a) By means of intensity and frequency thresholds, the single hazards can be classified into hazard categories (e.g. Heinimann *et al.*, 1998; Chiesa *et al.*, 2003; Moran *et al.*, 2004; Delmonaco *et al.*, 2006a; El Morjani *et al.*, 2007; Thierry *et al.*, 2008). Thereby,

thresholds are defined with reference to the objectives of the study. For example, the Swiss guidelines were developed for the determination of hazard zones (high, moderate and low) for spatial planning purposes (Loat, 2010). These zones are defined according to the following descriptors and their implications for spatial planning. In zones of high hazard persons out- and inside of buildings are endangered and sudden building destruction is possible, further building projects are prohibited (*Verbotsbereich*). In moderate hazard areas persons are at risk outside of buildings and usually buildings are only damaged but not destroyed, under the application of building codes further constructions are possible (*Gebotsbereich*). In low hazard regions persons are hardly at risk, only slight damage to buildings is to be expected and no prohibitions or conditions apply (*Hinweisbereich*). In accordance to the effect on humans and buildings, the numerical hazard intensity thresholds are defined as presented in Table 2.1. The thresholds were defined assuming an equivalence between, for example, a rock fall with a kinetic energy higher than 300 kJ and a flood higher than 2 m with respect to the consequences on humans and buildings. The frequency classification presented in the guidelines compounds the classes 1 - 30 years, 30 - 100 years, 100 - 300 years and more than 300 years. Finally the intensity and the frequency classes are opposed in a matrix and the final hazard class is determined from the combination of the intensity and the frequency class (Loat & Petrascheck, 1997). For instance the combination of high intensity and low frequency leads to high hazard, and low intensity and high probability to moderate hazard (Loat & Petrascheck, 1997).

In summary, the central issue in a classification scheme is the definition of the objective such as spatial planning and the determination of criteria, as for instance impact or humans an buildings. Subsequently, equivalent thresholds can be established for multiple hazards. However, without such an overall scheme for the specification of thresholds, classified hazards from different sources may share the same denomination but are most probably not equivalent and therefore not comparable.

b) In contrast to classification schemes, standardisation by means of indices is a semiquantitative and not a qualitative approach (e.g. Odeh Engineers, Inc, 2001; Dilley *et al.*, 2005; Bartel & Muller, 2007). This means, while the classified output of the previous approach is ordinal scaled, index schemes produce cardinal scaled results. Thus, it is not only possible to rank hazard levels but also to quantify the difference between two hazard levels and carry out simple mathematical operations, such as averaging calculations. For the index computation, the methodology is not as evident as for classification approaches. For instance, Odeh Engineers, Inc (2001) classify the single-hazard magnitudes, frequencies and proportion of the area potentially affected by a hazard event (the analysis is carried on a *sub-region level*). However, the second step consists of a multiplication of the classified frequency score, area impact score and intensity score yielding the continuous *hazard scores*. Bartel & Muller (2007) do not compare hazard in the sense of combinations of frequencies and magnitudes, but by probabilities of one scenario for each

Table 2.1.: Hazard intensity thresholds used in Switzerland for the standardised classification of avalanches (SLF, 1984), mass movements (LATELTIN, 1997) and floods (LOAT & PETRASCHECK, 1997) with the velocity v, flow depth h, kinetic energy E and depth of the mobilised mass M.

Intensity	High	Moderate	Low
Avalanches	pressure $\geq 30\,\mathrm{kN/m^2}$ or return period up to 300 a or less pressure avalanches with return periods of up to 30 a.	pressure $< 30\,\mathrm{kN/m^2}$ with a return period of 30 - 300 a, dust avalanches of $\leq 3\ \mathrm{kN/m^2}$ and return periods under 30 a	dust avalanches with $< 3\mathrm{kN/m^2}$ or less frequent then 30 a or theoretically possible events of > 300 a return period or statistically unseizable flowing avalanches
Landslides	$v > 0.1$ m/day or $v > 1$ m per event for displacements	$v > 2$ cm/a	$v \leq 2$ cm/a
Rockfall	$E > 300$ kJ	$300\ \mathrm{kJ} > E > 30\ \mathrm{kJ}$	$E < 30$ kJ
Potential slope debris flows	$M > 2$ m	$2\ \mathrm{m} > M > 0.5\ \mathrm{m}$	$M < 0.5$ m
Debris flows	$h > 1$ m and $v > 1$ m/s	$h > 1$ m or $v > 1$ m/s	not defined
Floods	$h > 2$ m or $h \cdot v > 2\ \mathrm{m^2/s}$	$h > 0.5$ m or $h \cdot v > 0.5\ \mathrm{m^2/s}$	$h < 0.5$ m or $h \cdot v < 0.5\ \mathrm{m^2/s}$

hazard. This means, for each hazard type, the annual probability of an event above a certain magnitude threshold is computed. Subsequently, for each location the single-hazard annual probabilities can easily be compared and the hazard with the highest probability can be identified.

Standardisations offer not only the comparison between single-hazards but also their combination to the overall hazard. Thereby, the central question is, how overlapping hazards are handled. Usual options for classification approaches are to adopt the highest class of all overlapping hazards (e.g. HEINIMANN *et al.*, 1998) or an intermediate rating between the coinciding hazards (e.g. CHIESA *et al.*, 2003). In the case of indices the single-hazard values can simply be summed or a weighted sum is calculated according to the importance of each hazard since they are cardinal-scaled. For instance, Bartel & Muller (2007) compute for each single-hazard the annual probability that an event with a magnitude above a certain level may take place. Subsequently they sum all probabilities to obtain the probability that any of the hazards takes place within a given year. By contrast, Greiving (2006) use the Delphi method, an approach to collect and synthesise knowledge from a group of experts by means of questionnaires, to weight single-hazard indices. The weighted single-hazards are then summed to form an *integrated hazard map*. By contrast to this method, El Morjani *et al.* (2007) weight the hazards on the basis of the human and economic impact reported in EM-DAT. In this way, the resulting overall hazard considers the differing importance of various threats for humans and assets.

Apart from the difficulties involved in comparing impact indicators, differences in hazard characteristics entail the development of specific analysis methods and models for each process. In Table 2.2, an impression is given of some of the decisive properties that influence not only the performance of multi-hazard analyses but also risk assessments, risk prevention measures, event management and regeneration. In their specific combination, these and many more properties and details give rise to very particular analysis models based on certain assumptions and featuring diverging levels of uncertainty. The resulting degree of difference between analysis approaches is illustrated very clearly in the report of the WMO (1999, p. vii). In this document “existing technologies used to assess the risks for natural disasters of different origins” for multiple meteorological, hydrological, volcanic and seismic hazards are presented. Already a short glance at the table of content and the brief descriptions of the assessment methods indicates many distinctions in the

Table 2.2.: Differences between hazards with respect to their characteristics using the examples of river floods, rock falls and earthquakes (compare also to Hewitt & Burton, 1971 and Delmonaco *et al.*, 2006b). The appraisals shown in this table are primarily comparative and qualitative. The qualitative scales (low - high) applied here are spanned by the three presented hazards.

	River floods	**Rock falls**	**Earthquakes**
Onset time	slow-onset	rapid-onset	rapid-onset
Predictability	(very) good	very difficult	(still) impossible
Frequency	rather medium to high	rather medium to high	rather low
Spatial extent	medium	low	high
Impact indicator	inundation depth, flow velocity or sediment/chemical transport	impact pressure	peak ground acceleration

fundamental approaching of the respective process (WMO, 1999):

- Meteorological hazards assessment: operational and statistical methods
- Techniques for flood hazard assessment: extent of past flooding; probable maximum flood and rainfall-run off modelling; estimation of flood discharge etc.
- Techniques for volcanic hazard assessment: mapping and modelling; human surveillance and instrumental monitoring of the volcano.
- Techniques for earthquake hazard assessment: earthquake source models; occurrence models; ground motion models etc.

Since no common terminology has been applied for the description of the methods, the differences seem particularly pronounced. By contrast, Delmonaco *et al.* (2006b) provide an overview of hazard methodologies based on a synthetic analysis of current approaches indicating differences between analysis approaches as well (Table 2.3). Primarily, this

Table 2.3.: Methods applied for the analysis of different hazards at different scales according to Delmonaco *et al.* (2006b)

	Site specific	**Local**	**Regional**	**National**
Volcanoes	deterministic	deterministic	deterministic	deterministic
Seismicity	quantitative, semi-quantitative or qualitative	damage scenarios	deterministic-quantitative	deterministic-quantitative
Landslides	deterministic	deterministic	statistical	susceptibility maps with simple statistical descriptive methods
Meteorological extreme events	no common methodology available	no common methodology available	no common methodology available	no common methodology available
Forest fires	not available	fire behaviour, potential assessment with fire simulation models	fire behaviour, potential assessment with fire simulation models	fire frequency distribution, empirical methods derived from statistical analysis
Floods	deterministic-quantitative	deterministic-quantitative	deterministic-quantitative	deterministic-quantitative

comparison shows that the type of hazard model usually applied depends in a hazard-specific way on the spatial scale. This implies, that, determined by the respective scale, hazards are analysed by either rather similar or rather distinct methods. For example, at a site specific scale volcanoes and landslides are both analysed with deterministic methods while at a regional scale deterministic or statistical approaches are common. At certain scales no models may be currently available such as site specific methods for the investigation of fires (Delmonaco *et al.*, 2006b). Moreover, despite apparent similarities large differences may be inherent in the approaches. For instance, in this overview (Table 2.3) landslides are addressed as components of one rather homogeneous group that are analysed by analogue modelling approaches. Indeed, they show many similarities, especially in comparison to other hazards that are not primarily determined by gravitation such as forest fires, or that are not related to moving material as is the case for hurricanes. A closer examination, however, reveals important differences that have to be accounted for in the analysis method, even between these rather similar process types. For example, Ayala-Carcedo *et al.* (2003, p. 327) mention significant differences in the susceptibility analysis of the run out of rock falls and other types of landslides because (a) the run out differs in mass size, mobility etc., (b) traces of past rock falls are generally absent, especially older ones and (c) at smaller scales "the blocks from rockfall cannot be cartographically displayed". Consequently, differing approaches have to be used to consider the respective characteristics. Another example is the recurrence of debris flows in the same torrent or river that allows an estimation of the return period. In contrast, shallow landslides and other landslide types do not recur since an event alters the slope conditions and makes a repeat of a similar incidence very improbable (vanWesten *et al.*, 2006). This implies that frequency analyses for debris flows and shallow landslides have to be carried out in different ways. A final example for the differences between landslide types relates to their predictability. Rock falls are triggered by earthquakes, freezing-thawing leading to the final destabilisation, heavy rainfall etc. (Dorren, 2003). However, these triggers are not predictable as in the case of earthquakes, or the exact moment of detaching is very difficult to forecast since the triggers are in first place promoters of rock falls leading only after continuous destabilisation to the actual triggering of an event. Therefore, the prediction of rock falls is very difficult. In contrast, in many studies rainfall thresholds are established to link their occurrence to a possible triggering of debris flows or shallow landslides (Remaître *et al.*, 2010). Since rainfalls are additionally mostly well predictable, it is more likely possible to forecast debris flows than rock falls, although still huge difficulties are related to factors such as material availability (Glade, 2005). These significant differences between processes of apparent similarity give a good indication of the degree of dissimilarity between obviously contrasting processes.

The difficulties arising with differing modelling approaches lie in the inherent assumptions, scale, required input, quality of the output and other factors (Marzocchi *et al.*, subm.). All these properties influence the character and the uncertainties of the result. Statistical methods for landslide modelling for example are based on the assumption, that those factors which have led to landslide occurrence in the past will also lead to landslides in the future (Dai *et al.*, 2002). This may also include indirect parameters such as altitude or exposition which actually represent temperature gradients or other meso-climatic conditions. Consequently, the assumption of equal influence of indirect factors in past and future holds only true if the relationship between the indirect factor and the parameter it actually represents remains unchanged. By contrast, physically-based methods are based on physical parameters such as gravitation, friction, viscosity etc. Although they attempt to describe the process itself and involve much more detail, they are still based on certain generalisations and assumptions. Expert assessments, again, are primarily based on the experience of the respective person and criteria that are in most cases not explicitly described (vanWesten *et al.*, 2006). Due to these differences, Delmonaco *et al.* (2006b, p. 60) call for "rigorous methodologies with rigorous data" and Marzocchi *et al.* (subm., p. n.a.) remark that the implicit assumptions and propagated uncertainties "should not be ignored, but they have to be incorporated into the final assessment in a coherent way". However, so far no clear guidelines and few indications are available, as to by which criteria this can be done.

In summary, the most obvious requirement for comparability is the sameness of the final output metrics and the choice of a common scale. To which extent, beyond these aspects, further criteria for the model choice can be effectively adopted to ensure comparability of the results has so far not received much attention. Although differences and difficulties have been mentioned by Delmonaco *et al.* (2006b) and Marzocchi *et al.* (2009) and the need for a coherent approach is clearly stated, general advice is still lacking. Shedding some light at this aspect is one of the aspirations of this study.

2.1.2. Hazard Relations

The existence of *relations* between natural hazards and the potentially resulting consequences is an issue of increasing importance in multi-hazard studies (e.g. Egli, 1996; Tarvainen *et al.*, 2006; dePippo *et al.*, 2008; Bovolo *et al.*, 2009; Marzocchi *et al.*, 2009; Kappes *et al.*, 2010). Thereby, *hazard relations* refers to many different types of influence one hazard may exert on another. However, the multiple kinds of relations as well as the associated terminology are still not clearly structured. Currently, the following phenomena are primarily described and studied in the literature: the triggering of one hazard by another such as river damming by a landslide (Carrasco *et al.*, 2003; Marzocchi *et al.*, 2009); multiple effects of one hazard phenomenon, e.g. volcanic eruptions causing lava flows, ash deposition, lapilli ejection, lahars etc. (Marzocchi, 2007; Zuccaro *et al.*, 2008); the simultaneous impact of several hazards for instance due to the same triggering event as in the case of landsliding, debris flows and floods due to heavy and prolonged rainfalls (Luino, 2005); and the alteration of the disposition of a hazard after the occurrence of another hazard, for instance the impact of a fire on the disposition to debris flows (Cannon & deGraff, 2009). To describe these phenomena a range of terms is in use. Below, a list of commonly applied terms is given:

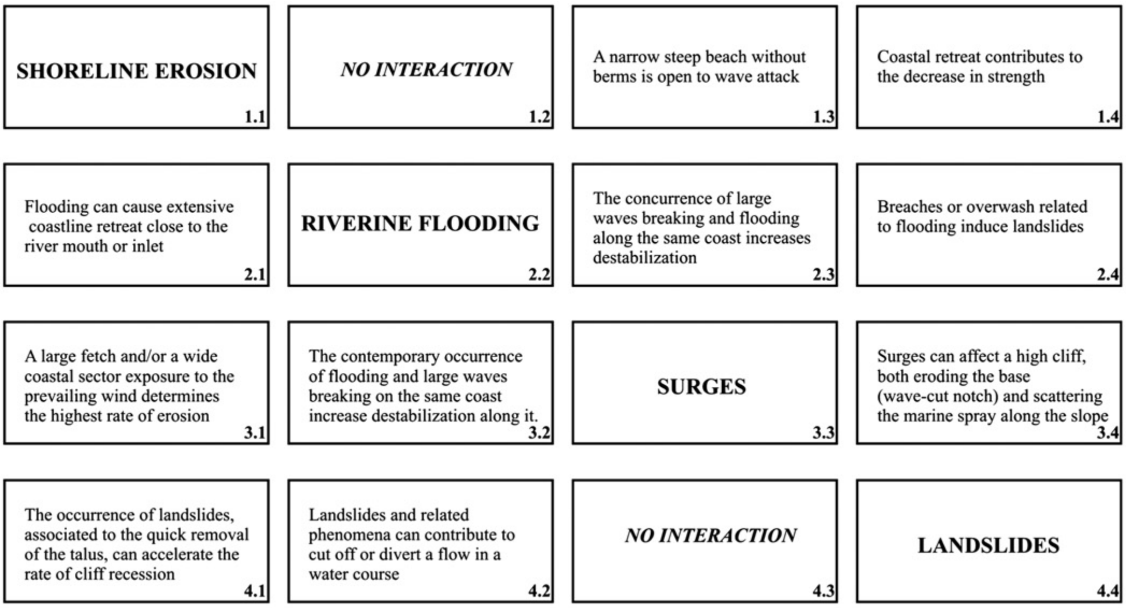
Cascades, cascading effects, cascading failures or cascade events	Delmonaco *et al.* (2006a); Carpignano *et al.* (2009); Zuccaro & Leone (2011); European Commission (2011)
Chains	Shi (2002); Erlingsson (2005), with the difference that at least the cited studies do not only include the natural but also e.g. technological hazards and refer to the resulting disaster. Thus, they are also called *disaster chains.*
Coincidence of hazards in space and time	Tarvainen *et al.* (2006, p. 84)
Coinciding hazards	European Commission (2011)
Compound hazards	Hewitt & Burton (1971); Alexander (2001)
Coupled events	Marzocchi *et al.* (2009)
Cross-hazards effects	Greiving (2006)
Domino effects	Luino (2005); Delmonaco *et al.* (2006a); Perles Roselló & Cantarero prados (2010); vanWesten (2010); European Commission (2011)
Follow-on events	European Commission (2011)
Interactions	Tarvainen *et al.* (2006); dePippo *et al.* (2008); Marzocchi *et al.* (2009); Zuccaro & Leone (2011)
Interconnections	Perles Roselló & Cantarero prados (2010)
Interrelations	Delmonaco *et al.* (2006b); Greiving (2006)
Knock-on effects	European Commission (2011)
Multiple hazard	Hewitt & Burton (1971)
Synergic effects	Tarvainen *et al.* (2006)
Triggering effects	Marzocchi *et al.* (2009)

However, few clear definitions of and delimitations between terms exist. Delmonaco *et al.* (2006a, p. 10) describe the *domino effect* or *cascading failure* as “a failure in a system of interconnected parts, where the service provided depends on the operation of a preceeding part, and the failure of a preceeding part can trigger the failure of successive parts". To name this phenomenon, the EUROPEAN COMMISSION (2011, p. 23) uses the term *coinciding hazards*, "also referred to as follow-on events, knock-on effects, domino effects or cascading events". By contrast, the term *hazard interactions* suggests a mutual relation between hazards although in many studies the authors refer not to reciprocal processes. For instance, TARVAINEN *et al.* (2006) establishes a division into *vice versa interactions* and interactions between two hazards in which only one process influences the other. HEWITT & BURTON (1971) present a broader explanation distinguishing between *compound* and *multiple hazard.* While they characterise *compound hazard* as "several elements acting together above their respective damage threshold–for instance wind, hail, and lightning damage in a severe storm", *multiple hazard* to "elements of quite different kinds coinciding accidentally, or more often, following one another with damaging force–for instance floods in the midst of drought, of hurricane followed by landslides and floods" (HEWITT & BURTON, 1971, p. 30).

The specific methods to deal with related hazards are as diverse as the terms and the phenomena falling into this category. However, according to DELMONACO *et al.* (2006a, p. 10) two general approaches can be distinguished: (a) the identification where different hazards overlap and might be coupled and (b) the investigation of all individual chains of one hazard triggering the next. Although DELMONACO *et al.* (2006a) refer in the first place to *hazard cascades* where one hazard triggers the next, method (a) is also applicable for other kinds of hazard relations which occur in zones of hazard overlap. This includes for example also the simultaneous impact of several hazards or the alteration of the disposition of a hazard after the occurrence of another hazard.

a) The simple identification of hazards' overlap zones and possible interactions is usually carried out by a separate modelling of the single-hazards and a subsequent overlay of the hazards in a GIS software. For the overlapping areas, the potential effect of spatial hazard coincidences has to be determined. For this step, TARVAINEN *et al.* (2006) as well as DEPIPPO *et al.* (2008) propose the use of a matrix as depicted in Figure 2.1. Thereby, DEPIPPO *et al.* identify for instance for overlap of riverine flooding (Figure 2.1 cell 2.2) and landslide hazard (cell 4.4.) the potential of flood-induced landslides with subsequent breaching of the dam (cell 2.4). Additionally, these areas may be prone to a reverse influence of landslides on flooding as well, by means of cut off or flow deviation (cell 2.4). At the identified locations, relations and interactions can then be analysed in more detail and with more sophisticated methods at a local scale.

b) To analyse the potential consequences of cascading effects in more detail, the possible series of events have to be examined. Especially event trees proved useful, although their elaboration is extremely demanding. First, a triggering event is defined and secondly, known possible subsequent incidences are identified and arranged in a tree-structure (EGLI, 1996; MARZOCCHI *et al.*, 2009). Finally probabilities are assigned to the single branches, a



SHORELINE EROSION 1.1	*NO INTERACTION* 1.2	A narrow steep beach without berms is open to wave attack 1.3	Coastal retreat contributes to the decrease in strength 1.4
Flooding can cause extensive coastline retreat close to the river mouth or inlet 2.1	**RIVERINE FLOODING** 2.2	The concurrence of large waves breaking and flooding along the same coast increases destabilization 2.3	Breaches or overwash related to flooding induce landslides 2.4
A large fetch and/or a wide coastal sector exposure to the prevailing wind determines the highest rate of erosion 3.1	The contemporary occurrence of flooding and large waves breaking on the same coast increase destabilization along it. 3.2	**SURGES** 3.3	Surges can affect a high cliff, both eroding the base (wave-cut notch) and scattering the marine spray along the slope 3.4
The occurrence of landslides, associated to the quick removal of the talus, can accelerate the rate of cliff recession 4.1	Landslides and related phenomena can contribute to cut off or divert a flow in a water course 4.2	*NO INTERACTION* 4.3	**LANDSLIDES** 4.4

Figure 2.1.: *Interaction matrix* according to dePippo *et al.* (2008). The processes are located in the diagonal and in the remaining cells the possible interactions are presented. For each cell the hazard situated in this line indicates the possibly influencing and the process of this column the influenced process.

very challenging step that is mostly based on serious assumptions and subjective appraisals (Figure 2.2). However, this method is, due to the immense multitude of possibilities and the lack of information to assess their probabilities, not applicable to examine all potential situations and incidences. Though, for the examination of specific scenarios at a local scale, this approach offers an insight into the potential occurrence of event combinations.
Apart from these two major approaches, in many hazard-pair-specific studies, methods are proposed to account for the specific relations between the two particular processes. Examples are the definition of earthquake intensity thresholds for the triggering of landslides (Harp & Wilson, 1995; Keefer, 2002), the analysis of increased debris flow threat following forest fires (deGraff *et al.*, 2007; deGraff & Ochiai, 2009; Cannon & deGraff, 2009), the identification of torrents potentially blocked by landslides (Costa & Schuster, 1988; Carrasco *et al.*, 2003; Perucca & Esper Angillieri, 2009), the examination of potential outburst of glacial lakes due to ice avalanches or debris flows (Huggel *et al.*, 2003, 2004) or the study of material propagation between soil erosion, rock fall, debris flows, shallow landslides and full-depth avalanches (Wichmann & Becht, 2003; Wichmann *et al.*, 2009).
In summary, a multitude of relations between different hazards exists that influence primarily the manifestation of hazards e.g. due to hazard cascades and the hazard level including frequency and magnitude. Although a multitude of terms and methods is applied to consider these phenomena, clear definitions or general concepts are rarely presented.

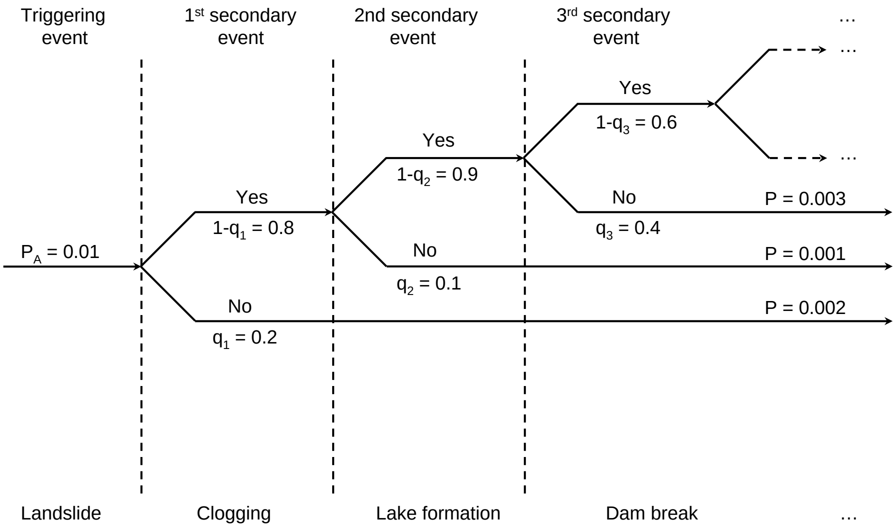


Figure 2.2.: Example of an event tree, translated and modified after Egli (1996) with the probability of the triggering event P_A, the conditional probability q_i of the non-occurrence of the event i and the total probability of the complete path P.

The compilation of current methods for the consideration of multi-hazard relations indicates a strong dependence on the scale as well as on the specific set of hazards involved.

Concluding, the comparability between hazards is a major challenge for the performance of multi-hazard analyses, nevertheless, standardisation techniques already provide a viable solution. Moreover, the consideration of hazard relations is an important issue for multi-hazard analyses. The neglect of this aspect may otherwise lead to the occurrence of unexpected and completely unforeseen effects due to a misjudgement of the actual hazard situation. Multiple approaches exist to take these phenomena into account, but, still no overall concept is available to coherently incorporate them into analysis procedures.

An alternative option to overcome the comparability problem is the performance of a full risk analysis for each individual hazard, and the subsequent comparison of the results. Risks are expressed in hazard-independent metrics such as number of fatalities, persons affected or monetary losses and can therefore be directly compared. For the computation of risks, hazards are related to the vulnerabilities of exposed elements at risk. Thus, after having assessed the hazard, the next step towards a full analysis of multi-hazard risks is the examination of vulnerability. The joint consideration of multiple hazards also leads in the vulnerability context to additional issues and difficulties. In the following section, details on the challenges and currently used solutions are provided, with emphasis on physical vulnerability.

2.2. Physical Vulnerability for Multiple Hazards

The revision of approaches for single-hazard physical vulnerability analyses presented in Papathoma-Köhle *et al.* (2011, A.2) gives an overview of a range of methods in use. However, in a multi-hazard context with the aim of generating comparable single-hazard assessments, a common approach is important to assure the comparability of the single risks. In addition to differing analysis methods, the effect of temporally and spatially overlapping hazards on the vulnerability also poses a considerable challenge. These two issues are presented in detail below.

2.2.1. Availability of Vulnerability Analysis Methods

Due to differences in hazard characteristics not only the methods to determine the hazard level but also those to commonly appraise the vulnerability differ between processes. While for example a variety of methods for earthquake vulnerability and damage assessments are used (Calvi *et al.*, 2006), vulnerability analyses for landslides, coastal erosion and volcanoes emerged much later and are still applied less frequently and are less well-established (Glade, 2003; vanWesten, 2004; Douglas, 2007; Foerster *et al.*, 2009). Also the "goal of assessments is different" since for instance for earthquakes the possible impact of an event is estimated, as earthquakes cannot be predicted or prevented. In contrast, for volcanic or landslide vulnerability assessments evacuation or prevention purposes have priority (Foerster *et al.*, 2009, p. 11). By implication, this affects the straightforwardness of the development and performance of multi-hazard vulnerability analyses and still only a few, especially only a few generic, approaches exist (Kappes *et al.*, subm.b, A.1).
The principal approaches to assess physical vulnerability are curves/functions, matrices/coefficients and index-/indicator-based methods (Foerster *et al.*, 2009). Although all three approaches are already in use in multi-hazard vulnerability analyses, they are not equally applicable for the whole range of hazards. For instance vulnerability curves, also referred to as damage, risk or fragility curves, are based on a large amount of data on damaged buildings collected after hazard events. Hereby, the event intensity is related to the caused damage at a certain type of building and curves are adjusted to the observed intensity-damage combinations (Menoni, 2006). Thus, this is a common approach for extensive hazards such as storms, floods or earthquakes but for very local hazards such as rock falls this method is less frequent used and curves are hardly available (one of the few examples is Borter & Bart, 1999). Though, for analyses that are restricted to extensive hazards, curves are well-applicable (e.g. Grünthal *et al.*, 2006). An example is the software tool HAZUS that offers the analysis of hurricane, earthquake and flood based on vulnerability curves (HAZards U.S., FEMA, 2003, 2007a,b).
In contrast to curves, damage matrices are discrete, or non-continuous, approaches (Foerster *et al.*, 2009). They "express in a matrix the combination of [classified] hazard levels and [stepwise] vulnerability" and are either developed on the basis of observed dam-

ages or, in the case of qualitative matrices, on rough appraisals (Menoni, 2006, p. 40). Therefore, their development is simpler, less data-demanding and more expert appraisal can be integrated (Menoni, 2006; Calvi *et al.*, 2006). For multi-hazard studies they are obviously more applicable since they are available or can be created with less required damage data for many types of hazards (Menoni, 2006).
An important constraint most curves and matrices share is the limitation that they consider only one building characteristic (Papathoma-Köhle *et al.*, 2011, A.2). This refers in most cases to the building type, for instance wooden, masonry, concrete or reinforced (e.g. Keylock & Barbolini, 2001; Büchele *et al.*, 2006). The study of Zezere *et al.* (2008) is an exception with the combined consideration of building type and condition. However, many more properties as for example design, shape or foundation of a structure influence the physical vulnerability of a building. Indicator approaches fill this gap since they consider a range of properties (used as indicators) and combine them to describe or quantify the vulnerability of an element at risk. For instance for the analysis of the building vulnerability, in the study of Puissant *et al.* (2006) the indicators building type, height and function were used and Schneiderbauer & Ehrlich (2006) propose parameters such as building material and age, size and height, location of dwelling, etc. However, in contrast to curves and matrices they are mostly used in a rather qualitative than quantitative way.

For the comparable analysis of vulnerability for multiple hazards, first, one approach has to be chosen to be applied for all processes. Moreover, equivalent criteria have to be used for the creation of curves, the definition of vulnerability matrices or the application of indicator approaches to ensure the comparability between the vulnerabilities towards multiple hazards. Thus, a coherent vulnerability analysis scheme to assure the comparability of the final single-risks is required. However, not only the coherent analysis of multi-hazard vulnerabilities is a challenging issue but also the consideration of effects emerging due to overlapping hazards. This aspect will be illustrated in the next section.

2.2.2. Effects of Related Hazards

The overlapping and relation of hazards does not only influence the threat natural hazards pose, but has also an important impact on the vulnerability. By reviewing the literature, different situations and settings turn out to lead to particular effects. Three types of effects could be distinguished: (a) the exposure of buildings to various hazards, (b) the simultaneous impact of hazards and (c) the sequential occurrence of hazard events in a short period of time and the same area. In contrast, cascading effects only alter the hazard level, but not the vulnerability characteristics. In the following, these three cases are illustrated in detail:
a) The exposure of buildings to various hazards. The building properties contribute differ-

ently to the hazard-specific vulnerabilities of a structure. For instance, large unprotected windows increase the vulnerability for winds but have a less negative effect on earthquakes (Table 2.4). By contrast, the number of storeys is of higher importance with respect to earthquakes and floods then to winds or hail. In zones where buildings are exposed to multiple hazards, the hazard-specific vulnerability has to be considered.

Table 2.4.: Relative contribution of building characteristics to the hazard-specific vulnerability after Middelmann & Granger (2000). (Note: the higher the number of * the higher the contribution to the building vulnerability).

Characteristic	**Flood**	**Wind**	**Hail**	**Fire**	**Earthqu.**
Building age	***	*****	**	*****	*****
Floor height or vert. regularity	*****	*		****	*****
Wall material	***	***	*****	****	****
Roof material		****	*****	****	***
Roof pitch		****	***	*	
Large unprotected windows	**	*****	****	*****	**
Unlined eaves		***		*****	
Number of stories	****	**		*	*****
Plan regularity	**	**		***	*****
Topography	*****	****		****	***

b) The alteration of the building vulnerability due to the simultaneous impact of two or more threats. This refers for example to an earthquake impact on a snow or volcanic ash covered house (e.g. Lee & Rosowsky, 2006; Zuccaro *et al.*, 2008). Due to the load on the roof, the structural properties of the building are modified and the earthquake exerts a modified effect. Thus, a separate consideration or a summing up of vulnerabilities cannot account for these implications.

c) The sequential impact. This relates to the cumulative impact of multiple hazards, so-called hazard sequences (Zuccaro *et al.*, 2008). Shortly after an impact, for example of an earthquake, the same structure is hit by a landslide triggered by the ground movement. Since the structure is already affected by the earthquake, the consequence of the landslide may differ from the effect it would have caused before the earthquake. Again, by summing of vulnerabilities or potential damages this cannot be accounted for.

The first step to deal with the effect of overlapping hazards is the identification of all processes that are known to pose a threat to a certain building. The second step is to determine which measures can be taken in each of the three situations.

a) Due to the hazard-specific contribution of building characteristics to the vulnerability of a structure towards each of the processes, buildings located in zones of overlapping hazards have to be carefully designed. This refers primarily to the identification of synergistic and especially contradictory properties. For example, heavy structures better resist to wind while light structures are favourable in the case of earthquakes (GIBBS, 2003; HOLUB & HÜBL, 2008). Nevertheless, for both, winds and earthquakes, symmetrical compact shapes proved more convenient. That implies, in zones of overlapping threats, multi-hazard designs and suitable building codes have to be developed, avoiding contradictions and seeking for synergies (e.g. GIBBS, 2003). This applies as well for the construction of protection measures such as reinforcements. The vulnerability reduction towards one hazard should not lead to an increase towards another hazard.

b) Since the consequences of simultaneous impacts depend on both hazards, LEE & ROSOWSKY (2006) propose the development and use of fragility surfaces instead of curves. Therefore, the loads of the two hazards at the x- and y-axis are plotted against the resulting vulnerability on the z-axis as displayed in Figure 2.3. However, the development of fragility surfaces is demanding and damage information for the development of such mathematical functions is difficult to obtain. Nevertheless, an alternative option is their elaboration on the basis of physical calculations (LEE & ROSOWSKY, 2006).

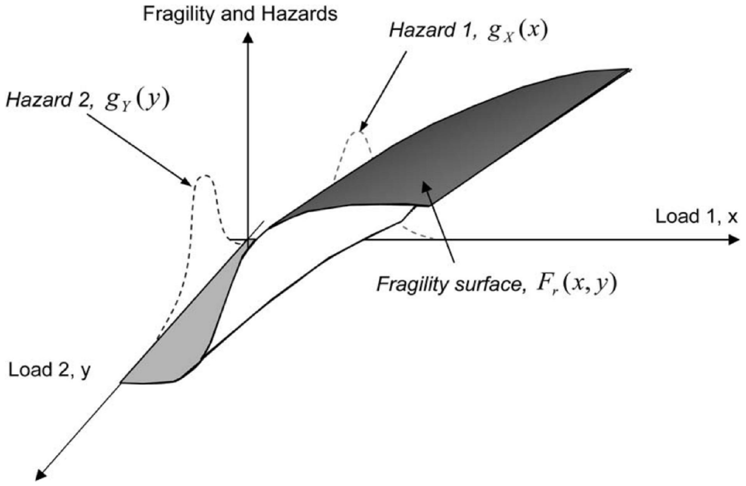


Figure 2.3.: Fragility surface after LEE & ROSOWSKY (2006).

c) For the case of the sequential impact of hazards, ZUCCARO *et al.* (2008, p. 430) recommend a dynamical updating of “the building inventory and the vulnerability functions” during the event sequence. Hereby, the situation is treated as “progressive deterioration of the building’s resistance characteristics that is essentially represented by the damage level” (ZUCCARO *et al.*, 2008, p. 420).

In conclusion, the consideration of the consequences of hazard overlapping on multi-hazard vulnerabilities is, in the framework of vulnerability analyses, in the early stages of development. Although, in the engineering field multi-hazard design is already an issue, in general the presented approaches to deal with overlapping are pioneer works. Nevertheless, while the exposure to multiple hazards is gaining increasing attention, hardly any study is available that would cover the topic of consequences of sequential impacts.

2.3. Multi-Hazard Risk

Being a combination of the analysis of hazard and vulnerability of elements at risk, multi-hazard risk studies face most of the previously identified challenges. This refers primarily to the difficulty to assure the comparability of the analysis results, be it at hazard, vulnerability or finally at risk level. Thus, an overall scheme for hazard and vulnerability analyses and their combination to risk is very important. However, in contrast to multi-hazard analyses, multi-hazard risk analyses exhibit the major advantage that they are not quantified in hazard-specific units but in damage- and loss-specific measures (except for qualitative and semi-quantitative approaches). This facilitates the comparison and standardisation by means of classification or index-creation is not necessary. Thus, according to Marzocchi *et al.* (subm.) and as coincided during the workshop “Multi-Hazard Risks - status quo and future challenges”[1] minimum prerequisite for comparability is the definition of common output metrics and the scale at which the modelling is carried out. Marzocchi *et al.* (subm.) refer to the scale term as the *space-time window* that has to be defined for the performance of a multi-hazard risk analysis. Thereby, the spatial scale refers to the size of the study area and the required degree of detail. The temporal resolution relates to the considered time window such as several days for the planning and performance of emergency activities, or weeks, years, decades or even centuries for land use planning (Marzocchi *et al.*, subm.). The risk metric corresponds to the type of risk to be examined as for instance economic, social, ecological, direct or indirect risks. Thereby, Marzocchi *et al.* (subm.) refer to quantitative metrics but, according to Kappes *et al.* (subm.b, A.1) qualitative and semi-quantitative approaches are also in use. In the following, the three types of approaches (qualitative, semi-quantitative and quantitative) are presented briefly and several examples are given.

In the case of qualitative multi-hazard risk analyses, usually the classified hazards and vulnerabilities are combined to risk according to a predefined scheme as for example illustrated in Figure 2.4 (e.g. Granger *et al.*, 1999; Sperling *et al.*, 2007; BBK, 2010). A basic requirement for the comparability of the final risk classes is the equivalence of all single-hazard classes and the compatibility with the vulnerability classes, which means an overall analysis scheme is needed. This also applies for index-based semi-quantitative methods. Here, risk is not the result of a classification step as in the case of the combination of hazards and vulnerabilities for qualitative analyses, but of a computation process.

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[1] December 20-21, University of Vienna, Vienna, Austria

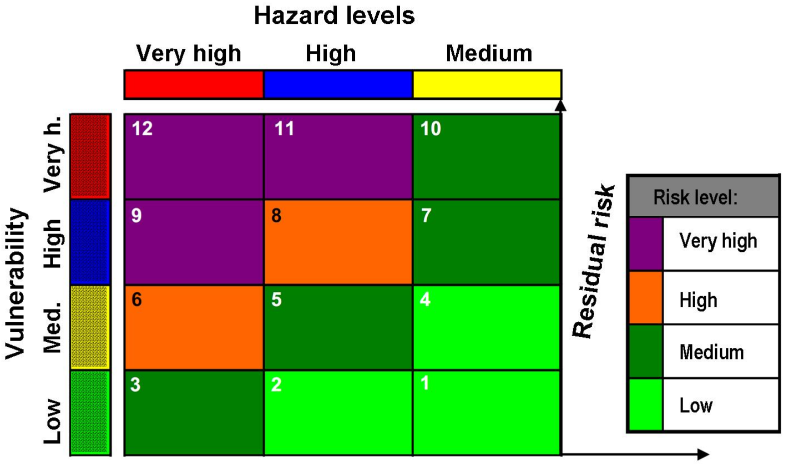

Figure 2.4.: Matrix for the combination of hazard and vulnerability to risk (translated, following SPERLING *et al.*, 2007)

Examples of index-based multi-hazard risk analysis schemes are provided by GREIVING *et al.* (2006) GREIVING (2006) and DILLEY *et al.* (2005). For instance, in the analysis concept proposed by GREIVING *et al.* (2006) the previously computed hazard and vulnerability indices are equally-weighted and summed to the *integrated risk*. For more detail refer to KAPPES *et al.* (subm.b, A.1).

In contrast to the previous two approaches, quantitative multi-hazard risk analyses provide information on potential damages or losses (e.g. VANWESTEN, 2002; GRÜNTHAL *et al.*, 2006; GARCIN *et al.*, 2008; BRÜNDL, 2008; MARZOCCHI *et al.*, 2009; SCHMIDT *et al.*, 2011; MARZOCCHI *et al.*, subm.). Thereby, a large multitude of different metrics and formula based on differing parameters are in use. For instance, BELL & GLADE (2004a,b) calculate the annual risk of loss of life in buildings and the economic risk to buildings and infrastructure while BRÜNDL (2008) analyse the collective and individual risks. GRÜNTHAL *et al.* (2006) and VANWESTEN *et al.* (2002) also calculate economic damages. However, they are not restricted to single scenarios and the respective risk but assess the potential damages related to the annual exceedance probabilities of the events by means of curves (e.g. Figure 2.5). Therefore, the annual exceedance probability of multiple scenarios with different return periods is calculated and plotted against the expected damages. This representation form offers the possibility to better account for hazard differences concerning their magnitude-frequency characteristics. For instance, while at higher annual exceedance probabilities floods and storms pose a higher economic risk, earthquake events may lead to much higher potential damages at lower exceedance probabilities due to this high magnitude (Figure 2.5). Furthermore, the area under the curve "represents the total [expected] damage for the specific type of hazard" (VANWESTEN *et al.*, 2002, p. 16). By combining all single-hazard risk curves VANWESTEN *et al.* derive the total risk curve "which represents the annual expected losses to buildings and contents of buildings for the various types of

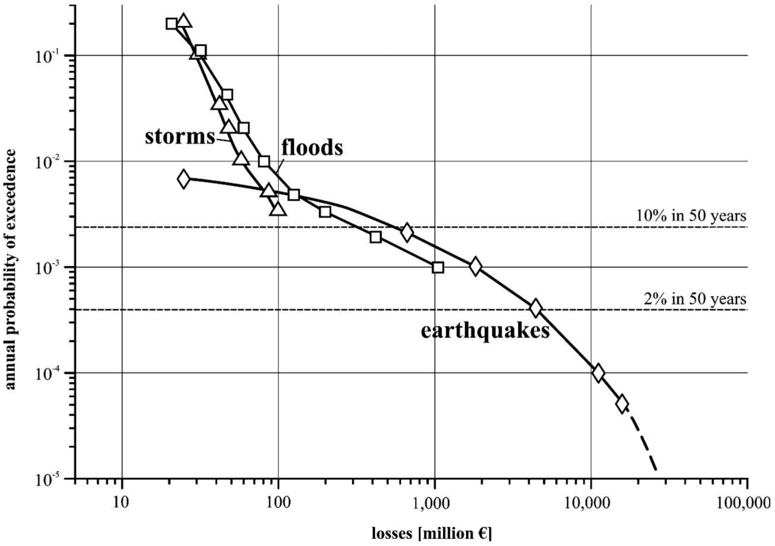

Figure 2.5.: Risk curves showing the "total direct monetary losses for buildings and contents in the sectors private housing, commerce and industry in Cologne" with respect to their annual exceedance probability (GRÜNTHAL *et al.*, 2006, p. 38).

natural hazards" (VANWESTEN *et al.*, 2002, p. 16).

All these distinct types of risks that are characterised or quantified and the differing approaches used therefor indicate that although no difficulties emerge in their comparison due to hazard-specific metrics, an overall analysis scheme is still necessary to assure the comparability of the results. This refers first to metric and scale, but also to the approach applied and the parameters considered. Furthermore, all assumptions and uncertainties that are propagated from the hazard and vulnerability analyses pose an important challenge for the design of multi-risk analysis schemes (MARZOCCHI *et al.*, subm.). Due to the contrast between modelling approaches the quality and uncertainties of the modelling results differs between single-hazard risks. However, it is difficult to consider these contrasts *rigorously* as demanded by DELMONACO *et al.* (2006b). Therefore they are mostly neglected so far although at least in the interpretation of the results the attempt should be made to consider these aspects.

2.4. Practical Challenges

Apart from the previously explained aspects which are directly related to the three steps of risk analyses, three additional challenges arise: the high data requirement in multi-hazard risk procedures, the multitude of steps the whole process consists of, and the difficulty to visualise the multi-dimensional output.

2.4.1. High Data Requirement

The consideration of different hazard types and elements at risk leads to the requirement of “a large amount of spatial and attribute data [...] to carry out a comprehensive multi-hazard risk assessment” (vanWesten, 2010, p. 206, see also Reese *et al.*, 2007b). The availability of multi-hazard inventories containing spatio-temporal information on past events poses the greatest problem. The multitude of challenges occurring in inventory-based single-hazard studies gives a good indication of the difficulties multi-hazard inventories face. For example, for landslides vanWesten *et al.* (2006, p. 174) mention that “[t]here are few places in the world that have fairly complete historical [...] records for the past 50-100 years”. Despite the fact that Italy is one of the few countries in which landslide “inventory databases have been made in a consistent manner” these databases suffer from several shortcomings (Blahut *et al.*, 2010, p. 37). For multiple records the exact date of occurrence is missing and events are depicted as points but no information is attached whether this refers to the scarp, transport or deposition area. Another critical aspect of landslide inventories containing different landslide types is the identification and naming of the event types according to an agreed classification. In the context of rock fall inventories, Chau *et al.* (2003) comment on the problem that many events are unreported or even unnoticed and inventories are thus incomplete. Moreover, Maggioni (2004) made the observation that the quality of the records depends on multiple circumstances. The records of those snow avalanche events having occurred far from settlements, in stormy periods or at night exhibit a lower quality and lack precise and complete information. In contrast, for other hazard types the information on past events is much better. This refers especially to processes that can be monitored continuously such as floods with discharge or earthquakes with seismic measurements (Bautista & Bautista, 2004; Glade, 2006). This indicates already that the methods by which information on past events is collected play an important role. For the compilation or completion of inventories several approaches can be used: (multi-temporal) aerial-photo and satellite image interpretation, field surveys, interviews, maps, reports and instrument monitoring (vanWesten, 2010). The applicability of each method is strongly dependent on the hazard characteristics as outlined in Table 2.5. For instance, Ayala-Carcedo *et al.* (2003, p. 327) state that in contrast to other landslide types, “trace[s] of a block movement[s], specially the older ones are generally absent”. Likewise, snow avalanches leave traces that vanish shortly after the event, latest during the next snow melt. However, “sharp trim lines in treed areas, new tree growth, and different species” give indirect indications on past events, visible in the field or on aerial photos (Mc Clung *et al.*, 1989, p. 122). In contrast, shallow and deep-seated landslides can directly be mapped in the field and in aerial photos (Thiery *et al.*, 2003). Digital surface models from airborne laser-scanning allow the recognition of landslide forms even below forest cover (Petschko *et al.*, 2010). By contrast, in the case of floods remote sensing is, if not during the flood itself, not always helpful (Table 2.5).

Table 2.5.: Methods for the compilation and completion of inventories for several hazards based on information from THIERY *et al.* (2003); BARRIENDOS *et al.* (2003); CHAU *et al.* (2003); BAUTISTA & BAUTISTA (2004); VANWESTEN *et al.* (2006); THIERY *et al.* (2007); APEL *et al.* (2009). $***$ indicates well applicability and wide use of the method, $**$ medium and $*$ rather seldom/no use and low/no usefulness. Documentary sources refer to documents from administrative, religious, private or notaries' archives.

	River floods	**Rock falls**	**Earthquakes**	**Shallow / deep-seated landslides**
Aerial photos & satellite imagery	$**$ During & shortly after events	$**$ Source & accumulation area	$*$ Damages directly after an event	$***$ Esp. photo series or in combination with DEMs
Field survey	$**$ Especially artificial marks e.g. at buildings or timely close to events	$**$ Direct observation, lichenometry, etc.	$*$ Only timely-close to an event, mapping on basis of damages	$***$ Mapping of the phenomenon itself
Documentary sources	$***$ Often effect on settlements, rather well documented	$*$ Less often effect on settlements, not that well documented	$***$ Often effect on settlements, thus rather well documented	$**$ Less frequently effect on settlements, only small proportion is documented
Instrumental monitoring	$***$ Discharge measurements	$*$ Not established	$***$ Seismograph	$**$ Extensiometers etc. to measure movement rates

Based on the difficulties presented in this section it becomes clear that multi-hazard inventories with comparable quality for all hazards are extremely difficult to obtain. Nevertheless, detailed inventories are a prerequisite for the performance of magnitude-frequency calculations and serve as a basis for the calibration and validation of hazard models. Different qualities of inventories may therefore lead to differing levels of quality and uncertainty of single-hazard analysis results.

2.4.2. Multi-Part Procedure

The performance of a multi-hazard risk analysis is composed of many single steps. This implies the hazard, vulnerability and risk analysis of each process taken into account and additionally all preparative and intermediate steps. Therefore, the modelling procedure is time-consuming due to the multitude of single steps to be performed by the modeller, error-prone because of potential mistakes in the conduct of all these steps, parameter entry and file naming, and the updating or analysis of scenarios is an unwieldy operation.

An approach to facilitate the performance of multi-hazard risk analyses is the automation of the whole sequence of single steps in software tools (Bell *et al.*, 2007). Thereby, the user is guided through the analysis process while standard steps such as format changes, calculation of derivatives, classifications etc. are carried out automatically. Moreover, such software tools enable not only fast analysis completion but also provide a better comparability of hazard and risk levels in space and time. This means that the results of different study areas as well as the outcome of repeated analyses, months or years later, can be better compared since the same analysis approach is used, and enables prioritisation of certain areas or identification of trends. The currently most known software tools are HAZUS for the USA (FEMA, 2008), RiskScape in New Zealand (Reese *et al.*, 2007a) and CAPRA in Central America (Central American Probabilistic Risk Assessment CEPREDENAC *et al.*, 2011). HAZUS offers hurricane, earthquake and flood hazard and risk modeling, RiskScape currently facilitates the analysis of volcanic ashfalls, floods, tsunamis, landslides, storms and earthquakes and CAPRA provides the examination of hurricanes, heavy rainfall, landslides, floods, earthquakes, tsunamis and volcanic hazards.

2.4.3. Visualisation of the Multi-Dimensional Output

The final challenge presented here relates to the large information content of the outcome of multi-hazard risk analyses. This affects the communication of the results and especially the visualisation in maps, since only a certain amount of information can be shown at once (Fuchs, 2009b; Kunz & Hurni, 2011a). Thus, the information content has to be distributed to multiple maps presenting different aspects of the multi-hazard risk analysis result. Several map types and approaches to communicate the information are currently in use (Kappes *et al.*, subm.b, see Appendix A.1):

Single variable visualisation: The depiction of each single-hazard, vulnerability or risk separately. However, this is in many cases only the first step of the exposition of analysis results followed by further maps presenting combined information (as e.g. in Odeh Engineers, Inc, 2001; Bell, 2002; Dilley *et al.*, 2005). The major strength of this presentation form is the clear and in depth visualisation of one parameter. Hereby, the map reader can identify the patterns of each hazard separately and in detail.

Visualisation of a joint variable: Depiction of the sum, product, maximum value etc. of hazards, vulnerabilities or risks in a so-called *synoptic map* (Kunz & Hurni, 2011a). This display form does not pose challenges concerning the visualisation since, as in the previous display format, only one parameter is shown although information on a multitude of hazards or risks is visualised jointly. However, details on single hazards, vulnerabilities or risks are lost in favour of the illustration of combined patterns. Examples are Bell (2002) presenting the individual risk to life, object risk to life and the economic risk resulting from multiple hazards by summing single risks up, or Dilley *et al.* (2005) showing the number of overlapping hazards.

Simultaneous visualisation of several variables: The advantage of this approach is that it allows to identify spatial relations between different parameters while also presenting information on each single one. However, it is important to avoid an overload of the maps with too much information since this leads to confusion and reduces the readability (Kunz & Hurni, 2011a). Overlaps aggravate this challenge since either one parameter is overlain by the other and thus not visible or with semi-transparency both are visible but details are more difficult to recognise. If many processes are considered it is not possible to visualise all of them in one map and they have to be separated into groups as for example in the study of UN-ISDR (2009a) where weather-related hazards (floods, tropical cyclones and droughts) and tectonic hazards (tsunamis, landslides and earthquakes) were presented in two separate maps. The BGR & DESDM (2009) propose another option by restricting the hazard information given for each single process to the high-hazard class. Consequently, the map offers information on the zones which "deserve most attention for mitigation efforts" (BGR & DESDM, 2009, p. 46) but which may miss the indication of the overall area threatened by significant hazard.

Web-mapping applications: In the era of GIS and web-mapping applications, digital, flexible and user-defined visualisations offer an interesting alternative to static analogue maps (e.g. Müller *et al.*, 2006; Salvati *et al.*, 2009; Frigerio *et al.*, 2010b; Frigerio & vanWesten, 2010; Kunz & Hurni, 2011b). They offer an interactive exploration of the information to the user by means of options such as zooming in/out, visibility of layers on/off, queries etc. A central issue is an adequate interface to guide the user, provide clear presentation and prevent misinterpretations (Kunz & Hurni, 2008, 2011b). If this is assured, interactive tools facilitate the understanding of the complex information by splitting it up and enabling the user to compose a map according to the specific needs.

Obviously, multiple types of map or visualisation techniques exist which can aid the clearer communication of multi-hazard risk analysis results. Their suitability depends on the precise objective and aspect to be communicated and who they are communicating to. Consequently, either the single hazard patterns or the overall hazard or risk level have to be transmitted, analogue maps in reports and articles or broad distribution of the results with web-mapping tools prove suitable.

2.5. In Conclusion: The Major Multi-Hazard Issues

Evidently, the performance of multi-hazard risk analyses is not a simple operation. Apart from the data- and time-consuming conduction of many single-hazard risk studies that requires know-how from different disciplines, many further aspects have to be considered. One important source of difficulties is the contrast in hazard characteristics. Hazards differ with respect to their properties such as time of onset, duration, physical properties, extent, parameter of influence on the built environment and humans. As a result, also modelling approaches adjusted to the hazard specifics contrast strongly. At the multi-hazard analysis level this leads to problems of comparing modelling results, not only due to differing impact indicators but also due to differing inherent assumptions and uncertainties. Moreover, the relations between hazards lead to effects on the hazard manifestation and hazard level. Although multiple methods and approaches exist to take this aspect into account, still no overall concept is available to coherently consider and incorporate them into analysis procedures. An option to overcome the problem of single-hazard comparability due to differing parameters of influence, i.e. differing metrics of the modelling result, is the performance of full risk analyses. Since risks are expressed in hazard-independent metrics such as monetary damages or number of fatalities, single-hazard risks are comparable without standardisation. The next step towards risk calculation is the analysis of the vulnerability of elements at risk. Thereby, the choice of a vulnerability analysis method applicable for all hazards is difficult since the approaches are not equally applicable for different hazards. Thus, an approach has to be selected that can be applied for all considered processes. In the context of multi-hazard and vulnerability analyses, the relation between hazards poses an additional difficulty. This refers not only to the triggering of one hazard by another or other types of influences between hazards but also to the simultaneous or subsequent impact on elements at risk. Approaches to consider these phenomena are still in the early stages of development. The final step of a multi-hazard risk analysis is the combination of hazards and vulnerabilities of elements at risk towards risk. To ensure a smooth process, the previous steps have to be carried out according to a coherent analysis scheme. However, this refers not only to the choice of methods producing compatible outputs with respect to the metrics but also to their suitability to produce results with similar inherent assumptions and uncertainties. Finally, the clear visualisation of the multi-dimensional content of the output is challenging since many aspects may be of interest and have to be communicated.

The most important aspects are summarised in the following seven *major multi-hazard issues*:

1. High data requirements give rise to difficulties in the practicability of multi-hazard analyses.
2. Scale differences between hazards and hazard models lead to the necessity of the definition of a common analysis scale that is moreover relevant to the output required.
3. Differing model principles, assumptions and uncertainties influence the character of the modelling results.
4. Hazard relations alter the actual hazard level and lead to very particular phenomena as hazard cascades or the like and exert influence on the vulnerability of elements at risk.
5. Units for quantifying hazards differ and also at the risk level several different metrics are at choice.
6. Multi-hazard risk analyses consist of many steps. Therefore, their performance is time-consuming, error-prone and unwieldy.
7. The visualisation of the multi-dimensional multi-hazard risk information is a challenge.

These *major multi-hazard issues* give a context to the further course of the methodological, technical and practical investigations presented in this study.

3. Meeting the Challenges: Development of a Conceptual Approach and Software Implementation

The central objectives of this study are the elaboration of a coherent GIS-based multi-hazard risk analysis and a visualisation scheme as well as their subsequent automation in a modelling and a visualisation tool. Thereby, the knowledge about aspects and challenges emerging in the multi-hazard context and the current approaches to solutions gained in the review are to be taken into consideration. In this process, a focus is on addressing and discussing of the previously identified *multi-hazard issues* and, where reasonable and possible, the integration of adjusted solutions into the concepts and software implementations. In this chapter, the concept development is presented (section 3.1), followed by an explanation of the elaboration of the software solutions named MultiRISK Modelling and MultiRISK Visualisation Tool forming together the MultiRISK Platform (section 3.2).

3.1. Concept Development

In the previous chapter, the need for overall analysis schemes, be it for multi-hazard, vulnerability or risk modelling, has been highlighted several times. Thereby, the determination of the spatial scale is a fundamental step in the development of a multi-hazard risk analysis scheme (cf. BORTER, 1999; MARZOCCHI *et al.*, subm.). Moreover, the scale is one of the seven *multi-hazard issues* determined previously. The choice of the scale depends primarily on the objectives of the study (e.g. for the national prioritisation of funds, municipal spatial planning or the construction of local structural mitigation measures) but is also related to the data availability. Since the data requirement is, especially in a multi-hazard context, an important difficulty and another *multi-hazard issue* to be explicitly considered, a preferably efficient approach is advisable. CASTELLANOS ABELLA (2008, p. 36) recommends for data-scarce cases a hierarchical, i.e. a top-down or *from top to bottom* approach because it "seems to be more economic" since "only areas detected at certain levels are studied in detail at lower levels". The *Top-down approach* refers to a multi-step method starting with rough and large scale analyses on the basis of which zones of interest are identified. For these zones of interest more local, detailed and sophisticated investigations are performed. For example, CASTELLANOS ABELLA (2008) distinguished for his multi-scale landslide risk assessment in Cuba between the national (1:1,000,000), regional (1:250,000), provincial (1:100,000), municipal (1:50,000), local (1:25,000) and site investigation level (1:10,000-1:1,000). This classification is strongly related to the management and political structure of Cuba and the information required for risk management at each level. At the province and municipal level, for instance, assessments enable the identification of "troublesome areas" for subsequent local or even geotechnical analyses (Castellanos Abella, 2008, p. 38). In the Swiss guidelines a multi-scale approach is proposed as well although they different levels are primarily defined according to the degree of detail with which the analysis is carried out without defining a specific scale (Borter, 1999): in a stage 1 analysis, areas with *protection deficits* are identified. This refers to zones in which the "maximum permissible intensity of the hazardous process and its recurrence interval" are exceeded (Borter, 1999, p. 8). In stage 2 studies, risks for spatial spatial elements identified in the first step are analysed, however, risks can also be directly examined in stage 2 level of detail. In stage 3, again, risks of individual objects determined in stage 2 may be specified, even though directly stage 3 analyses can be carried out as well.

This method of determining hotspots and analysing them in detail accommodates the multi-hazard topic in particular because the hazard situation due to a single hazard might be relatively clear from records and experience of past events, and focusing on *empirical hotspots* may be possible. Thus, torrents prone to flash floods and debris flows are often well-known, annually certain snow avalanche tracks reactivate and the zone potentially threatened by river floods can be narrowed down to the valley bottom. However, in a multi-hazard setting the distribution of all single- as well as the overall multi-hazard is much less obvious and mostly more widely spread over the whole area under consideration. In particular zones of overlapping hazards are difficult to locate without specific analyses. A first, rather general study can close this gap and support the determination of multi-hazard hotspots.

Based on the previous considerations, a top-down approach was adopted for this study. For the beginning this shall refer to two levels: a regional scale which is, in contrast to the terminology of Castellanos Abella (2008), between 1:10,000 and 1:50,000, and a local scale of >1:10,000. Thereby, the regional analysis is designed to serve for the identification of zones of potential risk and possible hazard relations to enable detailed local studies at these sites. In the present work, the elaboration of such a multi-scale multi-hazard analysis scheme is initiated with the development of the regional scale concept. The elaboration of a local analysis concept goes beyond the scope of this thesis although the function of this analysis level is already outlined here. In accordance with the thematic background of the Mountain Risks project[1] in the framework of which this work has been carried out, a set of five typical mountain hazards was chosen (cf. Stötter *et al.*, 1999): debris flows, rock

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[1] http://mountain-risks.eu, contract MCRTN03598

falls, shallow landslides, snow avalanches and river floods. The five processes are shortly defined below, for more detailed definitions refer to Papathoma-Köhle *et al.* (2011, A.2):

- *Debris flows* can be described as “masses of poorly sorted sediment, agitated and saturated with water [that] surge down slopes in response to gravitational attraction” and are triggered by water from rain fall and snow melt (Iverson, 1997, p. 245).
- *Rock falls* “start with the detachment of rocks from bedrock slopes” that are promoted and/or triggered by processes such as weathering, rainfall, frost shattering and seismic activity (Dorren, 2003, p. 70). After the detachment the rocks move downhill in freefall, “bouncing on the slope surface or rolling” (Dorren, 2003, p. 70).
- *Shallow landslides* are “slope failure[s] within the soil mantle or at the contact with the impermeable boundary below. The detached mass then slides downslope” (Borga *et al.*, 1997, p. 81). Principal triggers are rainfalls, snow melt and earthquakes (Borga *et al.*, 1997; Chang *et al.*, 2007; Remaître *et al.*, 2010).
- *Snow avalanches* are fast-moving mass movements of snow that can contain rocks, soil, vegetation or ice (Bründl *et al.*, 2010). According to the release, two types of avalanches can be distinguished: loose and slab avalanches (McClung & Schaerer, 1993). Natural triggers include the overload or internal weakening of the snowpack as well as earthquakes, while also humans or explosives may initiate the movement of avalanches (Bründl *et al.*, 2010).
- *River floods* can be described as the inundation of areas outside of the normal confines of the water course and are caused by high intensity and/or prolongued precipitations, snow melt or blockage of the flow (Boukalova & Heller, 2005; Jonkman & Kelman, 2005).

The integration of additional hazards and the implementation of further, smaller scales as the provincial or national scale proposed by Castellanos Abella (2008) is to be done in the future and in accordance with user needs. Thereby, this study can serve as a first step towards discussing the specific requirements of stakeholders.

For a regional analysis with the objective of identifying hotspots it is not necessary to carry out full-hazard and risk modelling. Instead susceptibility and exposure analyses shall be sufficient for this purpose (Borter, 1999; Fuchs *et al.*, 2001). This is accompanied by the advantage of far lower data requirements and thus much better applicability. Especially in the multi-hazard context in which extensive inventories for reliable assessments of magnitude-frequency relationships are rare, the practicalness of a regional analysis depends strongly on this aspect. Consequently, at this scale the performance of a vulnerability analysis is not necessary. However, vulnerability analyses also pose a considerable challenge in the multi-hazard context and therefore this topic is conceptually approached as well, but separately from the multi-hazard exposure analysis. This implies that the vulnerability analysis concept is not integrated into the exposure analysis and not incorporated into the MultiRISK Modelling Tool, but is presented separately as a first step towards a more local scale analysis.

The multi-hazard exposure analysis scheme to be elaborated here is composed of hazard modelling (subsection 3.1.1) extended by consideration of the consequences of related hazards (subsection 3.1.2). A validation step is performed on the hazard modelling to enable the evaluation and comparison of hazard model qualities (subsection 3.1.3). Subsequently, the approach to exposure analyses is introduced (subsection 3.1.4). The development of hazard-specific multi-hazard vulnerability analyses is then outlined (subsection 3.1.5). This represents a step towards a more local analysis and does therefore not form part of the exposure analysis. Finally, the development of a visualisation scheme is presented in order to display the multi-dimensional analysis results (subsection 3.1.6).

3.1.1. Hazard Modelling

Having defined the scale of the modelling, the next step in the development of a multi-hazard modelling scheme is the choice of the model set. In first place, this choice has to be adapted to the scale at which the analysis is carried out, in this case the regional scale. Considering the challenges identified in the previous section, two additional aspects, (a) the model principles and assumptions, and (b) the required data, are of high importance for the model choice.

a) The model principles: The need for comparability of the modelling results is the central issue in a multi-hazard analysis. However, as identified in the previous chapter, hazard characteristics and consequently the methods and approaches used for their analysis and computation differ. This includes the assumptions and principles behind the different methods used in setting up the models. Assuming that models following the same or similar principles and assumptions produce better comparable results, in this respect similar methods are selected. In a regional context, empirical models proved useful (Kappes *et al.*, 2011, A.3). In contrast to statistical models empirical models are transferable, "usable without the high data needs for calibration [that] deterministic models have" and therefore meet the requirements of a regional scale analysis (Kappes *et al.*, 2011, p. 628, A.3). Consequently, empirical models are to be chosen in the present study wherever possible.

b) The required input data: The data input for spatial models consists of two types, spatial data and information required for the model calibration. Spatial data refers to area-wide information on environmental parameters such as topography, land cover, geology or soils. The calibration of models is usually based on hazard inventories providing information on past events, laboratory analyses, field measurements etc. However, to apply an analysis scheme on a smaller scale, “it is important to use models which require only few input data that are more or less easy to obtain” (WICHMANN *et al.*, 2009, p. 72). Therefore, the required spatial input should focus on topography, land cover, geology and river courses, since this information is of high importance in GIS-based models and is widely available. Concerning the information needed for the model calibration or parameterisation, flexible methods have to be chosen. Since comprehensive multi-hazard inventories are difficult to obtain, models exclusively based on detailed inventories or field and laboratory studies are not suitable. Instead, models should be chosen that are based on limited input data that can be supplemented with expert knowledge or based on previous studies carried out in comparable cases. In this way the applicability of the model set can be assured, even in data-scarce settings.

The final choice of hazard models can, apart from the previously mentioned criteria, basically be considered as coincidental and the models are exchangeable by others fulfilling the required characteristics. However, the replacement of models obviously not suitable for a certain study site has always to be contemplated.

3.1.2. Consideration of Related Hazards

In the previous chapter, two main branches of influences exerted by related hazards could be distinguished: (a) effects on hazard manifestation and hazard level and (b) the implications for vulnerability. However, as became apparent in the review on current approaches, the terminology is not clearly defined and only few concepts exist to account for phenomena arising with related hazards. In this study the attempt is made to develop conceptual approaches for both branches and provide an overarching approach for a classification, characterisation and representation of the different aspects emerging from hazard relations. Thereby, the focus is on establishing a general overview of the emerging issues, and indicating how hazard relations can be considered in multi-hazard studies. The development approaches of these two concepts are outlined below.

a) For the characterisation and representation of modified hazard manifestations and hazard levels, two well-known conceptual models are employed (cf. KAPPES *et al.*, 2010, A.5): first, the systems theory as outlined by CHORLEY & KENNEDY (1971, based on von Bertalanffy, 1956) and secondly, the disposition and triggering model as outlined in ZIMMERMANN *et al.* (1997, dating back to SCHUMM, 1979) and KIENHOLZ *et al.* (2004). While the first concept is used to elucidate the provenance of hazard relations, the second concept supports the classification and description of hazard relations and facilitates their consideration in hazard analysis procedures. After a presentation of both conceptual models, their connection is outlined below.

The systems theory according to Chorley & Kennedy (1971, p. 1 et seq.)[2] describes a system as consisting of several parts which "exhibit discernible relationships with one another and operate together as a complex whole, according to some observed pattern". From a hazard/risk perspective "[n]atural processes [form part] of systems (ecosystems, geosystems, etc.) and only certain characteristics which possibly pose a threat to elements at risk convert them into hazards" (p. 351 Kappes *et al.*, 2010, A.5). For the investigation and modelling of a certain hazard, a kind of *subsystem* is constructed, containing the set of process and factors relevant to that particular hazard (refer also to Borter, 1999). This means that only those factors rated as relevant for the hazard under consideration are included in the modelling or, in other words, are extracted from the overall system and integrated into the subsystem. In multi-hazard analyses the single *subsystems* which are the single hazards with their respective influencing factors, are usually modelled in parallel and the final results are then brought together and compared. However, some of the factors may form part of multiple single-hazard subsystems or influence each other but cannot be observed in a related way. By contrast, a joint consideration of the hazards and their influencing factors may better consider their relationships and interactions.

To implement these rather theoretical considerations in a practical approach, the conceptual model of disposition and triggering is applied. This model assumes that the occurrence of a hazard event is the consequence of two factors, the disposition and the triggering (Heinimann *et al.*, 1998). The disposition describes the time dependent susceptibility of an area to formation and initiation of a hazardous process (Zimmermann *et al.*, 1997). Generally, two components of the disposition are distinguished, the basic and the variable disposition (Zimmermann *et al.*, 1997; Heinimann *et al.*, 1998, Figure 3.1). The basic disposition refers to the general setting of an area with parameters such as geology, relief or climate that are fixed or change only slowly over time. The variable disposition results from the influence of time-varying parameters that are subject to modifications by season, daytime, meteorological situation etc., for instance seasonal vegetation cover, temperature or water balance. It influences the temporal occurrence of hazard events as well as hazard magnitude. The triggering refers to the occurrence of episodic events with a short duration of minutes to days that initiate a hazard process given a certain disposition. In Figure 3.1 the interplay between time dependent disposition level and potential trigger is illustrated. Only where disposition level and trigger magnitude exceed a threshold is a hazard process initiated (Zimmermann *et al.*, 1997).

The distinction between basic and variable disposition as well as between variable disposition and trigger is mostly *not clearly evident* due to continuous transitions. However, for hazard analysis purposes this separation is very helpful since it relates to the dif-

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[2] In the present study only the conceptual model describing systems as interrelated parts is adopted from Chorley & Kennedy (1971) while considerations with respect to system states and the differentiation into fundamental and immediate causes leading to an incidence such as a mass movement are not integrated. Instead, the disposition triggering model as presented in Kienholz *et al.* (2004) is employed to describe the occurrence of a hazard event.

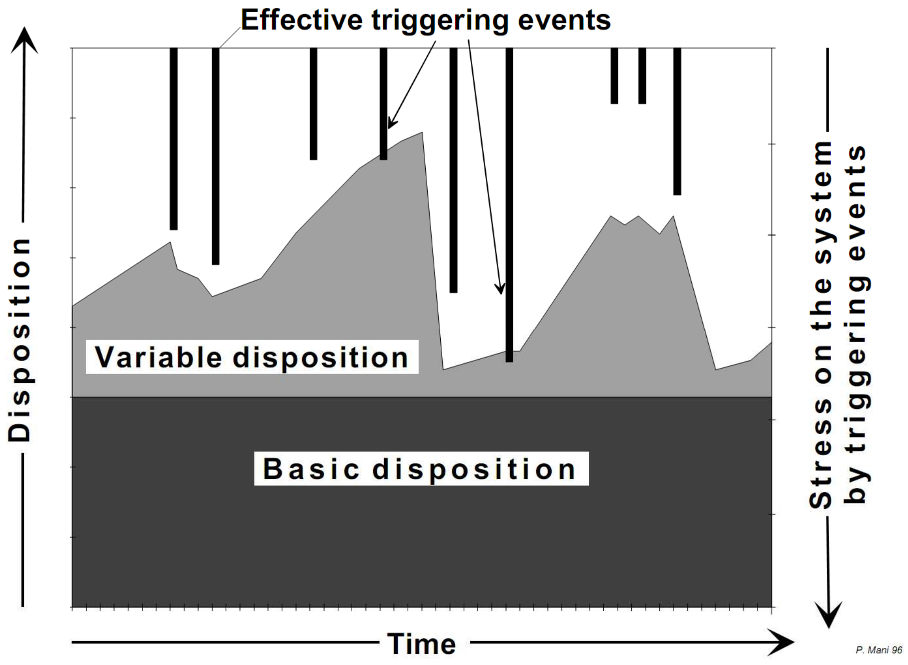

Figure 3.1.: Disposition triggering concept, modified following Kienholz *et al.* (2004, translated and modified after Zimmermann *et al.*, 1997). (Note: arrows indicate direction of increasing values).

ferentiation between susceptibility and full-hazard examinations (Zimmermann *et al.*, 1997). The basic disposition corresponds to the *susceptibility* and for primarily spatially oriented objectives such as spatial planning this information is highly valuable (Heinimann *et al.*, 1998). By contrast, the temporal disposition and the occurrence of triggering events are more difficult to assess due to the time variability and the precise prediction of hazard events is challenging. However, for emergency measures such as evacuations or road closures, information on the variable disposition and the triggering are indispensable (Heinimann *et al.*, 1998).

Combination of the concepts: The description of hazards as related systems' components allows for the creation of a joint multi-hazard subsystem for multi-hazard risk analyses. Therefore, the common set of influencing factors is related to the set of hazards under consideration (Figure 3.2, solid arrows). Moreover, the influence of one hazard on another (dashed arrows in Figure 3.2, e.g. hazard 2 on hazard 3) or on influencing factors (dotted arrows in Figure 3.2, e.g. hazard 1 on factor 3 and thereby on hazard 2) can be identified and subdivided into effects on disposition or effects on triggering. Concerning the disposition modification, this refers to phenomena such as an increase in the frequency of debris flows and floods due to vegetation loss, increased run off and sediment washout following forest fires etc. (deGraff *et al.*, 2007; deGraff & Ochiai, 2009). This implies that there exists a relation between the occurrence of a forest fire and the influencing factor

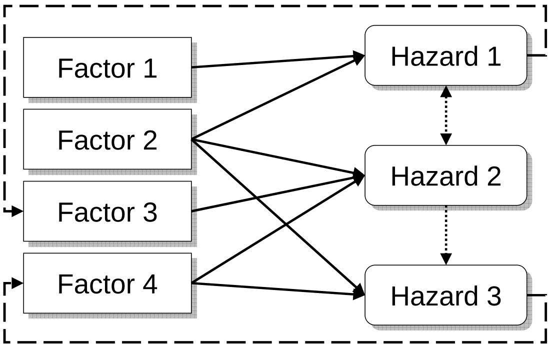

Figure 3.2.: Proposed structure of a multi-hazard sub-system. The solid arrows indicate the relation between influencing factors and hazards, the dashed arrows the impact of hazards on the factors and the dotted arrows the effects between hazards.

vegetation cover that leads to a modification of the disposition of debris flows and floods. Another example is the alteration of the density and locations of rainfall induced landslides after an earthquake due to the extensive disturbance of surface strata (Lin *et al.*, 2006). That implies an influence of the earthquake on the soil structure that, again, alters the disposition towards landslides. With respect to the triggering of one hazard by another, so-called *hazard cascades*, examples have been given in the previous sections, such as the triggering of landslides by earthquakes (Bommer & Rodríguez, 2002; Lee *et al.*, 2008; Miles & Keefer, 2009) or damming with subsequent dam break and debris flow formation due to the accumulation of landslide material in a torrent or river (Carrasco *et al.*, 2003). Subsequently, the relations and influences are, according to the modelling scale, approach, data input etc., integrated into the analysis procedure. In contrast to parallel performed single-hazard subsystem analyses, this allows not only to consider hazard relations but is also more efficient since duplication of intermediate steps is avoided.
The conceptual approach is elaborated in detail for the regional scale multi-hazard analysis scheme developed in this study. This comprises the following steps:

1. First, the multi-hazard subsystem has to be determined. This includes the set of hazards and all influencing factors considered relevant for any of the hazards. In a modelling context, the *influencing factors* refer to the input data used for the modelling such as land use, geology, soil type or rainfall.

2. Thereupon, possible relations between hazards (also via the influencing factors) have to be identified. Tarvainen *et al.* (2006) and dePippo *et al.* (2008, refer also to Figure 2.1) propose so-called *interaction matrices* in which the hazards are juxtaposed in opposition in a table and the possible effects are entered in the interjacent cells. Though they use this method for the determination of triggering effects, it

can also be applied to detect potential modification of the disposition. This implies that, for any combination of two hazards such as floods and landslides, the question has to be answered, first, what influence floods may have on landslide disposition and if floods can trigger landslides and, secondly, how landslides may alter the flood disposition and whether landslides can trigger floods.

3. Subsequently, the effect of disposition modifications or triggering chains of hazards is integrated into the modelling procedure itself. For the disposition issue this refers firstly to the alteration of influencing factors by the occurrence of a hazard event and, consequently, to the alteration of the disposition of all hazards related to this factor. By means of the establishment of the relation between the hazard modelling output of one hazard to the input for another hazard, this relation can be established (Kappes *et al.*, 2010, A.5). For instance, where the incidence of a hazard event such as forest fires or avalanches alters one or several of the input factors such as land cover, those models involving the altered input information have to be rerun to account for the new situation. To integrate triggering effects into the modelling procedure, the elaboration of event trees and the performance of consecutive hazard modelling in sequence are proposed (e.g. in CAPRA the earthquake modelling results are used as input into the landslide modelling tool, Phillips *et al.*, 2010). However, in susceptibility analyses the trigger is not directly incorporated as an influencing factor, and therefore such connection in series of the single-hazard models is not possible. In consequence, the consideration of triggering effects at a regional level does not go beyond the identification of zones potentially prone to specific hazard combinations and therefore potentially prone to certain cascades.
   The identification of those locations potentially prone to the previously identified hazard relations is the principal task of regional analyses (Delmonaco *et al.*, 2006a). By means of overlay of potentially interacting hazards those areas possibly prone to these effects are identified. For example, the analysis results of the flood and landslide modelling are superimposed, and in the overlapping zones a high potential for the occurrence of the previously determined disposition modifications or triggering relations has to be assumed.

b) The hazard relations described so far refer to the disposition modification or triggering between hazards. This leads in the first place to an alteration of the hazard level and a modification of the hazard manifestation. However, these phenomena are restricted to a change in the hazard component and apparently have no influence on the vulnerability. Instead, other types of hazard relations exert their influence on vulnerability. Examples presented in chapter 2 are the simultaneous impact of two hazards on an element at risk (Lee & Rosowsky, 2006), the sequential impact of multiple hazards (Zuccaro *et al.*, 2008) or the exposure to multiple hazards (Gibbs, 2003), indicating the importance of spatial and temporal properties of multiple hazards on the vulnerability. Where hazards spatially and perhaps also temporally coincide, the vulnerability may be altered altered. Therefore, these two aspects, the temporal and the spatial relation between multiple hazards, are used as a basis for a conceptual approach to describe phenomena emerging in a multi-hazard vulnerability context.

3.1.3. Hazard Model Validation

Model validation aims “to establish the degree of confidence of the model”(Beguería, 2006, p. 315) and thereby enables the sound interpretation of the modelling results (Chung & Fabbri, 2003). Beyond that, validation also allows for comparison of models based on various parameters or predictor sets as well as the comparison between different models (Beguería, 2006). Finally, model validation can be compared against the confidence requirements of the user (Beguería, 2006). These characteristics are particularly useful in a multi-hazard context where hazards and model characteristics vary strongly.

With respect to different hazard modelling approaches, a variety of validation methods is used. The basic principle validation procedures for predictive models share, is the comparison of the modelling result with recorded past events (Chung & Fabbri, 2003; Merz *et al.*, 2008). Two validation approaches can be distinguished: methods for discrete validation based on confusion matrices and calculating accuracy statistics such as the model’s sensitivity or efficiency (Beguería, 2006), and methods for continuous validation, for instance ROC (receiver-operating characteristic) plots and prediction rate curves (Beguería, 2006; Chung & Fabbri, 2003).

The selection of a validation technique is, like the model choice, strongly linked to the data requirements of the respective methods. Since extensive multi-hazard inventories are extremely scarce but necessary for the validation procedure, a suitable validation approach has to be flexible to also operate with little inventory information. Together with the requirement to be compatible with all single-hazard models and the objective to compose a well-applicable analysis scheme at a regional scale, this points towards a simple and not continuous method.

3.1.4. Exposure Analysis

In comparison to full risk analyses, the performance of exposure analyses is much simpler and easier to carry out. They consist of the identification of those elements at risk being situated in the susceptibility or hazard zones while a vulnerability of 1 is assumed (cf. vanWesten, 2004). In a GIS context the exposure is analysed by an overlay of the hazard or susceptibility zones with the elements at risk to localise and quantify the exposed elements at risk (vanWesten, 2004). According to Nadimpalli *et al.* (2007, p. 1674) this may include the “number and type of buildings, infrastructure and people exposed to the hazard of interest”. In the present study the emphasis is on the determination of exposed buildings and infrastructure.

3.1.5. Physical Vulnerability Assessment

The aim of a regional scale analysis is primarily the identification of areas potentially at risk. Furthermore, the criteria according to which the models are chosen indicate that regional modelling results are probably too inaccurate and imprecise to make reliable predictions of which buildings are actually exposed. Thus, an analysis of the vulnerability of exposed elements at risk is unnecessary in a regional scale analysis and their localisation and rough quantification is sufficient. Nevertheless, vulnerability analyses pose an important challenge in a multi-hazard context, as discussed in the previous chapter. Therefore, it is the objective of this study to also identify and propose ways to deal with these difficulties. The multi-hazard vulnerability approach developed here can be considered as a step towards a more local analysis.

As presented in section 2.2 (refer also to KAPPES *et al.*, in press, A.7) the three major vulnerability analysis approaches are curves, matrices and indicators (e.g. GLADE, 2003; GRÜNTHAL *et al.*, 2006; BIRKMANN, 2007; FELGENTREFF & GLADE, 2008). Each method has its disadvantages, starting with high requirement of information on past damages for the elaboration of vulnerability curves, through to the restriction of curves and matrices to only one vulnerability indicator, and the rather qualitative character of indicator approaches. However, each approach has also advantages in comparison to the other methods: vulnerability curves are continuous approaches while matrices offer classified and thus less detailed information. However, matrices are more applicable for less extensive processes, since less information is needed for their creation. Finally, indicator approaches consider multiple characteristics that influence the overall vulnerability of an element at risk. This last aspect, the possibility of indicator approaches to involve multiple element characteristics, appears to be highly promising in a multi-hazard context since element properties contribute in varying degrees to hazard-specific vulnerabilities. In the present study, the potential of vulnerability indicators in a multi-hazard context is explored by the development of an *indicator-based methodology to assess physical vulnerability for multi-hazards* (KAPPES *et al.*, in press, A.7).

Among the few approaches in this direction are the studies of GRANGER *et al.* (1999), PAPATHOMA & DOMINEY-HOWES (2003) and PUISSANT *et al.* (2006). While GRANGER *et al.* (1999) use multiple building characters as purely qualitative indicators to identify the suitability of edifices as shelters, PUISSANT *et al.* (2006) use indicators to assess the potential losses of buildings. PAPATHOMA & DOMINEY-HOWES (2003) developed an indicator-based approach to assess the physical vulnerability of buildings to tsunamis, the PTVA method (Papathoma Tsunami Vulnerability Assessment), that was later adapted to a landslide hazard context (PAPATHOMA-KÖHLE *et al.*, 2007). Although the analyses for tsunamis and landslides were carried out separately and the method can thus still not be called a multi-hazard vulnerability approach, it presents a high potential to be applied to a setting of multiple threats. The PTVA method consists, in its original version for tsunami vulnerability assessments, of four steps (Papathoma & Dominey-Howes, 2003): (1) the identification of the inundation zone and inundation depth zones, (2) the identification of the factors that affect the vulnerability of buildings and people and collection of data, (3) the calculation of the vulnerability of individual buildings within the inundation zone using a multi-criteria evaluation method, and (4) the display of building and human vulnerability. The core of the PTVA is the second step, the identification of characteristics of buildings and their surroundings that affect their vulnerability and can serve as vulnerability indicators. Table 3.1 shows the compilation of all indicators used either for the tsunami and/or the landslide vulnerability application. While several indicators such as building material or number of floors, may be relevant for both hazards, other properties such as condition of the ground floor refer only to one of them. This indicates that the set of indicators would have to be expanded in a multi-hazard context, although a core of indicators will probably show relevance for most of the processes.

Table 3.1.: Building vulnerability indicators of the PTVA method according to (Papathoma & Dominey-Howes, 2003; Papathoma-Köhle *et al.*, 2007, cf. Kappes *et al.*, in press). *Row of the building* describes the location of a building with respect to structures between this edifice and the coastline.

	Tsunamis	Landslides
Material of the building	x	x
Number of floors of the building	x	x
Warning signs on buildings		x
Characteristics of the slope side wall (windows or only wall)		x
Condition of the ground floor	x	
Building surroundings (e.g. walls)	x	x
Row of the building	x	
Presence of sea-defence	x	
Width of intertidal zone	x	x

The PTVA method shows a high potential to be adopted to a multi-hazard context and was therefore chosen as the basis for the development of a hazard-specific multi-hazard physical vulnerability approach (Kappes *et al.*, in press, A.7).

3.1.6. Visualisation

As outlined in subsection 2.4.3, the visualisation of multi-hazards and risks is a challenging task. Not only the single hazard patterns but also the zones of overlapping threats and the overall hazard and risk are of potential interest. However, it is not possible to transmit all this information in one single map without overloading it (Fuchs *et al.*, 2009; Kunz & Hurni, 2011a). Thus, several maps are necessary to depict the information content that multi-hazard risk analysis results offer. Taking account of the review in chapter 2, three options seem to be of specific interest:

1. The presentation of single-hazard information. The objective is the display of single-hazard patterns for the identification of areas of higher and lower susceptibility, full-hazard, risk and the like. For that purpose, susceptibilities, full-hazards, vulnerabilities, exposures or risks are presented in detail, which means that the distribution of spatial probabilities, hazard intensities, risk quantities and other parameters are shown.

2. The presentation of hazard overlays. The purpose of this representation form is the identification of areas of hazard overlaps while details on the single hazards are usually of less importance. The major challenge of this type of mapping is the potential overload with too much information. This can be avoided by a restriction of the amount of visualised information either by limiting the number of included hazards or by a reduction of the level of detail shown for each hazard. The most critical areas are the actual overlaps. By means of transparency, patterns, colour hue, value and saturation, shape, size and orientation, their clear representation can be achieved (Kunz & Hurni, 2011a).

3. The presentation of the overall susceptibility, full-hazard or risk resulting from merging of the single-hazard components. Without confusing details only the zones with highest susceptibility, full-hazard or risk are given. However, these maps do not offer information on the contributions of each single-hazard component. To get information on these details, single-hazard or overlay maps have to be consulted.

These three visualisation forms are used as core for the development of the visualisation scheme consisting of multiple maps.

3.2. Technical Implementation: The MultiRISK Platform

To facilitate rapid, time-saving and easily repeatable multi-hazard exposure modelling, the analysis scheme has been automated in the MultiRISK Modelling Tool. To enable a fast, clear and interactive display of the modelling results, the visualisation has been implemented in a web-mapping application called the MultiRISK Visualisation Tool. Together, the two Tools form the MultiRISK Platform and their development is outlined below.

3.2.1. The MultiRISK Modelling Tool

The analysis concept is GIS-based and thus a GIS software was chosen as foundation for the development of the modelling tool. Various purchasable programs such as ArcGIS[3], ERDAS[4] or MapInfo[5] as well as a wide range of free GIS software tools as for example SAGA GIS[6], GRASS GIS[7], or QGIS[8] are on the market. Among them, ESRI is with the ArcGIS software market leader in GIS solutions and "more than 300,000 organisations worldwide including each of the 200 largest cities in the United States, most national governments," companies, colleges and universities use their products (ESRI, 2010). Due to the use of ArcGIS by most national governments and practitioners, this GIS program was chosen as the basis upon which the modelling software tool MultiRISK was implemented. ArcGIS is compatible with several programming languages, among others Python, Visual Basic (VB), Visual Basic for Applications (VBA), VBScript and JavaScript (University of Delaware, 2005). Python offers, in contrast to the other languages, several advantages since it is easy-to-use, no compiling is needed, it is easy to integrate with other languages (e.g. C, C++, Java and Fortran), it is adjusted to the use with ArcGIS, offers a wide range of possibilities and it is automatically installed with ArcGIS (Butler, 2005). Therefore, Python was chosen for the programming of the modelling procedures.
In the modelling tool the following steps have been incorporated:

1. the hazard modelling (subsection 3.1.1)
2. the hazard model validation (subsection 3.1.3)
3. the exposure analysis (subsection 3.1.4)
4. in addition, the preparation of the data for display in the Visualisation Tool is associated as last step

Two aspects, the vulnerability assessment based on an indicator approach and the consideration of related hazards are still not included in this first version of the MultiRISK Modelling Tool. Concerning the vulnerability approach, the reason is the non-fit of scale, however, with the integration of a local scale analysis the vulnerability assessment will be included as well. With respect to the hazard relations, a manual performance by the user is still possible although this feature is not automated.

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[3] http://www.esri.com/software/arcgis/index.html
[4] http://www.erdas.com/Homepage.aspx
[5] http://www.pbinsight.com/welcome/mapinfo/
[6] http://www.saga-gis.org/
[7] http://grass.fbk.eu/
[8] http://www.qgis.org/

3.2.2. The MultiRISK Visualisation Tool

After each modelling procedure, the results have to be visualised and checked. For modellers without extensive GIS and cartographic experience, this can be a labourious activity due to the large amount of output information. However, also for experienced users the display of various hazard susceptibilities, validation results, exposure results and additionally the overlays with the assignation of colour, pattern etc. takes time. Web-mapping tools have been identified as a very promising alternative in the multi-hazard context (subsection 2.4.3). In such a digital approach the visualisation is automated, cartographic principles can be directly implemented and thus the user does not need profound GIS and cartographic knowledge, information can be explored interactively, e.g. after the modelling, and the final analysis results can even be published via the internet to be accessible to all stakeholders.

Due to these advantages, a web-mapping approach is chosen for the display of the multi-hazard exposure analysis results, combined with the three previously presented visualisation approaches as central to the visualisation concept. By these means, the outcome can be directly and automatically presented after the modelling and the final results can be transmitted to the stakeholders.

For the design of the web-mapping application, CartoWeb[9] based on a MapServer[10] engine was chosen. Both software programmes are open source, free of charge and released under the *GNU General Public License*[11]. With this combination of freely available components, several applications have already been developed, for example WebRiskCity (Frigerio & vanWesten, 2010), Barcelonn@ (Frigerio *et al.*, 2010c) and Historic@ (Frigerio *et al.*, 2010a). Such a web-mapping application can be run on a local server to visualise preliminary modelling outcome or can publish the final results on a web server to be accessible via the internet by stakeholders and other interested persons. The users get access by means of a standard internet browser and this implies that no specific software has to be installed for visualisation.

3.3. Summary

In this chapter, the methodological background for the development of a multi-hazard risk analysis scheme, under consideration of the *major multi-hazard issues*, has been outlined. This includes the challenges of high data requirement of multi-hazard risk analyses, scale differences between hazards and between modelling approaches, contrasts in model principles and assumptions, relations between hazards, units to quantify them and difficulties to present the results in a clear way. In this regard, a top-down design of the analysis scheme to use resources efficiently has been identified as promising approach and a first structure

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[9] http://www.cartoweb.org/

[10] http://www.mapserver.org/

[11] http://www.gnu.org/licenses/gpl.html, accessed 25 June 2011

with two levels, a regional and a local level, has been proposed. For the detailed elaboration of the regional scale analysis, criteria for the susceptibility modelling step, validation of the modelling results, consideration of related hazards, computation of exposure and visualisation of the analysis outcome have been outlined. In addition, the elaboration of an indicator-based vulnerability approach has been presented, as step towards a more local analysis since in a regional exposure analysis vulnerability assessments are not necessary. Subsequently, the implementation of the developed concepts in the MultiRISK Modelling Tool, a GIS-based application, and the MultiRISK Visualisation Tool, a web-mapping application, has been outlined.

4. MultiRISK: Completed Concepts and Software Platform

This chapter first comprises the presentation of the completed modelling and visualisation scheme. Subsequently, the software tools created for the modelling and visualisation and based on the developed concepts are introduced. Together these tools form the MultiRISK Platform and their principal aim is to facilitate the multi-hazard exposure analysis and to clearly present the analysis results. In this chapter, only a compilation of the most important results is presented, while the detailed results and discussion are given in the the papers KAPPES *et al.* (2010, in press); KAPPES & GLADE (acc.); KAPPES (2011); KAPPES *et al.* (subm.b,s) in the appendix.

4.1. Completed Concepts

The regional modelling scheme developed in the present study forms part of a top-down multi-hazard risk analysis approach. As an initial step in the top-down context, a regional overview is undertaken, which is designed to give an approximation of threatened zones, hazard overlaps and potential risk zones. This comprises the hazard analysis including the examination of possible hazard relations, followed by a hazard model validation to assess the models' qualities and an exposure analysis associated with a visualisation scheme to display the analysis results. Moreover, in a step towards a more local scale of analysis, the indicator-based vulnerability assessment approach is presented, including the effect of related hazards.

4.1.1. Hazard Modelling

Additionally to the analysis scale, two further criteria have directed the hazard model selection: the model principles and the required input data (subsection 3.1.1). Apart from these criteria, the choice of model can be considered coincidental, i.e. the selected models are exchangeable by others matching the requisites as well. The final model set is introduced in Table 4.1.

Table 4.1.: Presentation of the models and approaches chosen for the multi-hazard analysis scheme. For the processes of debris flow (DF), rock fall (RF), shallow landslides (SL) and snow avalanches (AV) only the source identification methods are presented. The run out modelling approach is the same for all four processes and is outlined below. In contrast, river floods (FL) are analysed in only one step.

	Modelling method	**Model parameter**
DF	Empirical source identification approach after HORTON *et al.* (2008) and modelled in Flow-R (HORTON *et al.*, 2008)	Planar curvature threshold Slope angle threshold Upslope area threshold Land cover / lithological units to be excluded
RF	Empirical source identification approach after e.g. COROMINAS *et al.* (2003)	Slope angle threshold Land cover & lithological units to be excluded
SL	Source identification with Shalstab (MONTGOMERY & DIETRICH, 1994; MONTGOMERY *et al.*, 1998), a hydrological model coupled with a limit-equilibrium sope stability model. However, it is applied without calibration to field data (soil properties) and offers in this mode only information on the influence of topography on the formation of shallow landslides	Soil bulk density Friction angle Critical rainfall threshold Lithological units to be excluded
AV	Empirical source identification approach after MAGGIONI (2004) Empirical run out modelling with Flow-R	Slope angle threshold Land cover units to be excluded
FL	Empirical modelling based on the extrapolation of an inundation depth in the area or physically-based modelling with hydrograph information, including roughness etc. with FloodArea (GEOMER, 2008)	Inundation depth or Hydrograph information

Details on the models are given in Kappes *et al.* (subm.a, A.4) and will not be repeated in depth here. However, the model characteristics will be shortly outlined with respect to the selection criteria:
The analysis of landslides and snow avalanches at a regional scale is usually carried out in a two step approach: the identification of source areas and the computation of the run out. For debris flows, rock falls and snow avalanches simple empirical models could be identified for the determination of potential source areas at a regional scale (Table 4.1). Thereby, *empirical models* are approaches in which a combination of empirical criteria such as specific geological units, land cover types or slope angles, is used to identify potential source areas. For instance, according to the methodology after Maggioni & Gruber (2003) and Barbolini *et al.* (2011), the area susceptible to snow avalanche formation refers to zones fulfilling the following conditions. Based on the assumption that snow will not start moving below a certain slope angle as e.g. 30^o, and above a second slope angle at about 60^o not enough snow accumulates, potential snow initiation zones can be confined to the range between 30^o and 60^o. Likewise, at ridge positions snow is usually blown off and therefore ridges are excluded as potential snow avalanche sources. Finally, dense forest stabilises the snow cover and thereby inhibits the movement of snow. By means of classification procedures and intersection of all these criteria, source areas are determined.
In contrast to these three hazards, empirical methods are not an equally common approach for the analysis of shallow landslides. Here, statistical and physically based methods are more common (e.g. Carrara *et al.*, 1991; Iida, 1999; Thiery *et al.*, 2007; Cervi *et al.*, 2010). However, a variety of simple physically-based models were transfered to the GIS context to be used with topographic input derived from DEMs, among them Shalstab (SHAllow Landsliding STABility, Montgomery & Dietrich, 1994; Montgomery *et al.*, 1998; Dietrich & Montgomery, 1998). This method couples a "hydrological model to a limit-equilibrium slope stability model to calculate the critical steady-state rainfall necessary to trigger slope instability at any point in a landscape" (Montgomery *et al.*, 1998, p. 944). Shalstab also provides the option for the model to be used without calibration to field data (soil properties) and offers the identification of "areas with equal topographic control on shallow landslide initiation" (Montgomery *et al.*, 1998, p. 945). In this mode the model corresponds more to an empirical than to a physically-based approach and is applicable to use with topographic input data. These are important reasons to choose Shalstab for the analysis of shallow landslides in this conceptual framework.
The run out of these four processes is analysed based on the approach proposed by Horton *et al.* (2008). This method consists of a combination of a flow direction with a flow inertia algorithm. By the relation of the two algorithms the spreading of the flow is modelled, while the stopping point of the flow is determined by the *Fahrböschung* (Heim, 1932), or *angle of reach* (Corominas, 1996). The *Fahrböschung* or *angle of reach* describes the angle of incidence of a line connecting the highest point of the source area to the point of the furthest run out. This line is not straight between the highest and the lowest point

but follows the flow and is unbended for the determination of the angle (Heim, 1932). For modelled or mapped source areas this angle enables the identification of the stopping point of the propagation and spreading of a moving mass.
In contrast to the four processes described so far, river floods are not modelled in two steps, and also the general modelling strategy differs strongly. The simplest method to model floods is the linear interpolation of the water level at a gauging station and its intersection with a DEM (Apel *et al.*, 2009). The area situated below this level is indicated as inundated, and the inundation depth is calculated by subtraction of flood level from terrain elevation (Apel *et al.*, 2009). However, this method does not control the water volume. This means, the defined water level is interpolated in channelised river sections as well as on floodplains where this gives rise to unrealistically big flooded areas and water volumes. By contrast, 1D/2D and 2D models consider the flow characteristics and hydrodynamics and account for the water volume, but need more input information such as river cross sections or roughness parameters. Although, the extrapolation of a certain water level corresponds to a simple empirical approach rather than hydrodynamic approaches, the problem it poses in flood plains is a serious limitation. For this analysis scheme the model FloodArea (Geomer, 2008) has been chosen since it offers both options. Thus those situations not facing the problem of ample flood plains can be analysed with the water level method, and in the other cases the simple discharge-based approach FloodArea offers can be chosen.

By combination of the hazard model set with all input parameters required for any of the models and the indication of intermediate steps, an overall analysis scheme has been constructed (Figure 4.1). This flow chart is illustrates the links between the input data, derivatives and model criteria to calculate the source areas and in a second step the run out as well as the one-step analysis of floods.

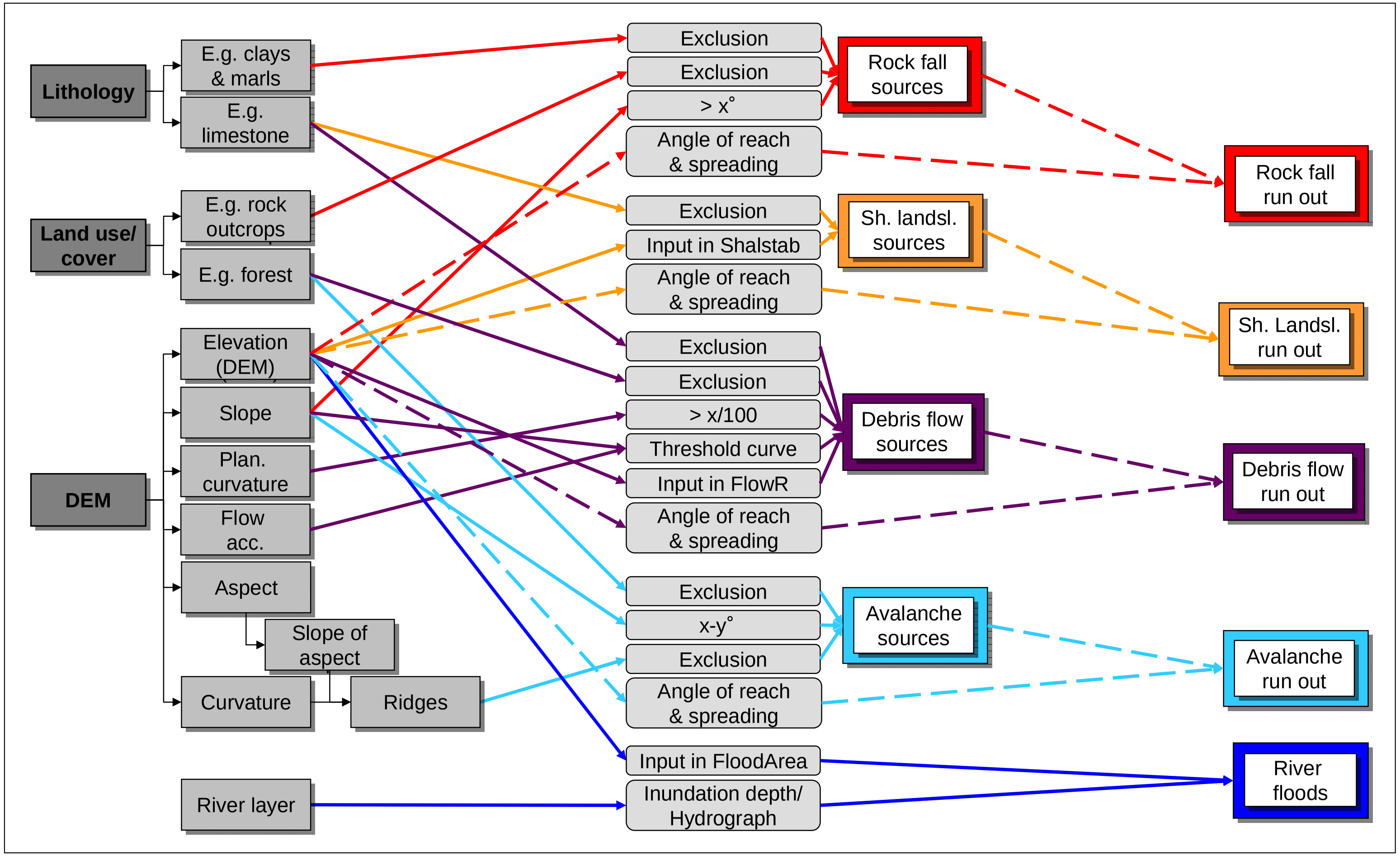


Figure 4.1.: Flow chart of the analysis scheme of the five mountain hazards under consideration (KAPPES *et al.*, subm.a). On basis of the input data (dark grey boxes on the left side) multiple derivatives are calculated (grey boxes). They form the input for the single-hazard models by means of which first the sources and subsequently the run out is analysed (coloured boxes). River floods form the exception, being modelled in one step.

For the consideration of related hazards in a multi-hazard context, three steps have been identified. (1) The establishment of a multi-hazard subsystem containing the set of hazards and *influencing factors*, (2) the identification of potential disposition modifications and triggering factors between components of the multi-hazard subsystem, and (3) the integration into the modelling procedure of those relations determined to be relevant at the scale under consideration and the spatial identification of areas of hazard overlap.

1) Each hazard model chosen so far is based on a set of input parameters. The restriction of all factors influencing this process to this set of parameters is done on the basis of their assumed importance and their availability at the respective scale of analysis. For the analysis of hazard relations the establishment of a multi-hazard subsystem has been proposed. This subsystem consists of the set of all five hazards as well as all *influencing factors* included into any of the analysis processes as model input (Figure 4.2). Those factors exerting an influence that is considered relevant at the respective scale of analysis and form input for the modelling of each of the five processes were linked to the respective hazards (coloured arrows in Figure 4.2).

2) In the previous chapter a subdivision of related hazards into the alteration of the disposition and the triggering of one hazard by another has been proposed. For the identification of relations in a hazard set under consideration, a juxtaposition of all involved processes in an *interaction matrix* has been suggested (see the example of DEPIPPO *et al.* (2008) in Figure 2.1). With respect to the five hazards forming part of this study, identi-

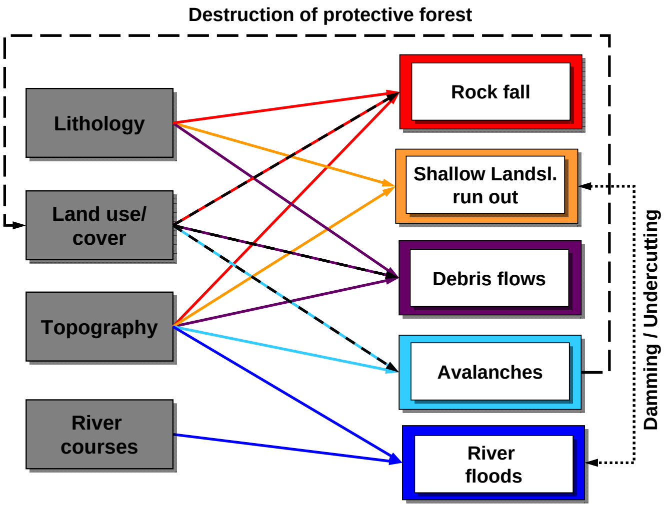


Figure 4.2.: Multi-hazard subsystem of the five hazards involved in the current study (right hand boxes) and with respect to the modelling approaches chosen for their analysis. The coloured lines indicate the first run of the model, the black dashed lines the potential feedback to the input data and the effect on the hazards illustrated by the coloured dashed lines (KAPPES *et al.*, 2010; KAPPES & GLADE, acc.).

fied relations are presented in Table 4.2, divided into disposition modifications and direct triggering. The matrix indicates three major groups of disposition influences: effects on the land cover, modifications of the material distribution and availability, and alterations of the surface characteristics and morphology. For the triggering of one hazard by another, principally the interaction between floods and landslides was identified. Shallow landslides accumulating their material in river channels may result in river damming, upslope inundation and, after a dam break, a flash flood or debris flow downstream. Although this effect can also result from damming by snow, rocks (mostly rock avalanches and not from single rock falls) or debris flows, it is mostly the result of shallow landslides. Flooding may lead to saturation of the slope toe and destabilisation or undercutting of the slope. This may result in slope failure and, in narrow river channels, to river damming with the

Table 4.2.: Matrix indicating the alteration of disposition and the *triggering* (in italic letters) between the five considered hazards modified after Kappes *et al.* (2010). The process indicated in each line defines the influencing, the process in the column the influenced component(note: "-" indicates combinations for which no potential relations have been identified so far).

Avalanches	Influence on vegetation cover (removal of forest)	Influence on vegetation cover (removal of forest)	Influence on vegetation cover	*River damming leading to flooding*
-	**Debris flows**	-	-	Change of river bed morphology (accumulation & erosion) *River damming leading to flooding*
Increased slope roughness	Supply of material	**Rock falls**	Increase of load	Material accumulation in river bed *River damming leading to flooding*
Alteration of surface roughness	Supply of material	-	**Shallow landslides**	Change of river course *River damming leading to flooding*
-	Remobilisation of material	-	Erosion/ saturation of landslide deposits *Slope undercutting leading to failure*	**River floods**

potential consequences previously outlined. Studies to analyse potential consequences in detail have to be carried out at a local scale by means of methods such as event tree analyses.
3) The implementation of the identified relations depends on the scale at which the study is carried out and the specific model characteristics. At the regional scale for which this analysis scheme is designed, only a few of the identified disposition alterations can be included into the model. Parameters such as the slope or surface roughness cannot be represented by the DEMs used for regional analyses, and information on material availability or displacement cannot be included in any of the input parameters. By contrast, the influence on the vegetation cover can be considered, since information on land use forms part of the input set. This relation can be incorporated and visualised in the multi-hazard subsystem as *feedback loop* as depicted in Figure 4.2. Consequently, the effect of an avalanche on forest cover can be analysed and based on the avalanche analysis result, an updated version of the land use is created. By input of this new land use file into the analysis process, the modified rock fall, debris flow and avalanche hazards can be calculated.

With respect to the cascading effects between hazards, the principal task of regional analyses is in the identification of locations potentially giving rise to this type of phenomenon (Delmonaco *et al.*, 2006b; Tarvainen *et al.*, 2006). By means of overlap of the modelling results, such as between from floods and shallow landslides, these zones can be determined for detailed analysis of potentially sequential occurrence of events with their respective probabilities for instance by means event trees (Egli, 1996; Delmonaco *et al.*, 2006b; Marzocchi *et al.*, 2009; Kappes *et al.*, 2010).

4.1.2. Hazard Model Validation

Due to its flexibility, simplicity and suitability at a regional level, the confusion matrix approach as outlined in Beguería (2006) was chosen for the validation of the susceptibility analysis outcomes. Confusion matrices are the result of a spatial overlay of modelling result with recorded past events. According to the four possible constellations of the output, a classification is performed into the four groups depicted in Table 4.3. Thereby, the true positives (a) indicate the area *correctly* identified as hazardous since past events confirm the threat while the false negatives (c) indicate errors of the model, i.e. zones which are obviously at threat but the model was not able to identify them. The false positives (b) “have to be thought of as cases highly propense to develop the dangerous characteristic in the future, and not merely as classification errors” (Beguería, 2006, p. 322). Since the objective of models is the identification of the areas potentially affected by future events, these zones are of high importance, although an overestimation of the susceptible area has to be avoided. The true negatives (d) are very difficult to interpret since hazard

Table 4.3.: Confusion matrix after BEGUERÍA (2006).

	Observed	**Not observed**
Predicted	True positives (a)	False positives (b)
Not predicted	False negatives (c)	True negatives (d)

inventories usually do not contain records of *safe zones*. Thus, the assumption that all areas are safe for which no past events are recorded is not valid and thus no *true negatives* can be determined. Therefore, conclusions based on this measure have to be drawn very carefully.

On basis of these four categories, several quality indicators can be identified (BEGUERÍA, 2006). Among them, in particular the *sensitivity* and the *positive prediction power* seem suitable in a multi-hazard context:

$$Sensitivity: \qquad a/(a+c) \tag{4.1}$$

$$Positive\ prediction\ power: \qquad a/(a+b) \tag{4.2}$$

The *sensitivity* quantifies the proportion of recorded events that have been modelled correctly, and by association the fraction that could not be accounted for. The *positive prediction power* serves as measure for the effectiveness of the model. The combination of both measures facilitates the appraisal of the model's effectiveness, i.e. an indication on its ability to predict future events without overestimating the area prone to hazards.

4.1.3. Exposure Analysis

In GIS environments this procedure is usually carried out by an overlay of the elements at risk with the susceptibility or hazard information (VANWESTEN, 2004). This overlay is either based on raster or on shape files. In the present study a shape file based approach is used, offering the possibility to upload the elements at risk either as points, lines or polygons. Furthermore, in the case of line or polygon upload, elements at risk can be treated either as entire units, this means an element at risk located partly in a susceptibility zones is either marked *exposed*, or the part actually situated in the zone is cut and marked. According to the three shape file types and the handling as entire units or the cutting of the exposed partition, the following three upload options are offered:

1. The upload of points, lines or polygons to be treated as entire units. Thereby, the number of exposed elements at risk is quantified. This is most suitable for buildings or pylons represented by points or polygons etc.

2. The upload of linear elements at risk to be cut according to the overlap with the susceptibility zones for the measurement of the exposed section. This option is especially applicable for the exposure analysis of roads, water supply lines and the like (e.g. BORTER, 1999; BUDETTA, 2004; ZISCHG *et al.*, 2005; WASTL *et al.*, 2008).

3. The upload of polygons to be cut according to the overlap with the susceptibility zones. The exposed area is measured. This is especially suitable for the examination of built-up areas or other land use units if information on single buildings is not available.

Two exposure options are given for the hazard processes: the exposure to source and the exposure to the complete hazard, since for example for shallow landslides it is important to differentiate between buildings situated on the moving mass or those hit by it (VANWESTEN *et al.*, 2006).

4.1.4. Physical Vulnerability Assessment

Based on the PTVA method that has already been used in the tsunami and landslide context (PAPATHOMA & DOMINEY-HOWES, 2003; PAPATHOMA-KÖHLE *et al.*, 2007), a multi-hazard indicator-based vulnerability approach has been developed (for more detail see KAPPES *et al.*, in press, A.7). The first step of the assessment of the hazard-specific physical vulnerability of structures in a multi-hazard context is the identification of vulnerability indicators. These indicators have to be available with reasonable effort and have to include those characteristics primarily influencing the vulnerability of a structure with respect to the considered hazards. While some indicators influence the vulnerability for several hazards, others may be rather specific and related to the vulnerability for just one process. Moreover, the level of importance of a certain indicator for the assessment of the hazard-specific vulnerability varies from processes to process. For instance in the case of buildings, for floods GRANGER *et al.* (1999) indicate the relevance of the floor height and number of floors while in the rock fall context HOLUB & HÜBL (2008) refer primarily to the strength of the outer wall and the existence, height above ground and size of windows. By contrast, in the case of avalanches BERTRAND *et al.* (2010) suggest the significance of building shape, mechanical properties of its material and anchorage of the foundation. These examples indicate not only the variation of potential indicators but also the necessity to weight the indicators for each single hazard according to its level of importance for the hazard-specific vulnerability. For each indicator, again, scores have to be defined that indicate to which degree a certain characteristic (e.g. one-, two- or three-storey edifice with respect to the vulnerability indicator *number of floors*) contributes to the vulnerability of a building (Kappes *et al.*, in press, A.7). Based on the scores and weights the Relative Vulnerability Index (RVI) is calculated, a measure of the vulnerability of a structure (Figure 4.3). Thereby *relative* refers to the missing relation to the hazard intensity.

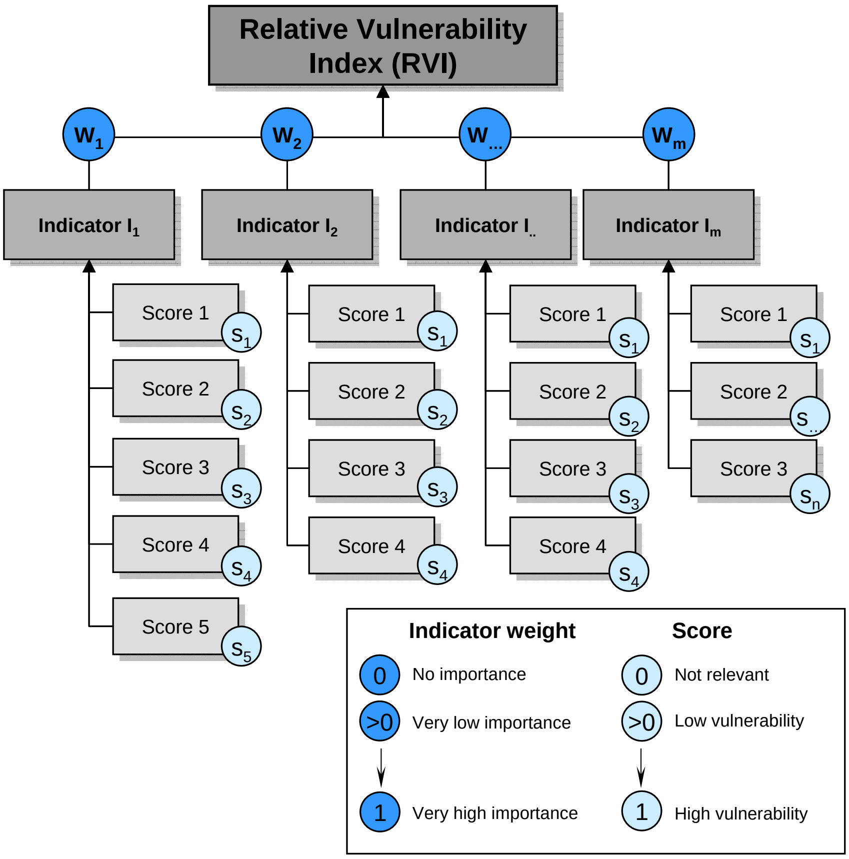


Figure 4.3.: Structure of the calculation of the relative vulnerability index on basis of indicator weights and scores according to Kappes *et al.* (in press, A.7).

That implies, within one susceptibility or hazard zone, buildings can be compared and prioritised. However, a comparison across several hazard zones is difficult since hazard and vulnerability cannot be combined to form some kind of *qualitative risk*. The scores are assigned according to the hazard type while the weights are chosen under consideration of the user-specific objective and the hazard-specific characteristics. For instance, the number of floors is an important influencing factor on the flood vulnerability of a building. However, it may be of higher importance in an emergency management context than in a spatial planning context since emergency services need to locate potential victims as soon as possible and especially in buildings without the possibility of vertical evacuation. The RVI is calculated according to the following formula (Kappes *et al.*, in press, A.7):

$$RVI = \sum_{1}^{m} w_m \cdot I_m s_n \tag{4.3}$$

with the weights $w_1 - w_m$ (with $\sum_1^m w_m = 1$) for the different indicators ($I_1 - I_m$) and the influence to vulnerability ($I_1 s_1 - I_m s_n$, with values between 0 and 1).

Finally, the effect of hazard relations on the overall vulnerability has to be assessed. As described in the previous chapter, the combination of spatial and temporal coincidence have been identified as those types of hazard relations that exert influence on the vulnerability. By opposing these two components, four possible combinations are identified (Table 4.4), giving rise to the following implications (Kappes *et al.*, in press, A.7):

Table 4.4.: Matrix of the influence of spatially and/or temporally related hazards on the vulnerability, modified after Kappes *et al.* (in press). (a)-(d) is described in the text.

	Spatially overlapping	**Spatially not overlapping**
Separated in time	a) An element is affected (threatened) by different hazards over time	b) Different elements within the area under consideration are affected by different hazards over time
Simultaneous or closely timed	c) An element is affected by two hazards at the same time or an element already affected by one hazard is hit by a second one afterwards	d) Different elements are affected at the same time by different hazards

a) A building situated in a zone threatened by multiple hazards is potentially exposed to differing types of impacts and loads over time. While certain building characteristics or reinforcement measures reduce the vulnerability for one process, they may lead to an increase towards another. UNEP (1992, Paragraph 7.61) make the example that "an earthquake-resistant house made of wood will be more vulnerable to wind storms". Consequently, building codes and design of mitigation measures have to consider the synergies and contradictions arising from certain building properties with regard to multiple hazards (Gibbs, 2003; Holub & Hübl, 2008; Holub, 2008). However, the inclusion of this aspect into the presented methodology is restricted to the identification of buildings confronted with this situation and the determination of contradicting characteristics. More detailed engineering knowledge is necessary to account for the possible effects and to develop more effective building codes.

b) The spatially and timely separate occurrence of multiple hazards within an area under consideration has no implications for the physical vulnerability.

c) The simultaneous or closely timed impact of various hazards an area can result either from the triggering of multiple hazards by one event, one hazard triggering another, or the coincidentally simultaneous or closely timed occurrence of two or more hazards. The eruption of a volcano with the different processes arising from this event including earthquakes, ash falls and pyroclastic flows is for instance one occasion in which near-simultaneous impact of two or more hazards is relatively probable (Zuccaro *et al.*, 2008). Therefore, the simultaneous impact of several hazards on an element at risk results in an overall vulnerability which may differ from the sum of their vulnerabilities. For instance Lee & Rosowsky (2006, p. 302) mention a "significant increase in effective seismic weight [due to snow load] when the structure is subjected to seismic loading". Zuccaro *et al.* (2008) made a similar observation for masonry buildings and reinforced/concrete structures under ash load during an earthquake. By contrast, Zuccaro *et al.* (2008, p. 429) observed a "positive effect of the vertical ash load on the roof that, when it does not reach the value of the roof collapse, produces on the structure a considerable stabilizing effect due to the total weight increment" when being hit by a pyroclastic flow. With the development of fragility surfaces (Figure 2.3) instead of a vulnerability curves, Lee & Rosowsky (2006) give an example of how this effect of related hazards can be considered. However, this is a rather engineering or technical problem that can only be considered at very small scales. Therefore, the presented methodology supports the identification of such situations, while further analyses and measures have to be based on engineering experience and technical knowledge.

The closely timed occurrence of two or more hazards is described by Zuccaro *et al.* (2008, p. 417) as a "sequence of events". An example is the impact of an earthquake triggered landslide on a building that is already damaged by the earthquake and will therefore behave differently. Zuccaro *et al.* (2008, p. 417) propose to consider such settings as "a progressive diminution of the resistance characteristics of the buildings". This enables the calculation of the vulnerability alteration within the hazard sequence and for instance may facilitate the inclusion of the vulnerability into event trees assessing the effect of potential hazards cascades.

d) The simultaneous impact of hazards on different zones within an area under consideration has no implications for the physical vulnerability.

4.1.5. Visualisation

The visualisation scheme elaborated for the presentation of the results of multi-hazard exposure analysis consists of a set of maps. Each map is designed to communicate a certain aspect of the modelling outcome with the three representation forms described in subsection 3.1.6 as core: single hazard information including all detail, overlays of multiple hazards, and joint variables as the overall hazard, susceptibility or risk. They are supplemented by several additional maps to provide background information for the interpretation of the results. The following is the final result of this combination of core representations and supplementary background:

1. General setting: In the first map, an overview of the general situation in the study site is given, including information on land use, geology, slope angle and planar curvature. These parameters are included in the modelling procedure and their patterns may provide the basis for a better understanding of the analysis results presented in later maps. The objective of this map is to offer introductory information and orientation in the respective area for the user.
2. Single hazards: After a general introduction into the area, the first analysis results are presented. According to the three core representation forms this refers initially to the display of single hazards separately and in detail, for instance presenting the inundation depth of floods. For the colour definition of each hazard the symbol kit of KIENHOLZ & KRUMMENACHER (1995) is proposed. It assigns red to rock falls, orange to shallow landslides, purple to debris flows, light blue to avalanches and darker blue to floods.
3. Overlapping hazards: The presentation of an overlay of hazards is important to facilitate the identification of zones of overlap. However, the display of all combinations of five superimposed processes would lead to 31 different combinations in total and for four processes to 15 possibilities. The clear representation of all different classes would be extremely difficult, even with colours and patterns etc. Therefore, the overlay is restricted to three hazards resulting in seven combinations, while each hazard is not only represented by its specific colour but also by a pattern.
4. Number of hazards: The presentation of the number of overlapping hazards offers information on the whole set of processes taken into account without disturbing details of the single threats. However, this gives no information on the overall susceptibility level, i.e. areas in which multiple hazards are superimposed are not at a higher threat than those prone to less hazards.
5. Past events: This map again provides background information to the user as preparation for the analysis results. In this case the uploaded past events used for the validation are shown before presenting the validation results to first draw the attention to the distribution of the records, the quantity of information available for each process, and the area covered by the inventory information.
6. Validation: The hazard model validation results are presented to transmit a spatial impression of the models' qualities and the predictions made. Thereby, the true positives, false negatives and false positives are depicted to transmit the information on modelling results confirmed by past events, past events that were not covered by the model and the area potentially prone to future incidents.

7. Exposure: Finally, elements at risk located in susceptibility zones are presented indicating potential risk areas.

4.2. The MultiRISK Platform

Although the developed concepts already give clear indications for the performance of multi-hazard exposure analyses at a regional level, the modelling is still time-consuming. Steps such as the data preparation, calculation of derivatives or reclassifications can easily be automated and facilitate the repetition of the investigation of scenarios, updating of the susceptibility and exposure analyses etc. The same applies for the visualisation of all output files resulting from the modelling process. Their upload in a GIS software, the definition of colours, transparency or the composition of multiple files is time-consuming. Whilst the examination of the result files in a GIS software is always possible, the programming of a visualisation tool also offers a fast inspection of the information after the modelling procedure and can be used for communication of the final results. In the following sections the two tools forming the MultiRISK Platform are presented in detail.

4.2.1. The MultiRISK Modelling Tool

The MultiRISK Modelling tool represents a first attempt at the automation of the previously developed analysis concept. In order to keep the software simple and transferable, hazard relations are still not included. However, only few steps have to be carried out by the user to link for example the output of a hazard model to the input files to consider the impact of one process on the disposition of another one.

The Modelling Tool consists of four major steps, the hazard modelling, the validation of the output by means of overlay with past events, the exposure analysis, and the preparation of the output files for subsequent presentation in the Visualisation Tool (Figure 4.4). The fundamental step in MultiRISK is the upload of data for the modelling procedure (DEM and, optionally, land use and lithology) or the upload of a previously created project (Figure 4.5). On this basis, either the susceptibility of hazards is modelled or further activities such as model validation or exposure analyses are performed or the visualisation of the results is prepared. For the hazard modelling stage the set of hazards to be considered has to be selected and the model parameters have to be entered (refer to Table 4.1 for the required model parameters). After a confirmation of the chosen parameters, the modelling procedure is performed. Thereby, meta-data is automatically assigned to each of the output files that contains information on the input data and the modelling parameters used for its creation.

In the next step, the validation of the analysis results is offered. Two options are provided, the validation of the modelled sources and the validation of the complete susceptible area including source instabilities and run out. After the upload of event records the calculation

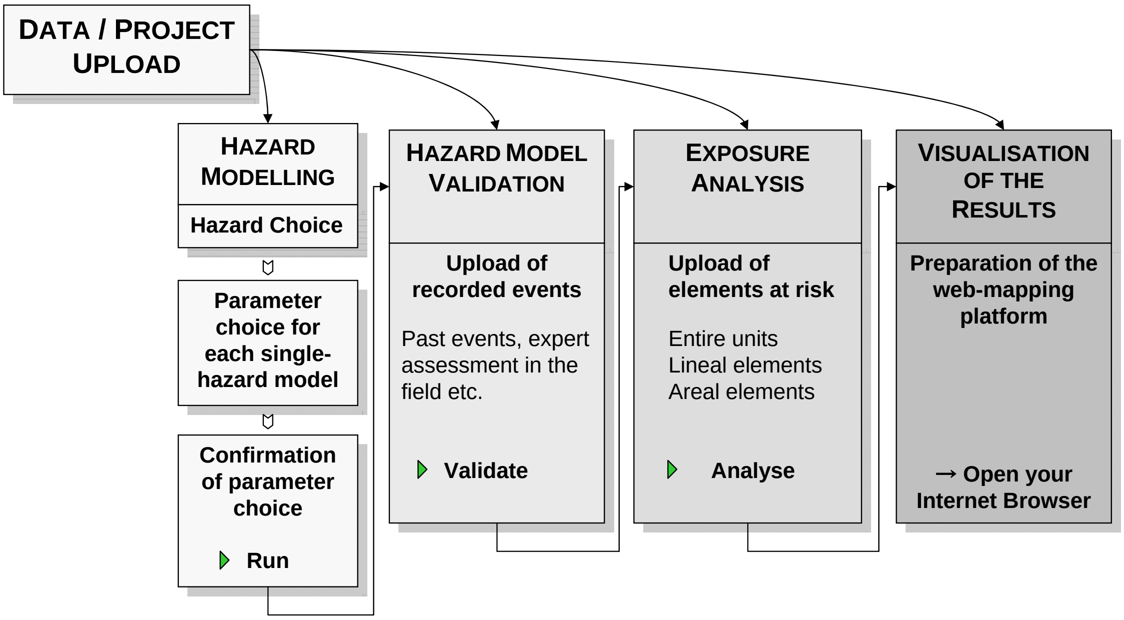
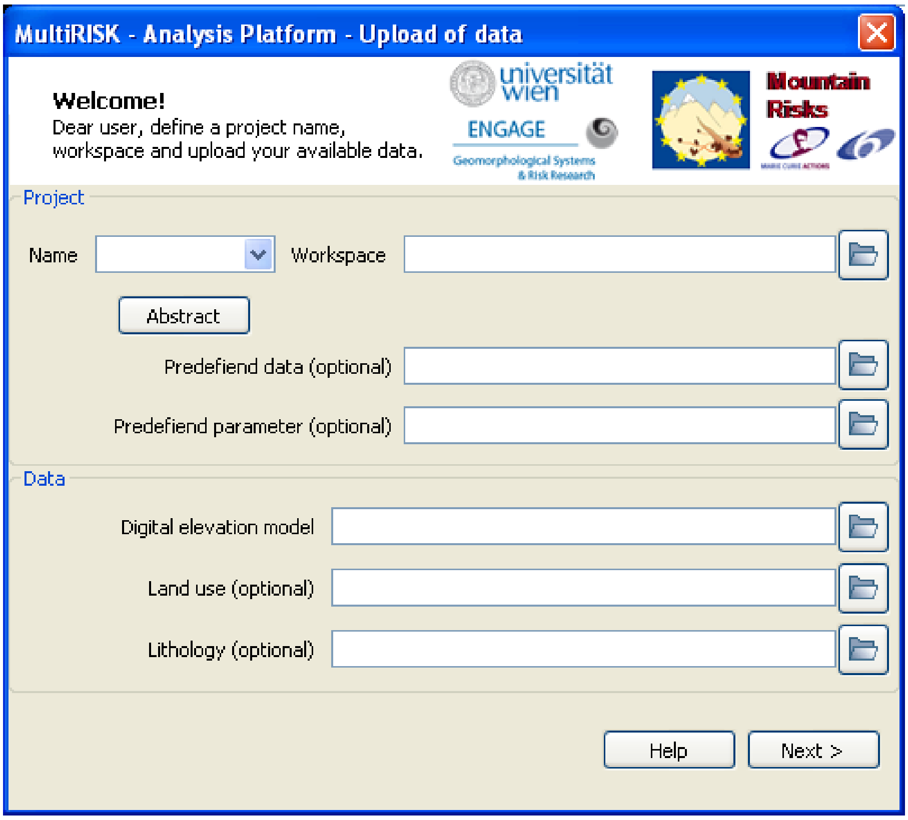


Figure 4.4.: Flow chart of the susceptibility step of MultiRISK Modelling Tool (KAPPES *et al.*, subm.a, A.4).

can be started.

Based on uploaded elements at risk (buildings, infrastructure etc.) the exposure analysis is carried out for the source areas as well as for the complete area affected by each of the hazards. This is primarily important for the occurrence of shallow landslides, since a building located on moving ground is differently affected than a building being hit by moving mass.

The final step initiates the preparation of the data for display in the MultiRISK Visualisation Tool. At first, the result files are automatically saved in the folder defined as *workspace* in the initial software interface (Figure 4.5). Thereby, the *Name* of the project determines the first part of all file names while associated abbreviations indicate the content of the files. Primarily, this includes the hazard set with the abbreviations _av for avalanches, _rf for rock falls, _sl for shallow landslides, _df for debris flows and _fl for floods. Furthermore the consideration of either sources _s, run out _r or the complete area _c is indicated and the performed activities are signalled such as the validation _vl or the overlay of all hazards resulting in the number of hazards _nr. For instance, the file Barcelo_rf_s contains the modelled rock fall source instabilities for the project *Barcelo* and the file Barcelo_av_c_vl is the result of the validation of the complete area susceptible to avalanches. However, for the visualisation, predefined file names are necessary and the files have to be located in a predefined folder. This implies that the changing project names and the project folder pose a problem for the web-mapping application. Therefore, all produced files are copied in the predefined folder with predefined names from which



MultiRISK - Analysis Platform - Upload of data

Welcome!
Dear user, define a project name, workspace and upload your available data.

Figure 4.5.: Screenshot of the initial interface of the MultiRISK Modelling Tool.

the visualisation tool obtains the information. For details on the single steps, file naming and screenshots of the interfaces please refer to the MultiRISK manual (Kappes, 2011, A.8).

So far, hazard relations are not automated in the MultiRISK Modelling Tool. Nevertheless, only few steps are necessary to integrate for instance the disposition alteration snow avalanches may cause due to forest destruction. Based on the avalanche modelling output a new land cover file can be created outside of MultiRISK, and this land cover file forms input of a second MultiRISK analysis cycle that is run for all processes depending on land cover information.

4.2.2. The MultiRISK Visualisation Tool

The set of seven maps presented in section 4.1.5 was implemented as seven single *shifts* in the web-mapping based Visualisation Tool (see Figure 4.6) and offer the interactive exploration of the different topics. The default background of each map is the hillshaded DEM since it facilitates the orientation in an area, especially in mountain environments and directly provides an impression of the topographic setting (Figure 4.6, 1a). Besides,

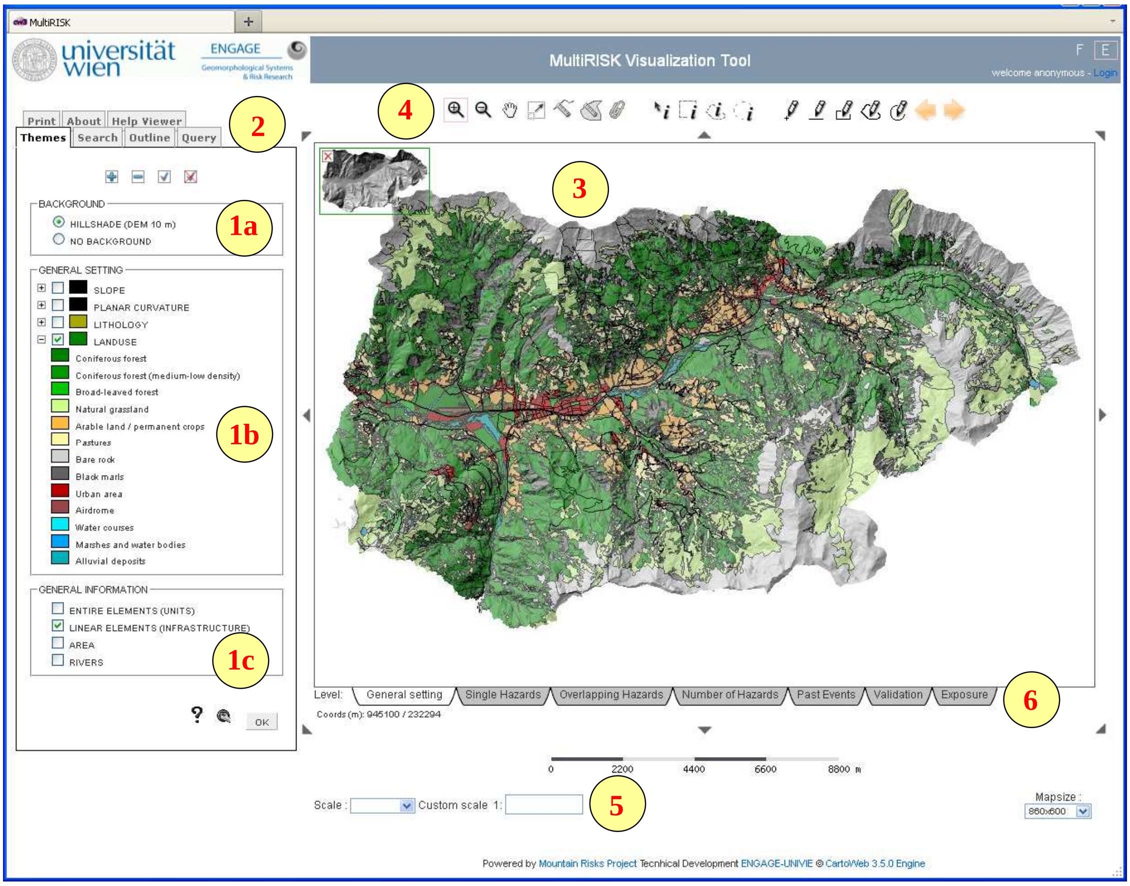


Figure 4.6.: Screenshot of the interface of the MultiRISK Visualisation Tool. The following descriptions refer to the red numbers in the graphic: 1) Layers tree, managed by the user. According to predefined options layers can be switched on, off, overlaid etc. 2) Tabs for query, printing and online guide. 3) Map area and key map visualisation. 4) Tools for cartographic interaction as zoom in/out, spatial query etc. 5) Scale and map size customization. 6) Tabs to access the different interactive maps.

in contrast to topographic maps, aerial or satellite images it is unobtrusive and enhances the information presented in each map. Further information available for visualisation in each map are the elements at risk and the rivers (Figure 4.6, 1c).

Certain rules ensure the clear visualisation of the files that are included in each map:

1. General setting: Either the land use, lithology, slope or planar curvature layer can be visualised (Figure 4.6). Land use and lithology are semi-transparent to facilitate the orientation in the area based on the translucent hillshaded DEM.

2. Single hazards: The visualisation of the five hazards under consideration is offered as a combination of the source areas and the run out. However, only one process can be displayed at a time (Figure 4.7a).

3. Overlapping hazards: The overlay of three processes is offered. For the representation of the seven combinations, each hazard is not only represented by a certain colour but additionally by a specific pattern (Figure 4.7b).

4. Number of hazards: This map provides information on the number of overlapping hazards. By means of a spatial query the information which hazards are overlapping is available (Figure 4.7c). With the hyperlink related to the question mark located in the layer tree, further information on the query can be accessed in a separate tab.

5. Past events: The files uploaded for the validation procedure are visualised. Thereby, information is displayed on one process at a time and either referring to the source or the complete area.

6. Validation: The validation result is presented separately for each hazard and either the source or of the complete validation is depicted. Additionally, a hyperlink situated in the layer tree offers the display of the confusion matrices in a separate tab.

7. Exposure: The hazard information forms the background for the display of the yellow highlighted exposed elements at risk. Either those elements at risk exposed to source instabilities or to the whole process can be visualised. Additionally, a hyperlink offers the numerical results of the exposure analysis in a separate tab.

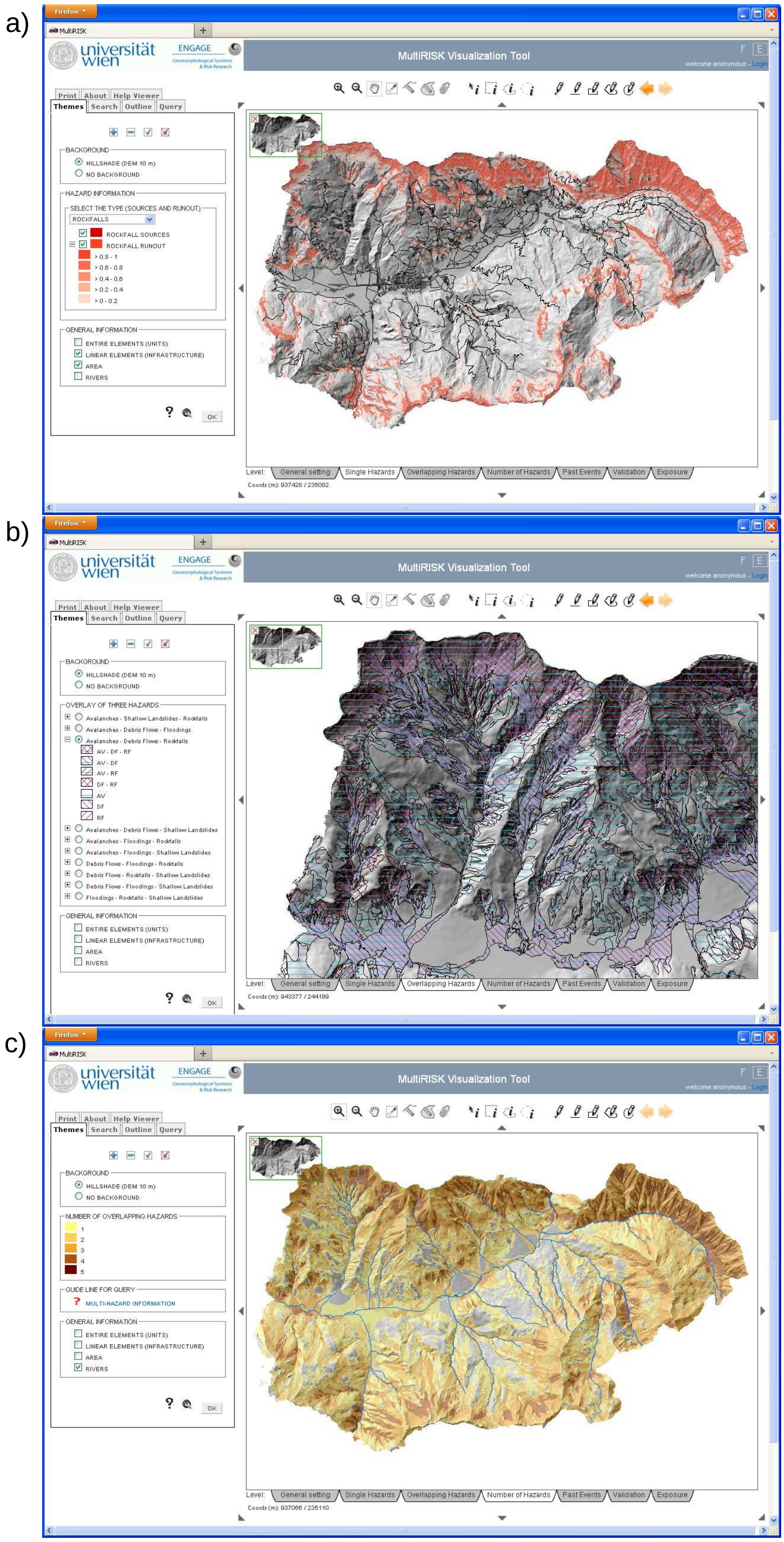


Figure 4.7.: Screenshots of the MultiRISK Visualisation Tool (Kappes *et al.*, subm.a, A.4). (a) The single hazards are shown separately, (b) the overlay of three processes is offered and (c) the number of overlapping hazards is presented. The results shown here stem from the case study in the Barcelonnette Basin.

4.3. Summary

In this chapter, a multi-hazard risk analysis concept based on a top-down approach has been presented. At its current stage, this concept includes two levels, (a) a regional analysis for the identification of zones prone to multiple hazards and potential risk areas followed by (b) a local detailed investigation of the identified areas. The complete regional multi-hazard exposure analysis scheme under consideration of related hazards has been outlined and indications for the connection and function of the local level analysis have been given, although the local analysis scheme was not developed in this study. Associated to the modelling scheme, the visualisation concept has been described through which a clear exploration of the analysis results is offered. As a step towards a more local analysis level, an indicator-based vulnerability assessment approach for user- and hazard-specific analyses has been proposed. Subsequently, the implementation of the modelling and the visualisation scheme into MultiRISK Tools has been outlined and both software applications have been presented.

5. Application of the Developed Concepts and the MultiRISK Platform

To test the usefulness and coherence of the analysis and visualisation scheme as well as the applicability and user-friendliness of the MultiRISK Platform, a case study has been carried out. For that purpose, one of the research sites of the Mountain Risks project has been chosen, the Barcelonnette basin. Due to its situation in the Alps it is prone to multiple hazards, among them the five processes included in the MultiRISK Platform (debris flows, rock falls, shallow landslides, river floods and avalanches).

5.1. Characterisation of the Barcelonnette Basin

5.1.1. General Setting

The study site is located in the Barcelonnette basin which lies in the Southern French Alps in the Département *Alpes des Haute Provence*. The considered zone encompasses almost the complete area of the municipalities Jausiers, Faucon de Barcelonnette, Saint-Pons, Uvernet-Fours, Enchastrayes and Barcelonnette. Only few marginal zones had to be excluded due to unavailability of aerial photos for the derivation of land use information. The population of these six municipalities amounts to nearly 6,000 inhabitants (INSEE, 2011). However, due to summer and winter tourism the number of people residing in the area is temporarily much higher as the large number of beds available in hotels and capacities in camping places indicate (INSEE, 2011). The valley extends between an altitude of 1,100 and 3,100 m a.s.l. and is drained by the Ubaye river in which a large number of torrents flow (Figure 5.1). It is characterised by (a) a mountain climate with pronounced interannual rainfall variability (735 ± 400 mm) and 130 freezing days per year, (b) a continental influence with large intra-day thermal amplitudes (>20^o) and multiple freeze-thaw cycles and (c) a Mediterranean influence with summer rainstorms providing occasionally more than 50 mm/h (FLAGEOLLET *et al.*, 1999; MAQUAIRE *et al.*, 2003). These summer rainstorms, as well as heavy rains on melting snow accumulations in spring, lead to high discharges (FLAGEOLLET *et al.*, 1999). Meso-climatic differences emerge due to the orientation of the valley in an east-west direction, especially between the north- and south-facing slopes (REMAÎTRE *et al.*, 2010). Geologically, the valley presents a structural window with autochtonous Callovo-Oxfordian black marls (the *Terres Noires*) below the

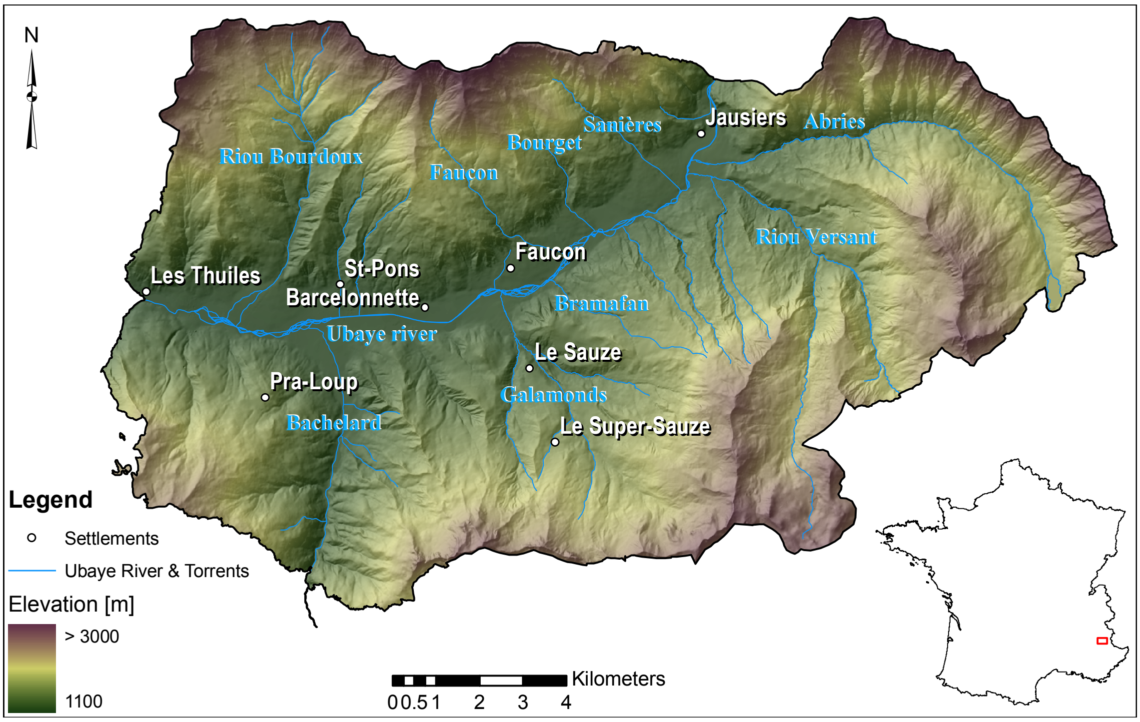


Figure 5.1.: Overview of the study area with indication of the principal settlements in white letters and catchments in blue letters (modified after Kappes *et al.*, 2011, A.3).

allochtonous Autapie and Parpaillon flysch (Évin, 1997; Maquaire *et al.*, 2003). As result of this geological setting, the upper slopes (1,900 - 3,000 m a.s.l.) consist of thrust sheets of cataclastic calcareous sandstones and are mostly steeper than 45^o (Kappes *et al.*, 2011, A.3). A layer of non-consolidated weathered debris between 0.5 and 5 m thickness covers large parts of these slopes leading to debris tracks. The lower slopes (1,100 - 1,900 m a.s.l.) are much gentler with angles of 10^o to 30^o and consist of the Callovo-Oxfordian black marls, fragile plates and flakes in a clayey matrix. These zones are mostly covered by Quaternary deposits such as poorly sorted debris at taluses, moraine deposits or landslide material (Kappes *et al.*, 2011, A.3). A multitude of debris cones from the torrents characterise the valley. Due to their fertility and shallow slopes several of the cones are populated such as Sanières, Bourget, Faucon or Saint-Pons (Weber, 1994). Weathering and disintegration of sand- and limestones give rise to the formation of sandy and loamy regolith. On flysch, sandy or loamy regolith may further develop to silty or clayey regolith (Blijenberg, 1998). The vegetation mainly consists of forests and alpine pastures with a dominance of alpine pastures and bare rock outcrops above the tree line which is located at about 2400 m at south-facing and 2200 m at north-facing shadowy slopes (Blijenberg, 1998). The forest cover had diminished in the 17th, 18th and 19th centuries drastically due to the use of wood and the extension of arable land (Remaître, 2006; Remaître

& MALET, 2010). This had led to a huge increase in torrential activity for which reason reforestation and check-dam construction has been initiated in 1864, and is still ongoing (REMAÎTRE, 2006).[1]

5.1.2. Natural Hazards

The location and the specific characteristics of the Barcelonnette basin give rise to the occurrence of a multitude of natural hazards:

- In the past, several severe river floods of the Ubaye River led to considerable damages. Among them primarily the events in 1856 which hit in first place Jausiers and in 1957 which concentrated on Barcelonnette and several neighbouring villages (SIVAN, 2000). Further cases of considerable high water or flooding are recorded for the years 1951, 1960, 1963, 1970, 2003 and 2008 (LECARPENTIER, 1963; SIVAN, 2000; BHATTACHARYA, 2010). Corrective measures to reduce the river flood risk comprise the construction of dykes and river channelisation, especially of the river sections in the cities of Jausiers and Barcelonnette.

- Between 1850 and 2004 alone, information on about 100 debris flow and 461 flash floods has been collected (REMAÎTRE, 2006). Most notably, the Riou Bourdoux was famous as the *alpine monster* or *the first torrent in France* (“le premier torrent de France”, DELSIGNE *et al.*, 2001, p. 527), due to the devastation it caused. Check-dam construction and reforestation led to a decrease in torrent activity, however, occasionally debris flow events still cause damage. The most recent example in the study area is the incidence of 2003 in the Faucon catchment that affected nine houses and involved the closure of the main road that crosses the valley (the R.D. 900) for several hours (REMAÎTRE, 2006; REMAÎTRE & MALET, 2010).

- The valley exhibits a great variety of slope movements in moraine deposits, due to slope undercutting and even in the hummocky and less steep slopes (THIERY *et al.*, 2007). THIERY *et al.* (2004) mapped about 250 active rotational and translational landslides in the year 2000. Furthermore, three big earth flows have developed in the black marls of the Barcelonnette basin (GUILLON, 2001; MALET *et al.*, 2004; VAN ASCH *et al.*, 2007; MAQUAIRE *et al.*, 2003): Super Sauze ($\sim$750,000 m^3), La Valette ($\sim$3,600,000 m^3) and Poche ($\sim$1,000,000 m^3). Despite their usually slow movement, they pose a notable threat due to their sediment volume and high mobility, including for the release of debris flows (MALET *et al.*, 2004).

- Areas prone to rock fall mostly lie far off from the built-up zones or other infrastructure, in the higher parts of the valley and therefore receive rather low attention in

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[1] This subsection is in large parts repeated from the article KAPPES *et al.* (subm.a, A.4).

the Barcelonnette basin. Exceptions are several spots in the municipality of Jausiers that are considered in the municipal risk prevention plan (RTM, 2000a).

- The avalanche inventories of the “Enquête Permanente sur les Avalanches” (EPA) and “Les Donnees de la Carte de Localization des Phonomènes d’Avalanche” (CLPA) indicate a rather high historic avalanche activity (MEDD, 2007). However, the threatened areas are mostly situated in uninhabited catchments as the Abries or in the upper zone of e.g. the Riou Bourdoux and the Sanières catchment.

- Moreover, the Barcelonnette basin is threatened by earthquakes. In a global comparison France exhibits only a medium seismicity, but, within France the department of Alpes de Haute Provence is among the most seismic ones (CETE, 1987). Two major events were recorded, one in 1887 with an intensity of VII - VIII on the MSK scale (Medvedev-Sponheuer-Karnik scale) and the other in 1959 with an intensity of VI - VII on the MSK scale. The centennial seismic intensity of Barcelonnette was assessed to 6.5 and the bicentennial seismic intensity to 7.0 on the MSK scale (CETE, 1987).

5.1.3. Risk Prevention Plans in the Barcelonnette Basin

Since 1982 the elaboration of *risk exposure plans* (Plans d’exposition aux risques, PER) that were succeeded in 1995 by the *natural risk prevention plans* (Plans de prévention des risques naturels, PPR), is obligatory for those municipalities in France that are exposed to natural hazards (MEDD, 1999; Delattre *et al.*, 2002; Fleischhauer *et al.*, 2006). These plans “aim at *regulatory risk zoning*, also with important legal significance for compensation rules” (Fleischhauer *et al.*, 2006, p. 43). The prefect of each *Département* is instructed to determine the municipalities at risk and demand the preparation of a PER or now PPR. Due to the hazard situation in the Barcelonnette basin, all municipalities are obliged to elaborate such a plan and the zoning is already taken into consideration for spatial planning. The PERs and PPRs indicate areas of high risk in which no further construction works are allowed (red zones), medium risk where new building projects can only be carried out under the consideration of specific requirements (blue zones), and no significant risk (white zones). In the Barcelonnette basin, the zoning is the result of a combination of modelling, information on past events and expert judgement and covers, as prescribed for PERs and PPRs, only the settled areas (Michel Peyron, RTM, personal communication).

5.2. Available Data

5.2.1. Area-Wide Spatial Data

A digital elevation model is available from the interpolation of digitised contour lines and breaklines of channels of the 1:10,000 topographic maps from IGN (Institut Géographique National). Scanning and georeferencing of the maps had been carried out by Thiery *et al.* (2007) and the interpolation was realised with the software program SURFER[2] using kriging on basis of a semivariogram elaborated by Thiery (2007). The resulting DEM was smoothened by 9-nodes averaging. A second DEM, or to be more precise a digital terrain model (DTM), is available from airborne interferometric synthetic aperture radar (IFSAR) with a resolution of 5 m. A visual comparison clearly indicates quality differences between the DEM and the DTM depending on the location in the valley. On tree-covered slopes the level of detail of the DEM is higher, attributable to the creation of the DTM by filtering out the forest from the digital surface model. This leads to a very strong smoothing of the respective zone. By contrast, in the nonforested flood plain and in particular in the river channel itself, the quality of the DTM is much higher than the quality of the DEM. This difference in quality between the DTM and the DEM in the flood plains is increased due to the long distances between elevation lines in areas of only slight elevation differences as flood plains. Thus, at the forested slopes the DEM, and in the nonforested flat flood plains the DTM show a higher level of represented detail.

Using aerial photographs of 2000 the land use was digitised and classified into dense coniferous forest, coniferous forest of average to low density, deciduous forest, natural grassland, arable land/permanent crops, pastures, bare rock, bare soil, urban areas, mining sites, water courses and marshes and water bodies by Bordonné (2008). The information on the lithology was digitised from the geological map (1:50,000) constituting the following ten classes (Bordonné, 2008): marls, torrential alluvium, limestone, boulder fields, talus slopes, flysch, gypsum, lacustrine deposits, calcareous marls and moraines.[3]

5.2.2. Inventory Data

With respect to the five processes considered in the MultiRISK Platform the following information on past events is available[3]:

- **Debris flows:** the envelopes (polygons) of the deposition of the debris-flow events observed in 1996, 2002 and 2003 at the Faucon, Sanières and Bourget torrent based on post-event field observations (Remaître, 2006).
- **Shallow landslides:** Information was extracted from the landslide inventory of Thiery (2007). This inventory was compiled at a scale of 1:10,000 by means of the

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[2] http://www.goldensoftware.com/products/surfer/surfer.shtml

[3] This paragraph is in large parts repeated from the article Kappes *et al.* (subm.a, A.4).

interpretation of aerial photos, field surveys and literature analyses (Thiery *et al.*, 2007). A limitation is that this inventory does not cover the whole basin but only the eastern half of the study area.

- **Rock fall:** Several indications concerning potential rock fall sources were derived from the landslide inventory of Thiery (2007). These records were complemented by information derived from the PPR of Jausiers indicating complete rock fall process areas including the run out zone (RTM, 2000a).
- **Avalanches:** The CLPA inventory - "Les Donnees de la Carte de Localisation des Phéonomènes d'Avalanche" (MEDD, 2007) - provides information on terrain observations and photo-interpretation results for the southeastern part of the study area. This includes primarily the north-facing slopes (parts of the Bachelard catchment, Galamonds, Bramafan Riou Versant and Abries nearly complete).
- **Floods:** Since no spatial records providing information on the extent of past events are available, recourse was made to the risk zones of the PPRs available for Jausiers, Enchastrayes, Faucon and Barcelonnette (RTM, 2000a,b, 2002, 2008). Especially for the river flooding, this information is highly valuable, since the river lies entirely in the settled area and no other data could be acquired. Non-spatial information, i.e. assessments about the 100 year discharge of the Ubaye at five points between Jausiers and Barcelonnette, are available from hydrological reports (IDEALP & Hydroetudes, 2008, 2010).

5.2.3. Data on Elements at Risk

A database with the footprints of all buildings, and that contains information on the type of building, use, building condition, material and number of floors, is available from the LIVE institute (Laboratoire Image, Ville, Environment) of CNRS, University of Strasbourg (for more detail on the database refer to Kappes *et al.*, in press, A.7 and to Puissant *et al.*, 2006). Moreover, digital information on infrastructure (roads and paths) and the outline of the settled areas is available from the LIVE institute. This data has been compiled in the framework of several projects, among them ALARM (Assessment of Landslide Risk and Mitigation in Mountain Areas, contract EVGI-2001-00018, 2002-2004).

5.3. Approach for the Performance of the Multi-Hazard Exposure Analysis

Based on the information compiled for the Barcelonnette basin, a case study is carried out. This comprises the performance of a multi-hazard exposure analysis with the MultiRISK Modelling Tool and the subsequent visualisation of the results with the MultiRISK Visualisation Tool. Moreover, potential hazard relations are investigated and finally a vulnerability analysis is carried out in the municipality Faucon de Barcelonnette. In this section, the application of the concepts and tools is explained.

5.3.1. Parameterisation of the MultiRISK Modelling Tool

The first step offered in the Modelling Tool is the susceptibility analysis. To perform this step, model parameters have to be chosen in accordance with the objectives of the study as well as the available information. However, in a multi-hazard context this is a challenging task because inventory information used for model calibrations is mostly difficult to obtain for multiple hazards. Moreover, the single-hazard models have to produce comparable results, which means with reference to a common basis or a common *scenario*. In full-hazard cases, this relates to certain scenarios such as 20, 50 or 100 year events or the annual probability of events above certain magnitudes. However, susceptibility analyses are not usually based on magnitude-frequency relations since susceptibility indicates only the propensity of an area to a certain process. Nevertheless, the model parameterisation can follow a conservative or a rather liberal expert estimate, or can be based on a set of event records. This implies that in a multi-hazard context a common *qualitative scenario* has to be defined according to which parameters are chosen. Since in the proposed top-down scheme the regional analysis is supposed to indicate as far as possible *all* zones potentially prone to hazards, hazard overlaps and risk, the adoption of a *worst-case scenario* is chosen.

Although many authors use the term *worst-case*, they refer to different definitions. For instance, BARTELS & VAN BEURDEN (1998, p. 118) apply this approach with the objective to “know any risk spot, regardless of areal unit size or shape”. BAXTER *et al.* (2008, p. 455) describe the worst-case context as “domain of low probability - high consequence incidents and uncertainty” and BOMMER & SCHERBAUM (2008) relate *conservative decisions* in a hazard analysis to the identification of the worst-case scenario. HUGGEL *et al.* (2002, p. 322) explain, that “a worst-case philosophy is followed to delineating the area which could be affected”. In this study, worst-case is defined as the choice of very conservative modelling parameters to identify as far as possible all potential hazard and risk spots.

However, between hazards, approaches to assess the worst-case scenario vary. For example with respect to landslide and avalanche modelling, expert appraisal related to observed events or information from comparable studies is often used. For instance, for the source identification of landslides and avalanches based on empirical rules, the conservative choice of the parameters offers a reasonable possibility to identify the overall area potentially susceptible. For instance, HORTON *et al.* (2008) decide to not exclude forested areas as potential source since "some debris flows can be observed in forests, and as the protective effect of trees can be removed by a fire or a cut down". For the definition of slope angle thresholds for the initiation of avalanches and landslides, frequently based on expert appraisal values are chosen that lead to a conservative estimate of the hazard situation (e.g. MORAN *et al.*, 2004). For the determination of the angle of reach for the run out modelling, large data sets of observed events and statistics carried out with these records give indications of potential maximum run out lengths (refer to COROMINAS, 1996; HUGGEL *et al.*, 2002; COROMINAS *et al.*, 2003; MORAN *et al.*, 2004).

While approaches to assess the worst-case scenario for landslides and avalanches are often expert- and experience-based, river flood worst-case methods follow different principles and contrast strongly to the strategies used for avalanches and landslides. In the river flood context, further terms referring to a meaning equivalent to *worst-case* are *extreme flood* or *maximum flood.* Thereby, RUIZ RODRIGUEZ + ZEISLER *et al.* (2001) define *extreme flood* as a very rare event with a recurrence probability that is too low to specify its return period and FRANCÉS & BOTERO (2003, p. 223) refer to the *probable maximum flood* as "the biggest flood physically possible in a specific catchment". For the calculation of the *maximum* or *extreme* floods very diverse methods are available. The presented approaches refer to simple methods, while sophisticated approaches such as the analysis of the probable maximum precipitation as input for a rainfall-run off model are not mentioned:

1. Estimation of the maximum discharge for the catchment area and potentially further influencing factors such as land cover (SCHICK, 1988; PEGRAM & PARAK, 2004; ABRAHAMSON & PENTLAND, 2010). Examples are the formulae proposed by FRANCOU & RODIER (1969) and KOVAC (1988, in PEGRAM & PARAK, 2004). For instance, ABRAHAMSON & PENTLAND (2010) propose the equation $Q = 17.795A^{0.8156}$ for the computation of the discharge Q based on the catchment area A for Vancouver Island, and $Q = 23.753A^{0.7808}$ for the British Columbia Coastal Region.

2. One option is the definition of the maximum or extreme flood on basis of a scenario with a defined return period (HUTTENLAU *et al.*, 2010). HUTTENLAU *et al.* (2010) cite several authors which describe the extreme flood with the 200 to 500 year event. RUIZ RODRIGUEZ + ZEISLER *et al.* (2001) use return periods between 1,250 and 10,000 years to assess the extreme flood for different sections of the Rhine delta. BRÜNDL (2008) applies the 1,000 year event to the modelling of the extreme flood of the river Lonza in a case study for the communities Gampel and Steg in the Canton Wallis.

3. Another approach is the increment of the water level of a certain flood scenario by a defined water depth. For instance UVM (2005) propose an increase of the 100 or 200 year flood by x m. For a section of the Oder the 200 year flood + 1 m has been applied (OderRegio, 2006) and at the Rhine, the 200 year flood + 0.5 m was chosen (Ruiz Rodriguez + Zeisler *et al.*, 2001).

4. Alternatively to the previous method, the discharge of a predefined scenario can be multiplied by a certain factor. Klumpp & Hörmann (2010) propose the multiplication of the 100 year flood by 1.6 and Hydrotec (2009) applied a factor of 1.3.

These methods show differences in their suitability to be used in a regional context. For the first approach the whole river catchment has to be considered. At a regional scale of about 1:10,000 and 1:50,000 the entire catchment is included in the area under consideration in only a few cases. This implies that for many cases, additional information for surrounding regions would have to be gathered, which complicates the procedure. For the second approach, statistical analyses of discharge time series have to be performed and extrapolated for very long periods, which has many uncertainties and assumptions. The third approach, the assumption of a certain additional water depth, is associated with specific characteristics of the river such as river size and morphology. Therefore, this measure is difficult to transfer to other rivers with different characteristics. By contrast, the multiplication of a certain commonly used scenarios such as the 100 or 200 year flood, with a defined factor, is more widely applicable and transferable to other rivers. Nevertheless, it also requires information of the scenario to use.

To perform the case study in the Barcelonnette basin, for landslides and avalanches the empirical models were parameterised by means of a literature review of comparable studies. Since not enough information is available in the basin to assess minimum angles of slopes prone to landslides or extrapolate worst-case angles of reach, those parameters found in the literature that lead to the most conservative assessment of the susceptible area have been chosen. For the river flood worst-case appraisal, the fourth method, multiplying the value of the 100 year flood by the factor 1.6 was chosen since it is applicable at a regional scale, does not require the definition and statistical calculation of a very low frequency event, and is better transferable to different river basins. The process of parameter choice is described in detail in Kappes *et al.* (subm.a, A.4) and is therefore not be repeated here in depth. Table 5.1 presents the final set of parameters chosen for the hazard analysis in MultiRISK.

For the validation step the inventory information previously presented is used and the exposure analysis is performed for single buildings, built-up areas and roads.

Table 5.1.: Parameters applied in the MultiRISK Modelling Tool for the Barcelonnette basin case study. The Holmgren exponent refers to the spreading algorithm for multiple flow directions (HOLMGREN, 1994). An exponent of 1 results in a wide spreading. As the value increases, the width of the flow spreading decreases.

	Sources		**Run out**	
	Parameters	Values chosen	Parameters	Values chosen
DF	Planar curvature threshold	$< -2/100\ m^{-1}$	Holmgren exponent	1
	Slope angle - upslope area threshold	Extreme fitting	Angle of reach	7^o
	Land use/cover & lithological units to be excluded	Outcropping limestone		
RF	Slope threshold	37^o	Holmgren exponent	1
	Land use/cover & lithological units to be excluded	Outcropping marls & clays	Angle of reach	29^o
SL	Soil bulk density	1,700 kgm^3	Holmgren exponent	1
	Slope threshold (friction angle)	28^o	Angle of reach	20^o
	Critical rainfall threshold	33 mm		
	Lithological units to be excluded	Outcropping limestone		
AV	Slope threshold	30^o-60^o	Holmgren exponent	1
	Land use/cover units to be excluded	Dense forest	Angle of reach	14^o
FL	Hydrograph, 100-year flood$*$1.6 with 48 hours duration			

5.3.2. Analysis of Hazard Relations

The proposed concept for the consideration of hazard relations consists of three steps, (1) the creation of a multi-hazard subsystem, (2) the identification of potential relations within and between the set of hazards and the set of influencing factors, and (3) the integration of hazard relations into the analysis scheme and the determination of those zones potentially prone to the effects. A multi-hazard subsystem with identified regional scale relations was presented in subsection 4.1.1. Based on this framework, the third step, the analysis of zones prone to hazard relations is carried out in the Barcelonnette basin. This comprises (a) the triggering of one hazard by another and (b) the disposition alteration. The detailed performance of this analysis is presented in KAPPES & GLADE (acc., A.6) and therefore only a resume is given here.

a) With respect to the triggering of one hazard by another, two possible combinations have been identified in the matrix presented in Table 4.2, the undercutting of slopes by floods and the damming of rivers or torrents by landslides. For the identification of potential slope undercutting during flood events, the shallow landslide source areas modelled with MultiRISK are overlain with the flood analysis result. However, an influence of the water beyond the overlapping area has to be expected due to water saturation and erosion of the toe. In order to consider this additional influence, the flooded area has been buffered. To test the method, in this first case study a buffer of 20 m has been assumed, corresponding to two pixels with respect to the resolution of the DEM of 10 m. The second type of relations between the two processes, the river damming by accumulation of landslide material in a river or torrent channel is performed by the overlay of the zones susceptible to shallow landslides with the water courses. However, only in narrow valleys or gorges, a damming can be expected since otherwise the water may deviate and remove the material slowly (Carrasco *et al.*, 2003). Therefore, Carrasco *et al.* (2003) propose to identify *gorge-type* valleys and to restrict the areas potentially prone to damming to those narrow river sections (for details refer to Kappes *et al.*, subm.a, A.4). Using the MultiRISK modelling results, an analysis of zones potentially prone to damming is performed.

b) An analysis of the disposition modification has not been carried out for the Barcelonnette basin. Since the multi-hazard susceptibility analysis performed with MultiRISK describes the worst-case scenario, the result would refer to the effect that all *potential* avalanches in the area may have on the forest stand and subsequently on the hazard situation. Since this is a highly improbable possibility and the usefulness of such an assessment is questionable, this step has not been performed. Nevertheless, such an analysis may be valid for a less extensive scenarios than the one used in this study.

5.3.3. Vulnerability Analysis

Based on the multi-hazard version of the PTVA a vulnerability analysis has been carried out for the municipality Faucon-de-Barcelonnette (KAPPES *et al.*, in press, A.7)[4]. Since the multi-hazard susceptibility areas resulting from the MultiRISK Modelling Tool do not exhibit the scale and level of detail required for the vulnerability analysis, the risk zones of the risk prevention plans (PPRs) are used instead, to determine the exposure of the buildings (Figure 5.2). Although called *risk zones*, the differing vulnerabilities of diverse structures is not considered, but a standard vulnerability of buildings and humans is assumed. Thereby, red zones indicate high and blue zones medium risk while in white zones no significant risk has to be expected (for details on the risk zones please refer to 5.1.3). By means of the multi-hazard version of the PTVA the buildings situated in

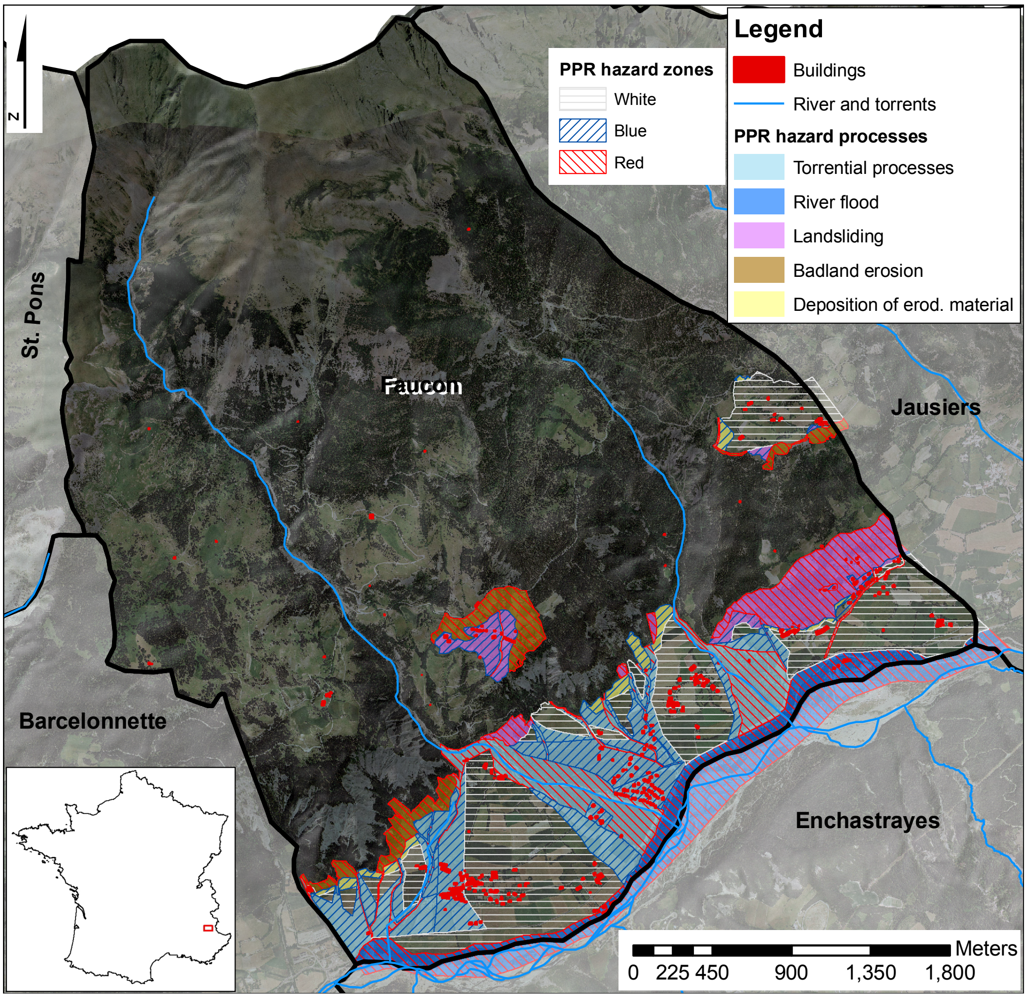

Figure 5.2.: Overview of the municipality of Faucon de Barcelonnette, situated between Jausiers, Enchastrayes and Barcelonnette (KAPPES *et al.*, in press, A.7).

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[4] The vulnerability assessment approach is not included in the MultiRISK Platform but forms a step towards a more local scale analysis.

these zones will be differentiated according to their hazard-specific vulnerabilities. This is done for the hazard zones of three of the five threats considered in the PPR, namely debris flows (torrent processes), river floods and landsliding while badland erosion and deposition of eroded material is not considered in this study. The PTVA offers not only hazard-specific vulnerability assessments but also customisation to user priorities. Two scenarios are developed to test this option, the *general* and the *emergency scenario* for three different hazards (Figure 5.3). The weighting of indicators for the *general scenario* is performed with the objective to support local authorities, insurance companies or house owners in the identification of buildings requiring vulnerability reduction measures. For the *emergency scenario*, weights are determined in order to identify those buildings in which inhabitants have the highest need for support during an event. Especially for emergency services and rescue teams this information is highly valuable. From a set of vulnerability indicators including building characteristics and information on the building surrounding, those relevant for each hazard were chosen (refer to KAPPES *et al.*, in press, A.7). Scores and weights forming the basis for the calculation of the relative vulnerability indices were assigned according to expert appraisal (Figure 5.3).

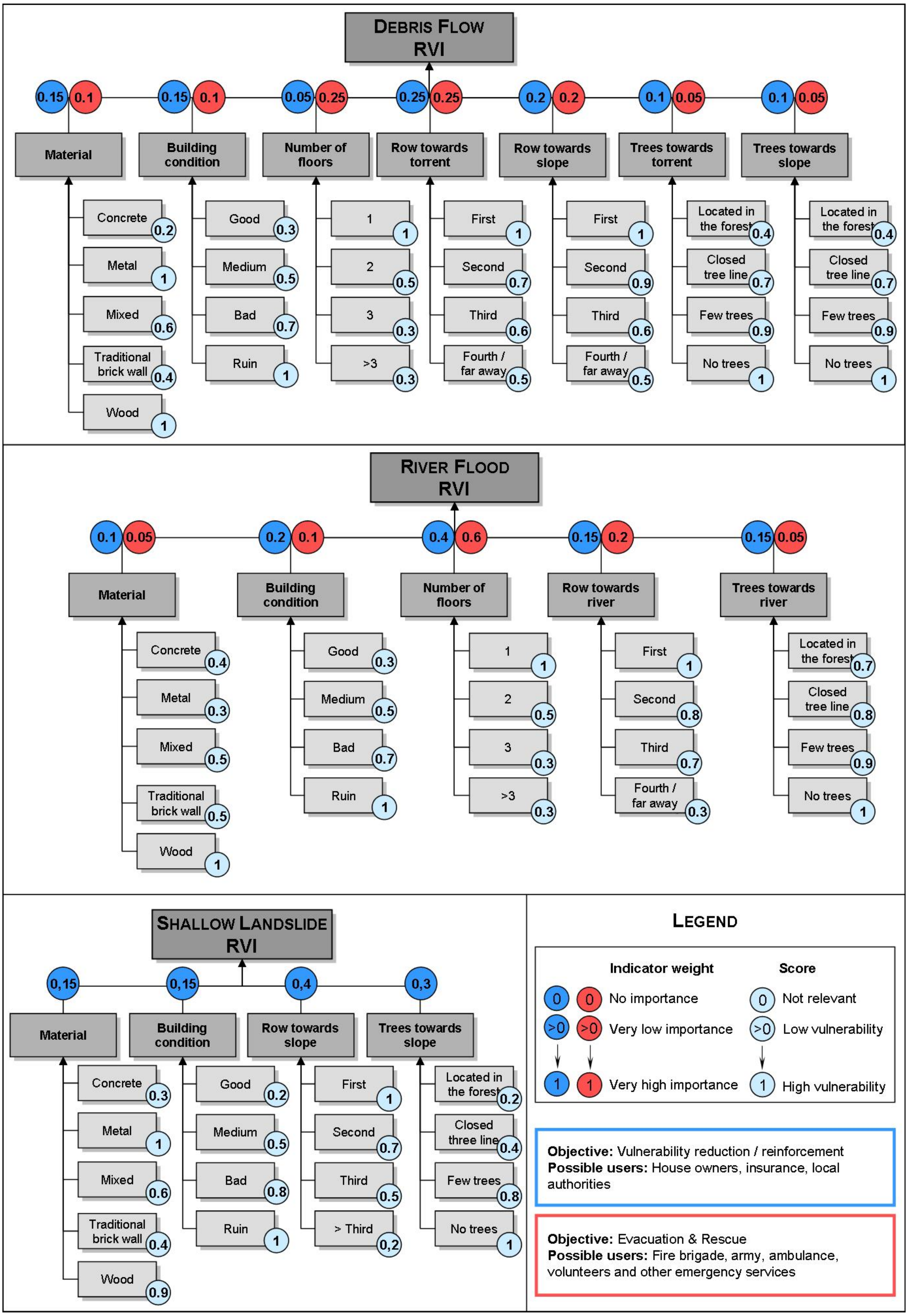

Figure 5.3.: Weights and scores assigned for the calculation of the relative vulnerability index for debris flows, river floods and shallow landslides, for the general and the emergency scenario (vulnerability reduction & reinforcement (blue) and evacuation & rescue (red), KAPPES *et al.*, in press, A.7).

5.4. Results and Discussion

In this section the results of the application of MultiRISK in the Barcelonnette Basin are presented. On basis, but outside of MultiRISK, hazard relations have been examined and the vulnerability of buildings and infrastructure of one municipality has been analysed in detail. The results and short discussions of these three analysis steps are presented below. For further detail refer to the articles in the appendix (Kappes *et al.*, 2010, subm.a; Kappes & Glade, acc.; Kappes *et al.*, in press).

5.4.1. Results from the MultiRISK Platform

The parameters presented in Table 5.1 were entered into the MultiRISK Modelling Platform and the analyses performed. Since the software tool is primarily developed for practical applications, issues such as comfort, functionality and time consumption are important parameters to assess its usefulness. Therefore, several technical aspects are outlined here. Having already prepared the input files and determined modelling parameters, the setup of the model including defining the project folder and project name, upload of the input files and entering the model parameters takes only several minutes. Altogether, the data preparation, derivative production and source identification of all processes took about 20 minutes[5]. The validation for all five processes took about 5 minutes and the exposure analysis around 5 minutes as well. The preparation of the data for the visualization accounted for around 10 minutes. The processes requiring much more time were the flood modelling with about 24 hours and the run out computations. With respect to the run out analyses, Flow-R offers two modes, the complete and the quick mode. In the complete mode, each single source pixel is propagated forwards. In the quick mode first the propagation of superior sources is calculated and, if lower ones follow the same path with a similar or lower kinetic energy, they are neglected. This reduction of single calculation steps provides a significant time saving (Kappes *et al.*, subm.a). With the choice of the quick mode for the run out calculations the modelling lasted in total for about 50 hours. The complete modelling took much longer as the values in brackets behind the duration of the quick analysis indicate (Table 5.2). Thus with the present computer specifications, it is not a really flexible method for scenario calculations or testing. By contrast, the *quick* run is much faster and leads to almost identical identification of susceptibility areas. Hence, the final modelling has been carried out in the quick mode and this is also the suggestion for further applications of the MultiRISK Modelling Tool on computers with similar specifications[6].

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[5] Computer specifications: Intel(R) Core(TM)2 CPU 6400 @ 2.13GHz, 2.13 GHz, 3.25 GB RAM, Windows XP.

[6] This paragraph is in large parts repeated from the article Kappes *et al.* (subm.a, A.4).

Table 5.2.: Modelling results of the worst-case multi-hazard exposure analysis performed in the Barcelonnette basin. The complete susceptible area refers to the proportion of the total catchment. TP - true positives, FP - false positives, FN - false negatives, TN - true negatives, SY - sensitivity and PPP - positive prediction power.

	Computation time quick & (complete)	**Complete susceptible area**	**Validation TP, FP, FN, (TN)**		**Quality indicators SY**	**PPP**	**Exposure Sources**	**Run out**
	[h]	[m^2]	[m^2]	[%]	[%]	[%]	Building no. [-], road length [m], settled area [m^2]	
DF	∼1 (∼36)	62,995,900 (17%)	210,936 62,784,964 42,259 (308,442,833)	0.06 16.9 0.01 (83.03)	83.3	0.3	1 463 225	1,143 110,911 1,249,831
RF	∼4 (∼11)	86,629,178 (23%)	555,834 86,073,344 53,328 (284,798,486)	0.15 23.17 0.01 (76.67)	91.3	0.6	10 6,638 4,389	49 40,081 34,765
SL	∼10 (∼336)	195,782,092 (53%)	503,463 195,278,465 40,394 (175,658,670)	0.14 52.57 0.01 (47.29)	92.6	7.4	297 104,327 157,803	872 228,825 651,148
AV	∼10 (>340)	212,672,507 (57%)	49,144,230 163,528,277 2,377,168 (156,431,317)	13.23 44.02 0.64 (42.11)	95.4	23.1	36 18,11 11,628	1,633 254,718 1,684,640
FL	∼24	10,447,502 (3%)	3,366,192 7,081,310 296,430 (360,737,060)	0.91 1.91 0.08 (97.11)	91.9	32.2	1,319 64,419 1,902,747	

The largest susceptible area has been determined for avalanches with over 200 km^2, followed by shallow landslides with almost 200 km^2. As a result, twice the number of buildings is exposed to avalanches with more than 1,600 buildings, while only about 900 buildings are situated in the area susceptible to shallow landslides. Much smaller areas have been identified for rock falls ($\sim$ 87 km^2) and debris flows ($\sim$ 63 km^2). Considering its smaller size, debris flows pose a comparatively high threat to buildings with about 1,143 buildings exposed while for rock falls a lowest number of buildings ($\sim$50) is identified to be exposed. The area prone to floods is by far the lowest ($\sim$ 10 km^2) but has the second highest number of buildings is exposed ($\sim$ 1,300). This very differing sizes of the susceptible areas are in a great measure attributable to the proportioning between slopes, that form the largest part of the area and that are prone to debris flows, avalanches, rock falls and shallow landslides, and the much smaller flood plain that is prone to river floods. At the same time, the villages and cities are located on the valley floor close to the river and on the torrent fans. This explains the comparatively high exposure to debris flows and floods despite the rather small areas prone to these hazards.

The validation of the susceptibility models (Figure 5.4) resulted in high sensitivity values of over 83% for any of the processes indicating low false negative proportions. However, the prediction power is low, especially for debris flows and rock falls with <1% and slightly higher for shallow landslides with $\sim$7%. Only for the snow avalanche and the river flood model higher values were identified with $\sim$23% and $\sim$32%. At first, this result indicates a considerable overestimation of the modelled susceptible areas, nevertheless these numbers have to be interpreted in the light of two aspects, (a) the process characteristics and (b) the size of the inventory used for the validation. (a) For instance, the occurrence of river floods and channel debris flows is clearly restricted to the area of the flood plain and the torrent channel, and the recurrence of these events is possible and probable. By contrast, the area prone to shallow landslides is less limited to a certain comparatively small zone but is in most mountain areas much larger. Moreover, the incidence of a shallow landslide event does not indicate the location of further events, since only a reactivation but not a recurrence is possible as in the case of river floods. These two aspects entail that already few recorded flood events may cover a comparatively large proportion of the area potentially affected in the future. On the contrary, in the case of shallow landslides the area potentially prone to failure is only in a very small fraction covered by past events which, moreover, can only reactivate. This indicates that the positive prediction power of floods may naturally be higher than of shallow landslides. (b) Furthermore, the size of the inventory plays an important role, the larger the inventory the higher can the positive prediction power be. This reflects in the validation results of the Barcelonnette basin: the inventories largest in area are available for floods and avalanches (see Figure 5.4) and the positive prediction powers for these two processes are the highest as well. However, in addition both processes, river floods and avalanches, are recurring hazards, an aspect

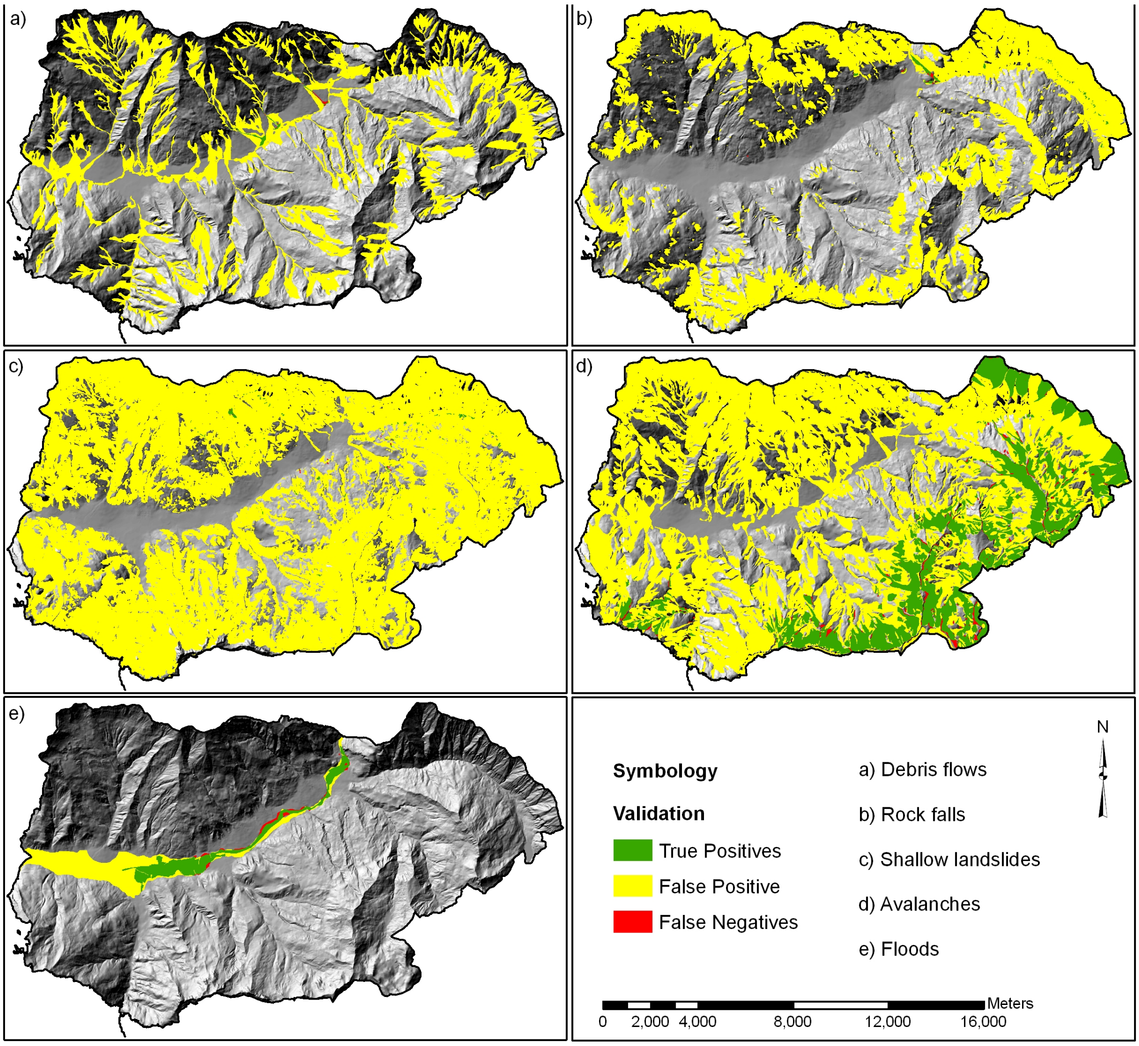
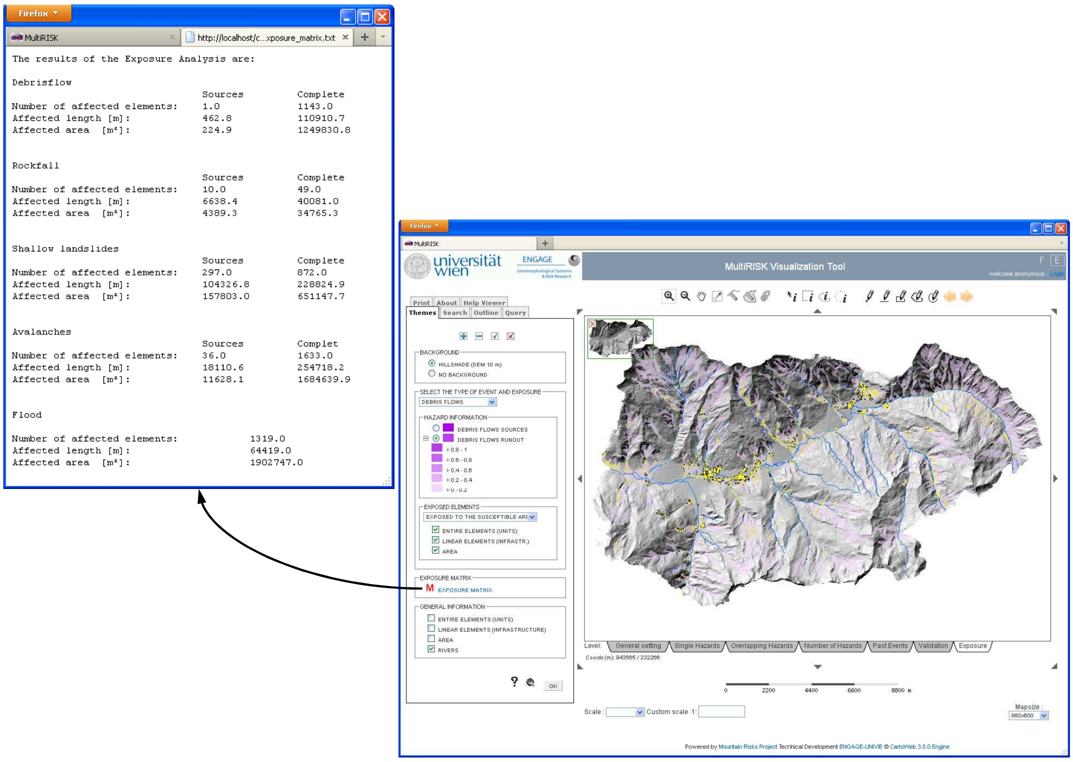


Figure 5.4.: Maps of the validation results (Kappes *et al.*, subm.a, A.4).

also influencing this result. This combination of effects hinders a direct comparison and ranking of model qualities and a careful interpretation is necessary. An approch to overcome this restriction could be the implementation of an uncertainty assessment to enable an evaluation of, and comparison between the quality of the modelling results of different hazard models. Moreover, uncertainty appraisals are important for decision-making and risk management as Granger *et al.* (1999, p. 3) illustrate with the statement that "the effectiveness of risk mitigation strategies is inversly proportional to the level of uncertainty that exists. Bell & Glade (2004b) present a qualitative method to estimate uncertainties in a multi-hazard context, nevertheless, uncertainty approaches are still rare in this field although several authors mention the importance to integrate this aspect (e.g. Granger, 1998; vanWesten *et al.*, 2010; Schmidt *et al.*, 2011).

In summary, the quality assessment of the modelling results, referring to their ability to correctly predict susceptible areas and the degree of overestimation of this prediction is the principal objective of a validation step. However, in a multi-hazard context it is rather difficult to rank the quality of modelling results of different hazards due to the differing characteristics of these hazards and inventory sizes. Thus a careful interpretation is recommended. Especially in the case of this study area, the shallow landslide susceptibility of 53% of the total area, seems extremely high, the small inventory size does not allow for a clear interpretation of this result. For a more detailed description and interpretation of the results described here, please refer to (KAPPES *et al.*, subm.a, A.4).

The visualisation tool offers, in addition to the purely numerical results, the spatial depiction of the modelling outcome. From a practical point of view, this proved a very fast option to get an overview of the modelling output and provided the expected advantage of rapid and interactive exploration of the results without time-consuming upload in a GIS software and the assignment of colours and patterns. Especially with respect to the spatial distribution of hazards towards each other, the Visualisation Tool facilitates a structured depiction. The map presenting the overlay of three hazards and the depiction of the number of overlapping hazards offer the interpretation of the distribution of single, three and all five hazards (Figure 4.7). For instance, in the Barcelonnette basin, the overlap of the susceptible areas of all three landslide types and the avalanche in the upper slopes becomes apparent (Figure 4.7 c). The midslopes are less prone to the overlap of these four processes and the superimposition of even all five hazards is very rare since rock falls and river floods hardly overlap. The information on which processes contribute to the respective number of overlapping hazards can be queried by clicking on the location of interest. Also with respect to the distribution of exposed elements at risk, the combined visualisation with the susceptibility zones offers a clear identification of the spatial patterns (Figure 5.5). Moreover, the comparison with the numerical results is enabled by means of a hyperlink that opens an additional tab in the internet browser with this information (Figure 5.5). This option is also available for the validation results where a hyperlink offers the confusion matrices.



```
The results of the Exposure Analysis are:

Debrisflow
                               Sources         Complete
Number of affected elements:   1.0             1143.0
Affected length [m]:           462.8           110910.7
Affected area  [m²]:           224.9           1249830.8


Rockfall
                               Sources         Complete
Number of affected elements:   10.0            49.0
Affected length [m]:           6638.4          40081.0
Affected area  [m²]:           4389.3          34765.3


Shallow landslides
                               Sources         Complete
Number of affected elements:   297.0           872.0
Affected length [m]:           104326.8        228824.9
Affected area  [m²]:           157803.0        651147.7


Avalanches
                               Sources         Complet
Number of affected elements:   36.0            1633.0
Affected length [m]:           18110.6         254718.2
Affected area  [m²]:           11628.1         1684639.9


Flood

Number of affected elements:           1319.0
Affected length [m]:                   64419.0
Affected area  [m²]:                   1902747.0
```

BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

SELECT THE TYPE OF EVENT AND EXPOSURE
DEBRIS FLOWS

HAZARD INFORMATION
○ DEBRIS FLOWS SOURCES
● DEBRIS FLOWS RUNOUT

EXPOSED ELEMENTS
EXPOSED TO THE SUSCEPTIBLE ARE
☑ ENTIRE ELEMENTS (UNITS)
☑ LINEAR ELEMENTS (INFRASTR.)
☑ AREA

EXPOSURE MATRIX
M EXPOSURE MATRIX

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☑ RIVERS

Coords (m): 943565 / 232266

Mapsize : 860x600

Powered by Mountain Risks Project Tecnhical Development ENGAGE-UNIVIE © CartoWeb 3.5.0 Engine

Figure 5.5.: Screenshot of the Visualisation Platform depicting the map that presents the exposed elements at risk. A hyperlink in the layer tree opens an additional tab in the internet browser showing numerical results of the exposure analysis.

5.4.2. Potential Hazard Relations in the Barcelonnette Basin

On the basis of the modelling results obtained from the analysis performed in MultiRISK, the zones potentially prone to hazard cascades have been examined outside of the modelling platform (for more detail refer to Kappes & Glade, acc., A.6). With respect to the potential slope undercutting during flood events, a multitude of zones has been identified in the basin. Figure 5.6 b indicates an area of undercutting of the River Ubaye. However, an overlay with elements at risk did not indicate any buildings potentially affected by landsliding due to undercutting. Only several smaller roads may be affected by this phenomenon. At these spots a more detailed analysis may be of interest if the roads are sufficiently important for the transport in the valley. The potential damming of the river due to the sliding mass is not to be expected since the Ubaye is mainly braided river and so does not block easily.

With respect to river damming by the accumulation of landslide material in a river or tor-

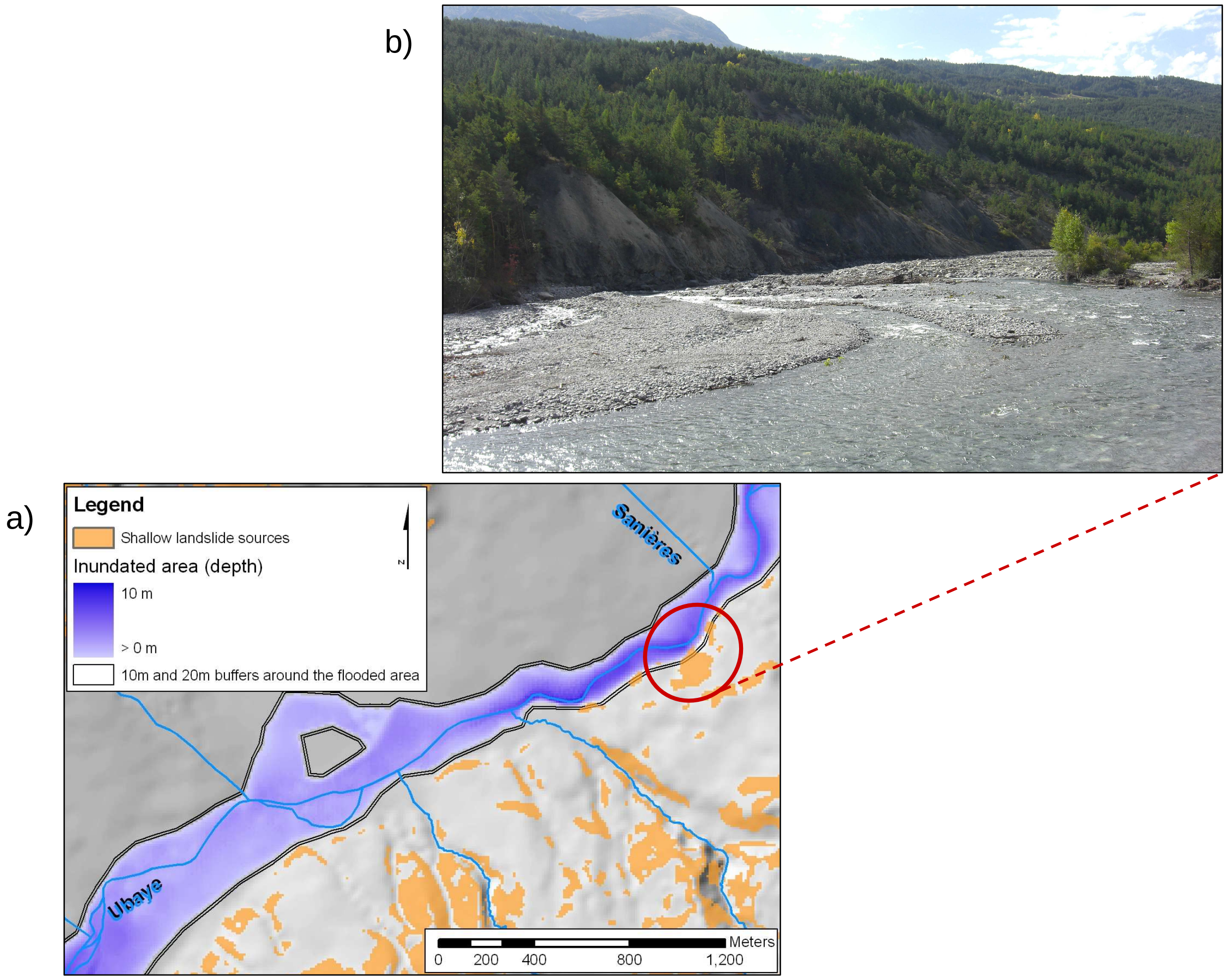


Figure 5.6.: Potential slope undercutting by the Ubaye river at the confluence of Sanières. The area in the red ellipse in the map (a) is illustrated by a photograph of the specific site indicating the destabilitsation of the respective slope (b) (Kappes & Glade, acc., A.6).

rent channel, many areas of the basin are apparently prone to this phenomenon. In Figure 5.7 an example of the Riou Bourdoux catchment is given, indicating a delimitation of the zones in which shallow landslides and river courses overlap, nevertheless, many spots may be prone to damming in a narrow channel. In other catchments of the basin show similarly high quantities of spots were identified as potentially prone to damming. Actually, the slopes of the torrents are very steep and in large parts unstable. However, not all unstable zones provide enough material to lead to a serious damming of the torrent. Probably a more detailed analysis of the shallow landslide potential has to be performed to identify sections potentially dammed by a sliding mass big enough to lead to water accumulation. Moreover, in local analyses the potential effect of a debris flow following the dam break has to be examined in detail to provide the necessary information to determine the potential

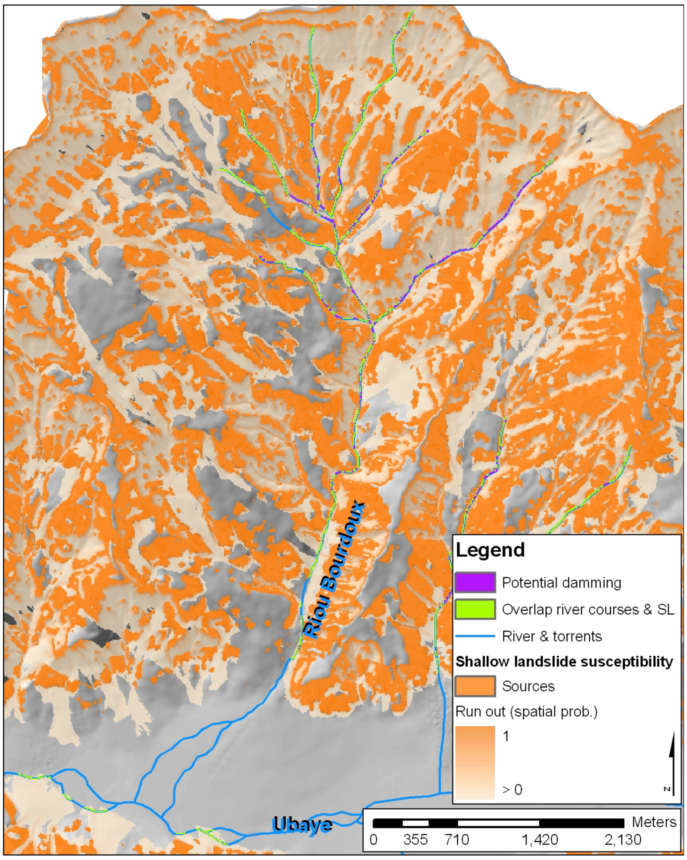


Figure 5.7.: Areas potentially affected by slope undercutting, example of the Riou Bourdoux catchment (modified after Kappes & Glade, acc., A.6). In green the overlap of the area susceptible to shallow landslides (SL) and river courses is presented. In purple those overlapping zones situated in gorge-type valleys are depicted.

consequences for exposed elements at risk.

The disposition modification is not considered for the Barcelonnette basin, since the assumption of forest destruction for the complete worst-case avalanche susceptibility area is highly unrealistic. Even for more rare scenarios it is still some kind of *worst-case* assumption that all possible avalanches will happen and completely destroy the forest situated in their run out zone. However, this assumption may be valid for a less extensive scenarios than the one used in this study. Therefore, no analyses with respect to the disposition modification have been carried out in this context.

5.4.3. Physical Vulnerability in the Faucon Municipality

The relative vulnerability index values for each building were calculated on basis of the assigned scores and weights, and classified into high, medium and low vulnerability classes according to the quantile classification method. That implies, the same number of buildings situated in the area at risk by one hazard is classified as high, medium or low vulnerability to provide a clear prioritisation in that area. The resulting vulnerability maps presented in Figure 5.8 offer indications for general risk reduction purposes as well as for emergency situations for debris flows, river floods and shallow landslides. However, the results for the two scenarios, the general and the emergency scenario elaborated for debris flows and floods, indicate only small differences, a situation that has to be ascribed to the lack of information. For instance for emergency managers, information on the distribution of the population would be of high importance. At this first stage only the physical environment has been considered, leading to a low degree of difference between scenarios. Nevertheless, the analysis results give first indications for the prioritisation of buildings to be reinforced or attended to in emergency situations. However, these indications offer in first place orientation for the prioritisation of buildings situated in either the blue or in the red area. By contrast, a prioritisation between hazard zones is much more difficult since hazard and vulnerability levels cannot be combined to rank the risks they face. For the detailed presentation and discussion of the results please refer to Kappes *et al.* (in press, A.7).

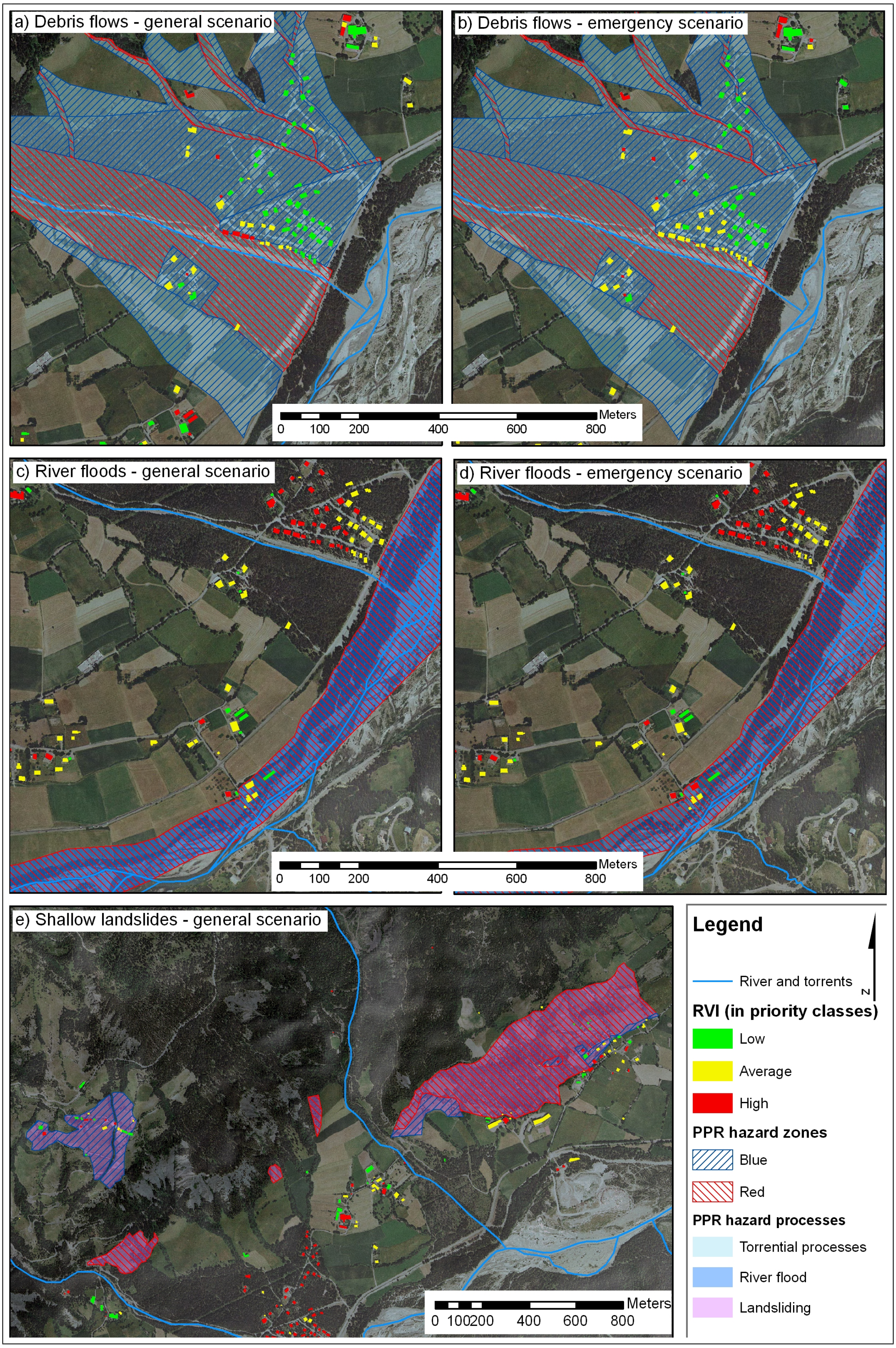


Figure 5.8.: Physical vulnerability maps of the Faucon municipality (Kappes *et al.*, in press, A.7).

5.5. Insights gained from the Concept and Platform Application in the Barcelonnette Basin

In the presented case study, the MultiRISK Modelling tool proved to be useful in multi-hazard exposure analyses when considering the very short time required from the user for the initialisation of the software. However, the modelling itself is still time consuming, especially in the complete run out modelling mode and for a worst-case scenario in which a large number of potential sources is identified and has to be propagated. The quick run out modelling mode is much faster and makes the tool applicable and more flexible with the current computer specifications. However, the most challenging aspect of the procedure is the definition of the parameters. In this case study a *worst-case* scenario has been chosen and seems to be generally suitable in a top-down approach, especially in a areas with low data availability and without previously performed hazard analyses. Nevertheless, the literature-based approach for model parameterisation used in this study led to an apparent overestimation of the susceptible areas. This effect has to be considered in the interpretation of the results or a more adjusted worst-case parameterisation of the respective area has to be performed.

The MultRISK Modelling results provided a good basis for the investigation of potential hazard relations even though they are still not implemented in MultiRISK. Although the usefulness of an examination of disposition alterations had to be questioned for a worst-case scenario, the identification of zones potentially prone to hazard cascades appears to be a promising approach. The next challenging step is to perform local detailed studies of potential cascades for the identified zones.

The MultiRISK Visualisation Tool proved supportive for the fast examination of the modelling results to check the modelling output. However, its applicability and user-friendliness has to be tested with external users. This applies even more for the necessity to test its usefulness for publishing the final modelling results on the internet and to be used by a range of stakeholders.

The vulnerability approach has only been presented in brief, details are presented in Appendix A.2. Nevertheless, it became apparent that this method to evaluate different element characteristics with respect to the hazard properties offers interesting possibilities for the prioritisation of the most vulnerable buildings. Thereby, the information on multiple building characteristics enables the calculation of relative vulnerability indices for multiple processes as well as for different stakeholders and objectives. The more information on buildings and inhabitants is available, the more supportive can the indications given by the final RVI be. However, the data requirements are a major limitation.

6. Discussion of the Hypotheses

At the beginning of this study two hypotheses have been outlined:

Hypothesis I	Multi-hazard (risk) analyses are not just the sum of single-hazard (risk) analyses.
Hypothesis II	A software platform provides practical advantages for coherent and reproducible multi-hazard risk modelling and visualisation.

Based on the two hypotheses in total five objectives have been formulated. These objectives directed the course of this study and are linked to each other: the first step has been the identification of challenges arising in the multi-hazard context, compiled in the *major multi-hazard issues*, and the current approaches to solution (hypothesis I, objectives 1 and 2). Secondly, under consideration of the identified issues and the knowledge gained from this review, an analysis and visualisation scheme has been developed (hypothesis I, objective 3). Thirdly, the conceptual approach has been implemented into the software platform MultiRISK (hypothesis II, objectives 1 & 2). Finally, to test the conceptual approaches and the technical realisations of the model, a case study has been carried out. In this chapter, the challenges and difficulties while fulfilling the objectives are discussed and on this basis the hypotheses are examined.

6.1. Is Multi- just the Sum of Single-Hazard Risks?

Hypothesis I	**Multi-hazard (risk) analyses are not just the sum of single-hazard (risk) studies**

In the framework of the first hypothesis, three objectives have been formulated: (1) to investigate aspects and challenges emerging in the multi-hazard risk environment, (2) to review the recent approaches used to cope with the identified challenges, and (3) to develop an analysis scheme considering the knowledge gained in the previous two steps. To fulfill the first two objectives, a detailed literature review has been performed (refer to chapter 2 and Kappes *et al.* (subm.b, A.1)). Thereby, not only studies dealing with multi-hazards in the sense of *all relevant hazards in a defined area* but in general those considering *more-than-one-hazard* have been examined. The literature review resulted in the compilation of seven *major multi-hazard issues* that provoke difficulties in the multi-hazard context.

These *issues* have guided the elaboration of an analysis and visualisation scheme, the third objective, and the knowledge gained about possible solutions provided the base for the development of solutions. The performance of a case study in the Barcelonnette basin provided the possibility to examine the usefulness and the coherence of the concepts as well as the practicalness of the software implementations. In the following, the experiences gained on the seven *multi-hazard issues* in the course of concept development, software implementations and the case study are outlined and subsequently the implications with respect to the first hypothesis are discussed:

1) High data requirements of multi-hazard analyses: For the performance of multi-hazard risk analyses, a large amount of information is necessary and this prerequisite reduces its practicality. In the first place this refers to the data necessary when summing up the required input for all considered hazards. Particularly challenging is the acquisition of inventories for all processes of comparative quality and extent but also the collection of detailed laboratory and field survey data. In the present study, a top-down design has been identified as a promising approach to create an effective and applicable analysis scheme. This concept consists of two levels, a regional and a local level, has been proposed. At the regional scale, susceptibility and exposure are modelled to identify zones of hazard overlap and potential risk for which subsequently detailed local analyses can be performed. This implies that the regional analysis can follow a simple approach and extensive inventory data for the establishment of magnitude-frequency relationships, laboratory or field survey information are not necessary. Subsequently, resources can be directed to the determined zones of hazard overlap and risk and detailed analyses are only carried out for these areas. Applying this approach in the Barcelonnette basin, it proved suitable to identify zones to be analysed in local studies, but during the regional multi-hazard susceptibility analysis challenges became apparent. Even though susceptibility analyses usually follow rather simple approaches, in a multi-hazard context the need to consider the comparability between hazards gives rise to challenges. Hazard susceptibility refers to the area possibly affected by a process and is usually not based on magnitude-frequency estimates. However, in a multi-hazard context, some kind of qualitative susceptibility scenario has to be defined according to which the parameters are chosen for each hazard. To give an example, in the landslide context, the calibration of susceptibility analysis models is frequently based on expert appraisal in combination with information on past events. For instance COROMINAS *et al.* (2003) define on the basis of expert knowledge and information on past events those combinations of geological material and threshold slope angle that lead to either to rock fall, debris flow, shallow landslide and rotational slide susceptibility. Since all four processes are analysed according to the same principle, it is possible to choose the parameters in a way that leads to an equivalence of the results. However, for example floods are analysed by models based on differing parameters and therefore independent criteria have to be defined to guide the parameterisation. In the

Barcelonnette case study, the *worst-case* scenario has been chosen as orientation, requiring more information and resources for parameterisation than an expert-based determination as presented in Corominas *et al.* (2003). This indicates that the performance of multi-hazard analyses may even lead to higher data-requirements since the comparability of the analysis results has to be considered.

Although the performance of multi-hazard analyses according to an overarching scheme to consider the comparability issue is demanding and may result in the requirement of additional information, the joint analysis of multiple hazards also offers advantages. With the joint data gathering, preparation and processing, time and effort can be saved. For the regional study carried out in the Barcelonnette basin, topographic, land use and lithology information had to be obtained, quality and format checked etc. In a multi-hazard context this has not to be done for each process separately but is done once and leads to an efficient procedure with less redundancies.

In summary, a top-down strategy as proposed by Castellanos Abella (2008) in the landslide context has also been identified as a promising approach to multi-hazard risk since it offers the most efficient use of resources, although the full effectiveness has still to be evaluated since only the first step, the regional analysis scheme, has been developed in detail. Nevertheless, multi-hazard analyses are datademanding since many processes, each with specific data needs, are analysed and moreover the comparability between hazards has to be considered. This leads to the requirement of an equivalent level of information for all hazards, the choice of a method providing comparable results and may thereby lead to the need of additional data. Nevertheless, the joint acquisition and preparation of input data offers time-saving and a more efficient procedure.

2) Scale differences: The analysis scale of multi-hazard risk examinations for risk management and reduction purposes is usually determined by the requirements of the stakeholders. Thereby, *scale* refers to the spatial extent of the area under consideration and the level of detail at which the results have to be provided and therefore the analysis is carried out. However, a scale determined according to practical needs matches the characteristics of each process of a set of considered hazards better or worse. For instance, in the present study a regional analysis has been performed. The hazard set under consideration includes rather local hazards with debris flows, rock falls, shallow landslides and snow avalanches with the result that the complete process areas are situated within the studied zone. However, since the modelling scale is rather small for the local processes, detailed analyses have to be performed on a local scale while at a regional scale an approximation is given. An exception are the river floods because usually at a regional level only part of the catchment of a river is located within the studied area, and implies that the process cannot be examined as a whole. As a consequence, certain approaches or methods for flood modelling are not usable since information is missing. This applies for instance to process-based rainfall-run off models or empirical estimates of the regional maximum flood as outlined in PEGRAM & PARAK (2004) since the required information concerning catchment characteristics, size etc. is not available. Other hazards as storms, hail or earthquakes exhibit a still much more diverging spatial scale and their modelling at a regional level is even more challenging. To only take earthquakes as an example, the process modelling solely within the Barcelonnette basin would not be possible since it is likely that earthquake sources lie outside of the basin and exert an effect. A possible solution to this problem is the inclusion of supraregional information and downscaling to a regional resolution under consideration of regionally relevant parameters. For instance in the case of earthquakes two very important factors differentiating the hazard intensity at a regional level are the topography (BOORE, 1972; BOUCKOVALAS & PAPADIMITROU, 2005; SHAFIQUE *et al.*, 2008; ANGGRAENI, 2010) and the soil & geology (BOUR *et al.*, 2000; WALD & ALLEN, 2007; ANGGRAENI, 2010; USGS, 2009). Shaking is increased at mountain tops and ridges while valleys face usually reduced ground motion (LEE *et al.*, 2009). With respect to soil characteristics, soft soils and regolith lead to an amplification of the ground motion whereas unweathered rock outcrops contribute to a lesser extent to shaking amplification (WALD & ALLEN, 2007; USGS, 2009). This example illustrates the need for information at a smaller scale as input at a more local, in this case at the regional, scale and raises the question, how this aspect can be included in a coherent way in a multi-hazard analysis scheme.

In the present study, the development of a multi-scale top-down approach has been proposed, focusing on the regional scale to provide information for local detailed analyses. This accommodates the local hazards since it offers the possibility to first identify hotspots and then focus in local analyses on these zones. An amplification of the considered levels towards smaller scales may offer a promising possibility to also take the hazard characteristics of extensive processes better into account. That implies that in an extended multi-scale approach one level does not only offer indications how to direct resources very efficiently at another level but may also form input in a downscaling approach. However, as pointed out before, primarily the user-specific needs determine in the required output and thereby the scale at which the analyses have to be carried out. Nevertheless, mostly this does not refer to precise and fixed levels but rather to a description of needs. Thus, a merging of the administrative levels and user-specific needs with the necessities in the multi-hazard context due to process-specific characteristics indicates a promising approach to the creation of a comprehensive multi-scale analysis scheme.

Apart from the spatial, also the temporal scale poses challenges in the multi-hazard context. Although few problems arose within the set of processes chosen for this study, the inclusion of hazards with very differing return periods such as earthquakes, may lead to difficulties. While for damaging landslides or floods, return periods of several decades to centuries are to be expected, damaging earthquakes rather exhibit return periods of centuries up to millennia. Consequently, the creation of high-frequency scenarios below the 100 year event are rather unusual for earthquakes and low-frequency scenarios roughly

above the 500 year event may be in use for earthquakes but less for floods. These contrasts also have an influence on the worst-case scenario modelling. In the context of river floods, *extreme* or *worst-case* may refer to a return periods of about 1,000 years as proposed by Bründl (2008) or to 1,250-10,000 years as in the study of Ruiz Rodriguez + Zeisler *et al.* (2001). By contrast, in the case of earthquakes scenario modelling reaches still longer return periods as the curves proposed by Grünthal *et al.* (2006, Figure 2.5) indicate. The inclusion of a process of such low frequencies but extremely high magnitudes with high spatial extent could lead to a distortion of the result. Due to the very high magnitudes earthquakes exhibit, although at very low frequencies, this process would dominate and worst-case damage assessment. Thus, for a set of temporally very distinct hazards, the objectives of a study and the suitability of an approach as the *worst-case* analysis have to be revised, especially with respect to the requirements of involved stakeholders and decision-makers. Grünthal *et al.* (2006) indicate a possible solution with damage curves opposing for each return period the damages to be expected (Figure 2.5). Thereby, these very differing relations between return period and damage can be clearly visualised, compared between hazards and considered in the decision-making process although high data-requirements are a disadvantage of such an approach.
In summary, spatial as well as temporal scales differ between hazards and towards stakeholders' needs. With respect to the spatial scale, the experiences made in the present study point towards the elaboration of a multi-scale analysis approach adjusted to stakeholder needs and process characteristics. With respect to the temporal scale the difficulty of including very high magnitude and low frequency processes into a worst-case approach has been identified and raises the question to what extent temporally very differing processes can be included in worst-case and in general in susceptibility analyses.

3) Differing model principles, assumptions and uncertainties: Assuming that models based on similar principles and assumptions may produce more comparable results, in this respect similar models have been selected. In the present study, a group of *empirical models* was chosen to build up the analysis scheme, although several challenges arose during the selection process. While snow avalanches, debris flows and rock falls are frequently analysed by empirical methods in a very similar manner, this approach is much less used for the analysis of shallow landslides. By contrast, for shallow landslide modelling, statistical and physically-based are more commonly applied to consider the process-specific characteristics. With respect to flood modelling the empirical approach is based on a very strong simplification and its application is restricted to certain settings, while physically-based approaches meet the qualitative requirements of a regional study possibly better. Thus, the question arises if models following similar principles will lead to comparable results, although they may be not equally well-fitting to the different processes. In this context, the results of the validation procedure provide interesting insights. With the creation of confusion matrices for the validation of the hazard modelling results, one approach was chosen for all processes. The method proved applicable for each of the processes and with the very variable inventory sizes. Nevertheless, as outlined in the previous chapter it is not possible to compare the quality measures of sensitivity and positive prediction power without considering the hazard characteristics and the inventory size. This indicates that the same method, in this case confusion matrices for model validation, may lead to qualitatively different results for distinct processes and therefore outcomes that have to be compared carefully. Transfered to the hazard modelling context, the same model does not offer necessarily results of similar quality for various hazards since the fit between hazard and model differs. Nevertheless, equivalently fitting models based on very contrasting principles will not provide comparable results either. Thus both aspects have to be considered in the model choice to find the best fitting and most similar modelling approaches. In summary, the use of similar models for similar processes is reasonable as long as these models are similarly well-fitting. Where this is not the case the differences in fit have to be included into the interpretation of the analysis results or alternative methods that match better have to be chosen. Thus, the model choice is not a very significant parameter to compare model qualities, and therefore the validation of modelling results takes an important role. However, as became apparent, the validation faces difficulties with differing process characteristics as well. This suggests to include the analysis of uncertainties into the modelling procedure to independently compare model qualities.

4) Hazard relations and their consequences: In the present study, two types of hazard relations have been examined: (a) those altering the hazard level and modifying the manifestation form and (b) those leading to a shift in the vulnerability of elements at risk (subsection 3.1.2).

a) For this type of hazard relations, a systemic approach proved viable by offering a description of the phenomena and considering them as processes pertaining to systems that are related and interact. Thus effects emerge that differ from the simple sum of processes and system components. For the detailed investigation of these relations a subdivision into disposition modifications and hazard cascades in which one process triggers the next has been applied and proved useful in the case study performed in the Barcelonnette basin.

b) With respect to effects on vulnerability, the spatial and temporal coincidence of hazards may lead to alterations of the vulnerability of physical structures.

Nevertheless it became apparent that not all identified relations can be considered at the regional, and perhaps not on any other scale. For instance, disposition modifications refer in parts to parameters that cannot be considered at a regional scale such as the surface roughness or the material availability. Also with respect to hazard cascades only those zones potentially prone to this effect can be identified while the consequences have to be investigated at a local scale. Likewise, the consequences arising with the simultaneous or sequential impact of multiple hazards on a structure cannot be analysed and considered in detail, but those buildings potentially prone to such effects can be identified and engineering approaches are necessary to propose possible solutions. However, it is important to make the informed decision to consider certain relations and neglect others at a specific scale and using a specific modelling set.

In summary, the most important step is the consideration of the existence of hazard relations, their identification and finally the informed decision to include or neglect them for scale, objective or other reasons. Thereby, each level of a multi-scale approach may take over specific tasks.

5) Differing units for quantifying hazards: A *worst-case* approach was used as basis for the creation of comparable and equivalent modelling results. Thus the results of the susceptibility analysis provide information on *susceptible or not susceptible* and can be compared and jointly visualised easily. Although this is a strong generalisation, at the regional scale and with the previously defined aim to identify zones potentially prone to hazards, hazard overlaps and risk, this approach meets the objectives. At the exposure level, number of buildings, length of roads and proportion of the built-area exposed to any of the hazards have been quantified.

In summary, the definition of a common basis, the worst-case scenario, is the basic requirement for any comparison. Beyond that, at the regional scale at which the present study has been carried out and with the defined objectives, the comparability of units has not been a major difficulty due to the simplicity of the approach. Therefore, no classification schemes or indices had to be calculated but only the differentiation between *susceptible* and *not susceptible*.

6) Multi-step procedure of multi-hazard risk analyses: The *manual* performance of all steps including preparative and intermediate operations is extremely time-consuming, error-prone and confounding, and the confusion of intermediate products, results and scenarios is very difficult to avoid. The MultiRISK Modelling Tool proved helpful although the modelling procedure is still rather lengthy since the software needs several hours to days and weeks for the calculation of the results. Nevertheless, much time and effort of the user is saved since preparative and intermediate steps are automated and confusion is avoided due to automatic meta-data saving and file naming. A clear disadvantage of such a software tool is the restriction to the offered models, options and choices. Therefore, it is very important to adjust the modelling tool to the needs of the user by adding further parameters and the exchange of inappropriate models. RiskScape is an excellent example of a very flexible and extensible software tool in which additional modules can be *plugged in* (SCHMIDT *et al.*, 2011). This flexibility is facilitated by means of clear specifications of the modules with respect to formats and required in- and outputs.

In summary, the application of a software tool proved very helpful, nevertheless adequate models, the adjustment to user needs and a flexible structure are important for its application.

7) Visualisation of the multi-dimensional result: The visualisation of the different aspects of information that the multi-hazard exposure analysis output offers is challenging. Especially the spatial distribution of the single-hazards relative to one another and their overlaps are difficult to display. In the present study a set of maps has been composed to in a stepwise fashion provide different facets of the information contained in the analysis results. Moreover, the implementation of these maps in a web-mapping application has been identified as very promising, since it offers the direct visualisation of the results after the completed analysis and enables the interactive exploration of the outcome. For the communication of the results to a wider range of stakeholders, web-mapping approaches provide not only the advantage of a very good availability for any interested person with internet access but also displays those aspects of specific interest. Nevertheless, the Multi-RISK Visualisation Tool is only a first version of an application to communicate the final analysis results. An adjustment to the specific objectives and requirements of stakeholders and users is indispensable.

In summary, a set of maps is necessary to transmit the multi-dimensional content of the analysis results. A web-mapping application has been identified as very promising approach to present these maps, and thereby enable the fast visualisation of the analysis results after the modelling as well as communication of the final results via the internet.

With respect to the hypothesis that multi-hazard (risk) analyses are not just the sum of single-hazard (risk) analyses, the seven *multi-hazard issues* can be subdivided into (a) practical and (b) systemic issues. High data requirements, differing metrics, the multi-step procedure and problems to visualise the results are first of all of practical nature. By contrast, differences in spatial and temporal scale between hazards, contrasts between model principles and assumptions of various processes and especially hazard relations are systemic issues.

a) Considering the hypothesis from a practical point of view, a multi-hazard risk analysis can in the fewest cases just be summed by separately created single-hazard risk analyses since scale, level of detail and metrics will most probably not match. Moreover, the process of harmonisation between modelling approaches to ensure the comparability of the results may lead to additional data requirement and thus information needs may exceed the simple sum of requirements for single-hazard analyses. Furthermore, the visualisation of multiple hazards is not supposed to be just the presentation of many single-hazard results since additional aspects such as the overlapping areas are of high interest. On the other hand, the high data requirements and the multi-step procedure suggest a contrary tendency. Here, rather an indication is given that a multi-hazard risk analysis can be *less* than the sum of separate single-hazard examinations since redundancies can be avoided such as data gathering, preparative and intermediate steps. By identifying duplicate operations and designing an overall analysis scheme as proposed in the present study, multi-hazard

analyses can be performed even more efficiently than the sum of single-hazard modelling.
b) From a systemic point of view, the clearest support of the hypothesis is the existence of relations and interactions between hazards. With a separate analysis of single hazards it is very difficult, if at all possible, to consider the potential interactions and establish relationships between them. By contrast, the joint consideration of all included hazards and their influencing factors facilitates the integration of as relevant identified relations in accordance with the analysis scale and objectives. Moreover, differing spatial and temporal scales of hazards and contrasting model assumptions and principles are an important challenge. They arise with the contrasting hazard characteristics. Especially with respect to the model assumptions and principles, the present study shows that it is very difficult to regard this aspect. However, it becomes also apparent that certain measures such as model choice, the joint validation and an assessment of uncertainties are possible and necessary to regard for this challenge. Furthermore, the importance of spatial scale of hazards with respect to their extent was outlined and a proposal was made how to take the process-specific into account by means of a multi-scale approach. To establish such an analysis scheme, the joint consideration of all hazards with their specific characteristics, the user-specific scales and requirements is needed.

In summary, with respect to some aspects a multi-hazard risk analysis may be more than just the sum of single-hazard risk analyses and regarding other issues it may be less than the sum. Nevertheless, in the fewest cases it is just the sum.

6.2. How Necessary are Software Tools?

Hypothesis II **A software platform provides practical advantages for reproducible multi-hazard (risk) modelling and visualisation**

In the framework of the second hypothesis, two objectives have been formulated: (1) to implement the developed analysis scheme into a modelling tool, and (2) to develop a visualisation tool to present the modelling results. In fulfillment of these two objectives, the software platform MultiRISK consisting of the Modelling and the Visualisation Tool has been created, based on the previsouly developed modelling and visualisation scheme. During the elaboration of the software and especially during the performance of a case study in the Barcelonnette basin, its practical advantages have been examined. On the basis of these experiences the hypothesis is discussed:
From a purely practical point of view, a software platform facilitates the modelling and visualisation procedure by taking over the majority of preparative and intermediate routine steps. The flow chart provided in Figure 4.1 indicates the multitude of single steps required in a rather simple regional scale multi-hazard analysis without considering the

validation and exposure analysis. Thereby, many technically necessary steps as format changes, reclassifications and selections are still not mentioned and contribute to an even more complicated procedure. Further time-consuming and recommendably coherent operations are the naming of the output files and the assignment of meta-data. To avoid future confusion the clear name definition including all indispensable information to recognise the file is necessary. Complete details shall then be given in the meta-data to make sure the data used and the parameters chosen for the modelling are known. In MultiRISK both procedures are automated and considering the large quantity of single files (easily more than 30) produced in one full exposure analysis of all five hazards, the case study confirmed that much time can be saved and confusion avoided. The visualisation faces directly related challenges, especially concerning the multitude of files to be visualised. The simple upload of 30 files and the assignment of colours and patterns is time consuming. Moreover, especially the joint visualisation of multiple processes has been a challenge that was met by a splitting into the combination of three and five hazards. However, the manual performance of each single step is time-consuming, especially for users without cartographic and GIS experience.

Moreover, it became apparent that a multi-hazard risk analysis has to be repeatable, not only due to scenario modelling (e.g. climate or land use change scenarios) and to enable the periodic update of the analysis but also to consider hazard relations. Even if the mechanism itself is not included into the analysis software, the possibility to rapidly repeat the core modelling is an important support for a practical and applicable consideration of hazard relations. In this study, especially the influence of hazard events on the disposition of the other processes requires a preferably fast and rapid performance of the analysis to facilitate the analysis of the current hazard level. On a local scale, this also applies for the hazard cascades where the output of one model can directly feed into the next, as already proposed in CAPRA (Phillips *et al.*, 2010). In this software, for instance the earthquake module is directly linked to the landslide module. This indicates that the more hazard relations to be considered and the stronger single hazard analyses can be linked, especially at a local scale, the more complicated the analysis scheme gets. Thereby, a software tool that considers the relations between single hazards and establishes links between models is increasingly helpful to incorporate these aspects in a multi-hazard risk analysis. This also applies to the visualisation of the analysis results. The more hazards and hazard relations are considered, the more challenging will be the visualisation of the results. In a first step this refers to the fast visualisation of the results, for instance during the calibration phase, and later to the communication of the results to further stakeholders and the public.

In summary, software applications for the modelling as well as the visualisation procedure are very practical to automate preparative and intermediate steps. However, with increasing complexity due to higher numbers of involved hazards with very differing characteristics and a multitude of relations and interactions between them, such tools gain importance.

7. MultiRISK - What is Next?

The field of multi-hazard risk analyses is a still rather young research subject and only recently attracting increasing attention. In this context, the present study contributed three major aspects:

1. the provision of an overview of challenges and difficulties in the multi-hazard environment subsumed in the seven *major multi-hazard issues* and current approaches to solutions

2. the development of an analysis and visualisation scheme and the implementation into software tools

3. the discussion of the identified *multi-hazard issues* in the light of the experience gained during the steps of this study and the elucidation that multi-hazard risk analyses are not just the sum of single hazard risks

From a scientific point of view still many aspects of multi-hazard risk analyses would need more detailed investigation. With respect to the analysis scheme, this refers to the inclusion of further and more contrasting hazards, and the development of an approach to consider these differences. Moreover, the full elaboration of the multi-scale analysis scheme including the local as well as a smaller scale is a future challenge. An important aspect is the integration of an uncertainty assessment to enable external evaluation of the quality of the modelling results and facilitating comparison between different hazard models. Nevertheless, this study has been done with regard to the practical utility in a risk management or governance framework. For the initiation of a dialog with decision-makers and stakeholders, a first version of such a concept and software tool is very helpful if not even required as starting point. However, many more practical, administrative and legislative problems and difficulties will have to be solved when attempting to integrate such an approach into a risk governance framework and thus further scientific work is most effectively done under consideration of these issues. At first this refers to the separation of responsibilities and tasks with respect to risk analysis and management of multiple hazards. Here, the question will arise, if such a tool is desired and in the case of divided responsibilities it is necessary to determine if and how it can be used. The next step is the legislative framework with respect to single natural hazards or even multi-hazard. Which information is required at which level for making which decisions and what kind of data and resources is available to develop the required output? Or are there no statutory provisions for the multi-hazard context and the need for such a tool is still not perceived?

Thus, the development of a first conceptual approach to the multi-hazard topic was necessary to investigate challenges from a scientific perspective and identify approaches to solution as well as the development of a first software proposal to detect the possibilities and create a basis for discussions. Nevertheless, at this point, the next step should be the contacting of stakeholders to jointly identify ways for its application.

Bibliography

Abrahamson, B. & Pentland, R. (2010). *Probable maximum flood estimator for British Columbia.* Tech. rep., Agriculture and Agri-Foods Canada. URL `http://www.env.gov.bc.ca/wsd/public_safety/dam_safety/cabinet/probable_maximum_flood_estimator_for_bc.pdf`. Access 2 July 2011.

Alexander, D. (2001). *Natural hazards.* In Alexander, D. & Fairbridge, R. (Eds.), *Encyclopedia of environmental science.* Kluwer Academic Publishers, Dordrecht, The Netherlands, 421–425.

Anggraeni, D. (2010). *Modelling the impact of topography on seismic amplification at regional scale.* Master's thesis, International Institute for Geo-information Science and Earth Observation.

Apel, H., Aronica, G., Kreibich, H. & Thieken, A. (2009). *Flood risk analyses - how detailed do we need to be?* Natural Hazards **49**: 79–98.

Arnold, M., Chen, U., R.S. Deichmann, Dilley, M., Lerner-Lam, A., Pullen, R. & Trohanis, Z. (2006). *Natural disaster hotspots: case studies.* The World Bank.

van Asch, T., van Beek, L. & Bogaard, T. (2007). *Problems in predicting the mobility of slow-moving landslides.* Engineering Geology **91**: 46–55.

Assmuth, T., Hildén, M. & Benighaus, C. (2010). *Integrated risk assessment and risk governance as socio-political phenomena: a synthetic view of the challenges.* Science of the Total Environment **408**: 3943–3953.

Ayala-Carcedo, F., Cubillo-Nielsen, S., Alvarez, A., Domínguez, M., Laín, L., Laín, R. & Ortiz, G. (2003). *Large scale rockfall reach susceptibility maps in La Cabrera Sierra (Madrid) performed with GIS and dynamic analysis at 1:5,000.* Natural Hazards **30**: 325–340.

Barbolini, M., Pagliardi, M., Ferro, F. & Corradeghini, P. (2011). *Avalanche hazard mapping over large undocumented areas.* Natural Hazards **56**: 451–464.

Barredo, J. (2009). *Normalised flood losses in Europe: 1970-2006.* Natural Hazards and Earth System Sciences **9**: 97–104.

BARRIENDOS, M., COEUR, D., LANG, M., LLASAT, M. C., NAULET, R., LEMAITRE, F. & BARRERA, A. (2003). *Stationarity analysis of historical flood series in France and Spain (14th-20th centuries).* Natural Hazards and Earth System Sciences **3**: 583–592.

BARTEL, P. & MULLER, J. (2007). *Horn of Africa natural hazard probability and risk analysis.* Tech. rep., USAID.

BARTELS, C. & VAN BEURDEN, A. (1998). *Using geographic and cartographic principles for environmental assessment and risk mapping.* Journal of Hazardous Materials **61**: 115–124.

BAUTISTA, M. & BAUTISTA, B. (2004). *The Philippine historical earthquake catalog: its development, current state and future directions.* Annals of Geophysics **47**: 379–385.

BAXTER, P., ASPINALL, W., NERI, A., ZUCCARO, G., SPENCE, R., CIONI, R. & WOO, G. (2008). *Emergency planning and mitigation at Vesuvius: A new evidence-based approach.* Journal of Volcanology and Geothermal Research **178**: 454–473.

BBK (2010). *Methode für die Risikoanalyse im Bevölkerungsschutz.* Tech. rep., Bundesamt für Bevölkerungsschutz und Katastrophenhilfe. URL `http://www.bbk.bund.de/cln_027/nn_402322/SharedDocs/Publikationen/Broschueren__Flyer/Methode__Risikoanalyse-BS,templateId=raw,property=publicationFile.pdf/Methode_Risikoanalyse-BS.pdf`. Access 25 June 2011.

BEGUERÍA, S. (2006). *Validation and evaluation of predictive models in hazard assessment and risk management.* Natural Hazards **37**: 315–329.

BELL, R. (2002). *Landslide and snow avalanche risk analysis - methodology and its application in Bíldur, NW-Iceland.* Master's thesis, Rheinische Friedrich-Wilhelms-Universität Bonn.

BELL, R. & GLADE, T. (2004a). *Multi-hazard analysis in natural risk assessments.* In *International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation.* Brebbia, C.A., Rhodes, Greece, 197–206.

BELL, R. & GLADE, T. (2004b). *Quantitative risk analysis for landslides - examples from Bíldudalur, NW-Iceland.* Natural Hazards and Earth System Sciences **4**: 117–131.

BELL, R., REESE, S. & KING, A. (2007). *Regional RiskScape: a multi-hazard loss modelling tool.* In *Coastal Communities Natural Disasters.* Auckland.

VON BERTALANFFY, L. (1956). *General system theory.* General Systems Yearbook **1**: 1–10.

BERTRAND, D., NAAIM, M. & BRUN, M. (2010). *Physical vulnerability of reinforced concrete buildings impacted by snow avalanches.* Natural Hazards and Earth System Sciences **10**: 1531–1545.

BGR & DESDM (2009). *Guidebook for assessing the risks to natural hazards - case study: Province of Central Java.* Tech. rep., Bundesanstalt für Geowissenschaften und Rohstoffe and the Geological Agency of Indonesia.

BHATTACHARYA, N. (2010). *Flood risk assessment in Barcelonnette, France.* Master's thesis, University of Twente.

BIRKMANN, J. (2007). *Risk and vulnerability indicators at different scales: applicability, usefulness and policy implications.* Environmental Hazards **7**(1): 20 – 31.

BLAHUT, J., VANWESTEN, C. & STERLACCHINI, S. (2010). *Analysis of landslide inventories for accurate prediction of debris-flow source areas.* Geomorphology **119**: 36–51.

BLIJENBERG, H. (1998). *Rolling stones - triggering and frequency of hillslope debris flows in the Bachelard Valley, southern French Alps.* Ph.D. thesis, Unniversiteit Utrecht.

BOMMER, J. & RODRÍGUEZ, C. (2002). *Earthquake-induced landslides in Central America.* Engineering Geology **63**: 189–220.

BOMMER, J. & SCHERBAUM, F. (2008). *The use and misuse of logic trees in probabilistic seismic hazard analysis.* Earthquake Spectra **24**: 997–1009.

BOORE, D. (1972). *A note on the effect of simple topography on seismic SH waves.* Bulletin of the Seismological Society of America **62**: 275–284.

BORDONNÉ, M. (2008). *Cartographie de laves torrentielles dans le bassin de Barcelonnette.* Master's thesis, Université Louis Pasteur, Strasbourg.

BORGA, M., DALLA FONTANA, G., DA ROS, D. & MARCHI, L. (1997). *Shallow landslide hazard assessment using a physical based model and digital elevation data.* Environmental Geology **35**: 81–88.

BORTER, P. (1999). *Risikoanalyse bei gravitativen Naturgefahren - Methode.* Umwelt-Materialien 107/I, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland.

BORTER, P. & BART, R. (1999). *Risikoanalyse bei gravitativen Naturgefahren - Fallbeispiele und Daten.* Umwelt-Materialien 107/II, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland.

BOUCKOVALAS, G. & PAPADIMITROU, A. (2005). *Numerical evaluation of slope topography effects on seismic ground motion.* Soil Dynamics and Earthquake Engineering **25**: 547–558.

BOUKALOVA, Z. & HELLER, J. (2005). *Report on current availability and methodology for natural risk map production.* Deliverable 2.1, ARMONIA.

BOUR, M., CHASSAGNEUX, D. & MOUROUX, P. (2000). *Influence of a low resistance layer on seismic soil response using CyberQuake.* In *Proceedings of the 12th World Conference on Earthquake Engineering.* Upper Hutt, New Zealand.

BOVOLO, C. I., ABELE, S. J., BATHURST, J. C., CABALLERO, D., CIGLAN, M., EFTICHIDIS, G. & SIMO, B. (2009). *A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield.* Computers & Geosciences **35**(5): 924 – 945.

BRITTON, N. (2002). *Institutional arrangements for total risk management in New Zealand: issues and solutions.* In *Regional Workshop on Best Practices in Disaster Mitigation.* 47–58.

BRÜNDL, M. (2008). *Risikokonzept für Naturgefahren - Leitfaden.* Tech. rep., Nationale Plattform für Naturgefahren PLANAT, Bern. URL `www.riskplan.admin.ch`. Access 24 January 2009.

BRÜNDL, M., BARTELT, P., J., S., KEILER, M. & GLADE, T. (2010). *Snow avalanche risk analysis - review and future challenges.* In ALCÁNTARA-AYALA, I. & GOUDIE, A. (Eds.), *Geomorphological Hazards and Disaster Prevention.* Cambridge University Press, 49–61.

BÜCHELE, B., KREIBICH, H., KRON, A., THIEKEN, A., IHRINGER, J., OBERLE, P., MERZ, B. & NESTMANN, F. (2006). *Flood-risk mapping: contributions towards and enhanced assessment of extreme events and associated risks.* Natural Hazards and Earth System Sciences **6**: 485–503.

BUDETTA, P. (2004). *Assessment of rockfall risk along roads.* Natural Hazards and Earth System Sciences **4**: 71–81.

BUTLER, H. (2005). *A guide to the Python universe for ESRI users.* ArcUsers **April-June**: 34–37.

CALVI, G., PINHO, R., MAGENES, G., BOMMER, J., RESTREPO-VÉLEZ, L. & CROWLEY, H. (2006). *Development of seismic vulnerability assessment methodologies over the past 30 years.* ISET Journal of Earthquake Technology **43**: 75–104.

CAMENZIND-WILDI, R., BAUMANN, R., GUGGISBERG, C., LOAT, R. & DIETHELM, E. (2005). *Empfehlung: Raumplanung und Naturgefahren.* Tech. rep., Bundesamt für Raumentwicklung, Bundesamt für Wasser und Geologie, Bundesamt für Umwelt, Wald und Landschaft. URL `http://www.news-service.admin.ch/NSBSubscriber/message/attachments/458.pdf`. Access 27 October 2011.

Cannon, S. & deGraff, J. (2009). *The increasing wildfire and post-fire debris-flow threat in Western USA, and implications for consequences of climate change.* In Sassa, K. & Canuti, P. (Eds.), *Landslides - disaster risk reduction.* Springer Verlag, Berlin Heidelberg, Germany, 177–190.

Carpignano, A., Golia, E., Di Mauro, C., Bouchon, S. & Nordvik, J.-P. (2009). *A methodological approach for the definition of multi-risk maps at regional level: first application.* Journal of Risk Research **12**: 513–534.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V. & Reichenbach, P. (1991). *GIS techniques and statistical models in evaluating landslide hazard.* Earth Surface Processes and Landforms **16**: 427–445.

Carrasco, R., Pedraza, J., Martin-Duque, J., Mattera, M., Sanz, M. & Bodoque, J. (2003). *Hazard zoning for landslides connected to torrential floods in the Jerte Valley (Spain) by using GIS techniques.* Natural Hazards **30**: 361–381.

Cascini, L., Bonnard, C., Corominas, J., Jibson, R. & Montero-Olarte, J. (2005). *Landslide hazard and risk zoning for urban planning and development.* In Hungr, O., Fell, R., Couture, R. & Eberhardt, E. (Eds.), *Landslide risk management.* Taylor & Francis, London, UK, 199–235.

Castellanos Abella, E. A. (2008). *Multi-scale landslide risk assessment in Cuba.* Ph.D. thesis, International Institute for Geo-information Science and Earth Observation, Enschede, Netherlands.

CEPREDENAC, ISDR, IDB & the World Bank (2011). *CAPRA Portal (Central American Probabilistic Risk Assessment).* URL `http://www.ecapra.org/en/`. Access 2 July 2011.

Cervi, F., Berti, M., Borgatti, L., Ronchetti, F., Manenti, F. & Corsini, A. (2010). *Comparing predictive capability of statistical and deterministic methods for landslide susceptibility mapping: a case study in the northern Apennines (Reggio Emilia Province, Italy).* Landslides **7**: 433–444.

CETE (1987). *Commune de Barcelonnette: plan d'exposition aux risques naturels.* Tech. rep., Centre d'Etudes Techniques de l'Equipement, Aix en Prevence.

Chang, K.-T., Chiang, S.-H. & Hsu, M.-L. (2007). *Modeling typhoon- and earthquake-induced landslides in a mountainous watershed using logistic regression.* Geomorphology **89**: 335–347.

Chau, K., Wong, R., Liu, J. & Lee, C. (2003). *Rockfall hazard analysis for Hong Kong based on rockfall inventory.* Rock Mechanics and Rock Engineering **36**: 383–408.

CHIESA, C., LABEN, C. & CICONE, R. (2003). *An Asia Pacific natural hazards and vulnerabilities atlas.* In *30th International Symposium on Remote Sensing of Environment.*

CHORLEY, R. & KENNEDY, B. (1971). *Physical geography - a systems approach.* Prentice-Hall International Inc., London, UK.

CHRISTEN, M., BARTELT, P. & GRUBER, U. (2007). *Hazard mapping and GIS: stimulating avalanche, debris flow and rock-fall.* GIM International **21**: 23–25.

CHUNG, C.-J. & FABBRI, A. (2003). *Validation of spatial prediction models for landslide hazard mapping.* Natural Hazards **30**: 451–472.

COROMINAS, J. (1996). *The angle of reach as a mobility index for small and large landslides.* Canadian Geotechnical Journal **33**: 260–271.

COROMINAS, J., COPONS, R., VILAPLANA, J., ALTIMIR, J. & AMIGÓ, J. (2003). *Integrated landslide susceptibility analysis and hazard assessment in the Principality of Andorra.* Natural Hazards **30**: 421–435.

COSTA, J. & SCHUSTER, R. (1988). *The formation and failure of natural dams.* Geological Society of America Bulletin **100**: 1054–1068.

CRED (2009). *EM-DAT: Emergency Events Database.* URL `http://www.emdat.be/`. Access 15 July 2009.

DAI, F. C., LEE, C. F. & NGAI, Y. Y. (2002). *Landslide risk assessment and management: an overview.* Engineering Geology **64**(1): 65–87.

DE MARCHI, B. (2003). *Risk governance: public participation and risk governance.* Science and Public Policy **30**: 171–176.

DEGRAFF, J., CANNON, S. & GALLEGOS, A. (2007). *Reducing post-wildfire debris flow risk through the burned area emergency response (BAER) process.* In *Proceedings of the 1st North American Landslide Conference, AEG Special Publication no. 23.*

DEGRAFF, J. & OCHIAI, H. (2009). *Rainfall, debris flows and wildfires.* In SASSA, K. & CANUTI, P. (Eds.), *Landslides - disaster risk reduction.* Springer Verlag, 451–474.

DELATTRE, A., GARANCHER, T., ROZENCWAJG, C. & TOURET, T. (2002). *Jurisque - prévention des risques naturels.* Tech. Rep. 3, Ministere de l'Écologie et du Développement durable.

DELMONACO, G., MARGOTTINI, C. & SPIZZICHINO, D. (2006a). *ARMONIA methodology for multi-risk assessment and the harmonisation of different natural risk maps.* Deliverable 3.1.1, ARMONIA.

Delmonaco, G., Margottini, C. & Spizzichino, D. (2006b). *Report on new methodology for multi-risk assessment and the harmonisation of different natural risk maps.* Deliverable 3.1, ARMONIA.

Delsigne, F., Lahousse, P., Flez, C. & Guiter, G. (2001). *Le Riou Bourdoux : un "monstre" alpin sous haute surveillance.* Revue forestère française **LIII**: 527–540.

dePippo, T., Donadio, C., Pennetta, M., Petrosino, C., Terlizzi, F. & Valente, A. (2008). *Costal hazard assessment and mapping in Northern Campania, Italy.* Geomorphology **97**: 451–466.

Dietrich, W. & Montgomery, D. (1998). *Shalstab: a digital terrain model for mapping shallow landslide potential.* Tech. rep., NCASI. URL http://calm.geo.berkeley.edu/geomorph/shalstab/index.htm. Access 15 November 2009.

Dilley, M., Chen, U., R.S. Deichmann, Lerner-Lam, A. & Arnold, M. (2005). *Natural disaster hotspots: a global risk analysis.* URL http://books.google.at/books?id=X3osIdnSBdgC&dq=natural+disaster+hotspots:+a+global+risk+analysis&printsec=frontcover&source=bl&ots=_mTk8waWyO&sig=THRQUwJOWajOsNusJSMwUcUK450&hl=de&ei=EVpTStbxBZeYmwOrt7wF&sa=X&oi=book_result&ct=result&resnum=5. Access 07 July 2009.

Dorren, L. K. (2003). *A review of rockfall mechanics and modelling approaches.* Natural Hazards and Earth System Sciences **27**(1): 69–87.

Douglas, J. (2007). *Physical vulnerability modelling in natural hazard risk assessment.* Natural Hazards and Earth System Sciences **7**: 283–288.

Egli, T. (1996). *Hochwasserschutz und Raumplanung. Schutz vor Naturgefahren mit Instrumenten der Raumplanung - dargestellt am Beispiel von Hochwasser und Murgängen.* vdf Hochschulverlag AG, ETH Zürich. ORL-Bericht 100.

EGU (2011). *NH10 - Multihazards.* electronic. URL http://meetingorganizer.copernicus.org/EGU2011/sessionprogramme/NH#NH10. Access 25 May 2011.

El Morjani, Z., Ebner, S., Boos, J., Abdel Ghaffar, E. & Musani, A. (2007). *Modelling the spatial distribution of five natural hazards in the context of the WHO/EMRO Atlas of Disaster Risk as a step towards the reduction of the health impact related to disasters.* International Journal of Health Geographics **6**.

EM-DAT (2009). *Natural Disasters Trends.* Tech. rep., CRED. URL http://www.emdat.be/natural-disasters-trends.

Erlingsson, U. (2005). *GIS for natural hazard mitigation - experiences from designing the HazMit GIS expert system suggests the need for an international standard.* In *GIS Planet.* Portugal.

ESRI (2010). *ArcGIS - a complete integrated system.* URL `http://www.esri.com/software/arcgis/index.html`. Access 6 July 2011.

European Commission (2011). *Risk assessment and mapping guidelines for disaster management.* Commission staff working paper, European Union.

Évin, M. (1997). *Géology de l'Ubaye.* Sabenca, Association de la Valeia,, Barcelonnette, France.

Felgentreff, C. & Glade, T. (Eds.) (2008). *Naturrisiken und Sozialkatastrophen.* Spektrum Akademischer Verlag.

Felt, U., Callon, M., Goncalves, M., Jasanoff, S., Jepsen, M., Joly, P.-B., Konopasek, Z., May, S., Neubauer, C., Rip, A., Siune, K., Stirling, A. & Tallacchini, M. (2007). *Taking European knowledge society seriously.* Tech. Rep. EUR22700, European Commission. URL `http://ec.europa.eu/research/science-society/document_library/pdf_06/european-knowledge-society_en.pdf`. Access 19 January 2011.

FEMA (1996). *Guide for all-hazard emergency operations planning.* Tech. rep., Federal Emergency Agency. URL `http://www.fema.gov/pdf/plan/slg101.pdf`. Access 29 September 2009.

FEMA (2003). *Multi-hazard loss estimation methodology: earthquake model. HAZUS-MH MR3.* Technical manual, FEMA. URL `http://www.fema.gov/plan/prevent/hazus/`. Available at: http://www.fema.gov/plan/prevent/hazus/.

FEMA (2007a). *Multi-hazard loss estimation methodology: flood model. HAZUS-MH MR3.* Technical manual, Department of Homeland Security, Federal Emergency Management Agency. Access 09 January 2009.

FEMA (2007b). *Multi-hazard loss estimation methodology: hurricane model. HAZUS-MH MR3.* Technical manual - appendices, FEMA.

FEMA (2008). *HAZUS-MH MR3 Patch 2: Release notes.* Tech. rep., FEMA.

Flageollet, J.-C., Maquaire, O., Martin, B. & Weber, D. (1999). *Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France).* Geomorphology **30**: 65–78.

Fleischhauer, M., Greiving, S. & Wanczura, S. (2006). *Natural hazards and spatial planning in Europe.* Tech. rep., ARMONIA.

Foerster, E., Krien, Y., Dandoulaki, M., Priest, S., Tapsell, S., Delmonaco, G., Margottini, C. & Bonadonna, C. (2009). *Methodologies to assess vulnerability of structural systems.* Del. 1.1.1., ENSURE. URL `http://eea.eionet.europa.eu/Public/irc/eionet-circle/airclimate/library?l=/public/2010_citiesproject/interchange/project_deliverables/ensure_del111pdf/_EN_1.0_&a=d`. Access 24 March 2011.

Francés, F. & Botero, B. (2003). *Probable maximum flood estimation using systematic and non-systematic information.* In Thorndycraft, V., Benito, G., Barriendos, M. & Llasat, M. (Eds.), *Proceedings of 2002 PHEFRA workshop-palaeofloods, historical floods and climatic variability: applications in flood risk assessment.* 223–229.

Francou, J. & Rodier, J. (1969). *Essai de classification des crues maximales.* Floods and their computation : 518–527.

Frigerio, S., Blahut, J., Sterlacchini, S. & Poretti, I. (2010a). *Landslides historical dataset and population distribution: Historic@, the experience of the Consortium of Mountain Municipalities of Valtellina di Tirano, Italy.* In Malet, J.-P., Glade, T. & Casagli, N. (Eds.), *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence.* CERG Editions, Strasbourg, 491–497.

Frigerio, S., Skupinski, G., Kappes, M., Malet, J.-P. & Puissant, A. (2010b). *A WebGIS service for managing, sharing and communicating information on mountain risks: a pilot study at the Barcelonnette Basin (South French Alps).* In *Geophysical Research Abstracts, EGU General Assembly.*

Frigerio, S., Skupinski, G., Puissant, A., Malet, J.-P. & Rose, X. (2010c). *An open source WebGIS platform for sharing information and communicating about risks: the Barcelonnette Basin (South French Alps) as pilot study.* In Malet, J.-P., Glade, T. & Casagli, N. (Eds.), *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence.* CERG Editions, Strasbourg, 477–483.

Frigerio, S. & vanWesten, C. (2010). *RiskCity and WebRiskCity: data collection, display, and dissemination in a multi-risk training package.* Cartography and Geographic Information Science **37**: 119–135.

Fuchs, S. (2009a). *Mountain hazards, vulnerability, and risk - a contribution to applied research on human-environment interaction.* Habilitation, University of Innsbruck.

Fuchs, S. (2009b). *Susceptibility versus resilience to mountain hazards in Austria - paradigms of vulnerability revisited.* Natural Hazards and Earth System Sciences **9**: 337–352.

Fuchs, S., Dorner, W., Sprachinger, K., Rochman, J. & Serrhini, K. (2009). *Flood risk map perception through graphical semiology.* In Samuels, P., Huntington, S., Allsop, W. & Harrop, J. (Eds.), *Flood risk management. Research and practice.* Taylor & Francis, London, UK, 705–714.

FUCHS, S. & KEILER, M. (2006). *Natural hazard risk depending on the variability of damage potential.* In POPOV, V. & BREBBIA, C. (Eds.), *Risk Analysis V: Simulation and hazard mitigation*, vol. 91. WIT Press, Southampton, UK. WIT Transactions on Ecology and the Environment, 13–22.

FUCHS, S., KEILER, M. & ZISCHG, A. (2001). *Risikoanalyse - Oberes Suldental, Vinschgau: Konzepte und Methoden zur Erstellung eines Naturgefahrenhinweis-Informationssystems.* Innsbrucker Geographische Studien.

FUCHS, S., KEILER, M., ZISCHG, A. & BRÜNDL, M. (2005). *The long-term development of avalanche risk in settlements considering the temporal variability of damage potential.* Natural Hazards and Earth System Science **5**(6): 893–901.

GARCIN, M., DESPRATS, J., FONTAINE, M., PEDREROS, R., ATTANAYAKE, N., FERNANDO, S., SIRIWARDANA, C., DE SILVA, U. & POISSON, B. (2008). *Integrated approach for coastal hazards and risks in Sri Lanka.* Natural Hazards and Earth System Sciences **8**: 577–586.

GEOMER (2008). *FloodArea - ArcGIS extension for calculating flooded areas: user manual.* Geomer GmbH and Ingenieurgemeinschaft Ruiz Rodriguez + Zeisler + Blank.

GIBBS, T. (2003). *Multi-hazard design - contradictions and synergies.* In *Leaders: International course on development and disasters with a special focus on health.* St. Ann, Jamaica.

GLADE, T. (2003). *Vulnerability assessment in landslide risk analysis.* Die Erde **2**: 123–146.

GLADE, T. (2005). *Linking debris-flow hazard assessment with geomorphology.* Geomorphology **66**: 189–213.

GLADE, T. (2006). *Herausforderungen bei der Abgrenzung von Gefáhrdungsstufen und bei der Festlegung gefáhrdeter Zonen von Naturgefahren.* In *55. Deutscher Geographentag.* Trier, Germany, 453–462.

GLADE, T., ANDERSON, M. & CROZIER, M. (Eds.) (2005). *Landslide hazard and risk.* Wiley, Chichester, UK.

GRANGER, K. (1998). *ASDI from the ground up: a public safety perspective.* Tech. rep., Australian Geological Survey Organisation (AGSO), Canberra, Australia.

GRANGER, K., JONES, T., LAIBA, M. & SCOTT, G. (1999). *Community risk in Cairns: a multi-hazards risk assessment.* Tech. rep., Australian Geological Survey Organisation (AGSO). URL `http://www.ga.gov.au/hazards/reports/cairns/`. Access.

GREIVING, S. (2006). *Integrated risk assessment of multi-hazards: a new methodology.* In SCHMIDT-THOMÉ, P. (Ed.), *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions*, vol. 42. Geological Survey of Finland, 75–81.

GREIVING, S., FLEISCHHAUER, M. & LÜCKENKÖTTER, J. (2006). *A methodology for an integrated risk assessment of spatially relevant hazards.* Journal of Environmental Planning and Management **49**(1): 1–19.

GRÜNTHAL, G., THIEKEN, A., SCHWARZ, J., RADTKE, K., SMOLKA, A. & MERZ, B. (2006). *Comparative risk assessment for the city of Cologne - storms, floods, earthquakes.* Natural Hazards **38**(1-2): 21–44.

GUILLON, J. (2001). *Interprétation morphologique de l'évaluation du glissement-coulée de Poche et caractérisation physico-mécanique des matériaux marneux.* Master's thesis, Université Louis Pasteur, Strasbourg.

GUZZETTI, F., REICHENBACH, P., CARDINALI, M., GALLI, M. & ARDIZZONE, F. (2005). *Probabilistic landslide hazard assessment at the basin scale.* Geomorphology **72**(1-4): 272 – 299.

HARP, E. & WILSON, R. (1995). *Shaking intensity thresholds for rock falls and slides: evidence from 1987 Whittier Narrows and Superstition Hills Earthquake strong-motion records.* Bulletin of the Seismological Society of America **85**: 1739–1757.

HEIM, A. (1932). *Bergsturz und Menschenleben.* Beiblatt zur Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich.

HEINIMANN, H., HOLLENSTEIN, K., KIENHOLZ, H., KRUMMENACHER, B. & MANI, P. (1998). *Methoden zur Analyse und Bewertung von Naturgefahren.* Umwelt-Materialien Nr. 85, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland.

HEWITT, K. & BURTON, I. (1971). *Hazardousness of a place: a regional ecology of damaging events.* Toronto Press, Toronto and Buffalo.

HOLMGREN, P. (1994). *Multiple flow direction algorithms for runoff modelling in grid based elevation models: an empirical evaluation.* Hydrological Processes **8**: 327–334.

HOLUB, M. (2008). *Technischer Objektschutz - Stand der Technik und künftige Anforderungen.* In *Interpraevent.*

HOLUB, M. & HÜBL, J. (2008). *Local protection against mountain hazards - state of the art and future needs.* Natural Hazards and Earth System Sciences **8**: 81–99.

HORTON, P., JABOYEDOFF, M. & BARDOU, E. (2008). *Debris flow susceptibility mapping at a regional scale.* In *4th Canadian Conference on Geohazards.* Université Laval, Québec, Canada.

Huggel, C., Kääb, A., Haeberli, W. & Krummenacher, B. (2003). *Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps.* Natural Hazards and Earth System Sciences **3**: 647–662.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P. & Paul, F. (2002). *Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps.* Canadian Geotechnical Journal **39**: 316–330.

Huggel, C., Kääb, A. & Salzmann, N. (2004). *GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery.* Norwegian Journal of Geography **58**: 61–73.

Huttenlau, M. & Stötter, J. (2011). *The structural vulnerability in the framework of natural hazard risk analyses and the exemplary application for storm loss modelling in Tyrol (Austria).* Natural Hazards **58**: 705–729.

Huttenlau, M., Stötter, J. & Stiefelmeyer, H. (2010). *Risk-based damage potential and loss estimation of extreme flooding scenarios in the Austrian Federal Province of Tyrol.* Natural Hazards and Earth System Science **10**: 2451–2473.

Hydrotec (2009). *Hochwasserschutzplan Solmsbach.* Tech. rep., Regierungspräsidium Gießen. URL `http://www.hessen.de/irj/RPGIE_Internet?cid=f95a2a5d2807b19fc5b9fe2f31e52e62`. Access 12 November 2010.

IDEALP & Hydroetudes (2008). *Etude hydraulique globale de la vallée de l'Ubaye - Diagnostic.* Tech. rep., Syndicat mixte contre les crues du bassin Ubaye-Ubayette.

IDEALP & Hydroetudes (2010). *Etude hydraulique globale de la vallée de l'Ubaye - Plan de gestion.* Tech. rep., Syndicat mixte contre les crues du bassin Ubaye-Ubayette.

Iida, T. (1999). *A stochastic hydro-geomorphological model for shallow landsliding due to rainstorm.* Catena **34**: 293–313.

INSEE (2011). *Statistiques locales.* URL `http://www.statistiques-locales.insee.fr/esl/accueil.asp`. Access 6 July 2011.

IRGC (2005). *An introduction to the IRGC risk governance framework.* Tech. rep., International Risk Governance Council.

IRGC (2010). *Risk governance deficits: analysis, illustration and recommendations.* Policy brief, International Risk Governance Council, Geneva, Switzerland.

Iverson, R. (1997). *The physics of debris flows.* American Geophysical Union **35**: 245–296.

JONKMAN, S. & KELMAN, I. (2005). *An analysis of the causes and circumstances of flood disaster deaths.* Disasters **29**: 75–97.

KAPPES, M. (2011). *MultiRISK: a Platform for Multi-Hazard Risk Analyses and Visualization - Users' Manual.* Tech. rep., University of Vienna.

KAPPES, M. & GLADE, T. (acc.). *Landslides considered in a multi-hazard context.* In *Proceedings of the Second World Landslide Forum.* Rome, Italy.

KAPPES, M., GRUBER, K., FRIGERIO, S., BELL, R., KEILER, M. & GLADE, T. (subm.a). *A multi-hazard exposure analysis tool: the MultiRISK Platform.* Geomorphology .

KAPPES, M., KEILER, K., M.AND VON ELVERFELDT & GLADE, T. (subm.b). *Challenges of dealing with multi-hazard risk: a review.* Natural Hazards .

KAPPES, M., KEILER, M. & GLADE, T. (2010). *From single- to multi-hazard risk analyses: a concept addressing emerging challenges.* In MALET, J.-P., GLADE, T. & CASAGLI, N. (Eds.), *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence.* CERG Editions, Strasbourg, 351–356.

KAPPES, M., MALET, J.-P., REMAÎTRE, A., HORTON, P., JABOYEDOFF, M. & BELL, R. (2011). *Assessment of debris flow susceptibility at medium-scale in the Barcelonnette Basin, France.* Natural Hazards and Earth System Sciences **11**: 627–641.

KAPPES, M., PAPATHOMA-KÖHLE, M. & KEILER, M. (in press). *Assessing physical vulnerability for multi-hazards using an indicator-based methodology.* Applied Geography **in press**.

KASPERSON, R., RENN, O., SLOVIC, P., BROWN, H., EMEL, J., GOBLE, R., KASPERSON, J. & RATICK, S. (1988). *The social amplification of risk: a conceptual framework.* Risk Analysis **8**: 177–187.

KEEFER, D. (2002). *Investigating landslides caused by earthquakes - a historical review.* Surveys in Geophysics **23**: 473–510.

KEILER, M., KNIGHT, J. & HARRISON, S. (2010). *Climate change and geomorphological hazards in the eastern European Alps.* Philosophical Transactions of the Royal Society A **368**: 2461–2479.

KEILER, M., ZISCHG, A., FUCHS, S., HAMA, M. & STÖTTER, J. (2005). *Avalanche related damage potential - changes of persons and mobile values since the mid-twentieth century, case study Galtür.* Natural Hazards and Earth System Science **5**(1): 49–58.

KEYLOCK, C. & BARBOLINI, M. (2001). *Snow avalanche impact pressure - vulnerability relations for use in risk assessment.* Canadian Geotechnical Journal **38**(2): 227–238.

Kienholz, H. (2003). *Early warning systems related to mountain hazards.* In Zschau, J. & Küppers, A. (Eds.), *Early warning systems for natural disaster reduction.* Springer, Berlin Heidelberg, Germany, 555–564.

Kienholz, H. & Krummenacher, B. (1995). *Symbolbaukasten zur Kartierung der Phänomene.* Tech. rep., Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bundesamt für Wasser und Geologie (BWG).

Kienholz, H., Krummenacher, B., Kipfer, A. & Perret, S. (2004). *Aspects of integral risk management in practice - considerations with respect to mountain hazards in Switzerland.* Österreichische Wasser- und Abfallwirtschaft **56**: 43–50.

Klumpp, E. & Hörmann, F. (Eds.) (2010). *Arbeitspaket 6: Risikoprävention & Management: Praktiker Workshop - Risikomanagement an alpinen Wildbächen und Flüssen.* Alpine Space. URL `http://www.adaptalp.org/index.php?option=com_docman&task=doc_details&gid=201&Itemid=79`. Access 12 November 2010.

Kunz, M. & Hurni, L. (2008). *Hazard maps in Switzerland: state-of-the-art and potential improvements.* In *Proceedings of the 6th ICA Mountain Cartography Workshop.* Lenk, Switzerland.

Kunz, M. & Hurni, L. (2011a). *How to enhance cartographic visualisations of natural hazards assessmet results.* The Cartographic Journal **48**: 60–71.

Kunz, M. & Hurni, L. (2011b). *Interactive functionality of cartographic information systems for natural hazards data.* In *Proceedings of the 25th International Cartographic Conference.* 107, Paris, France.

Lateltin, O. (1997). *Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten.* Tech. rep., Bundesamt für Raumplanung (BRP), Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Umwelt, Wald und Landschaft (BUWAL).

LeCarpentier, C. (1963). *La crue de juin 1957 en Ubaye et ses consquences morphodynamiques.* Ph.D. thesis, Université de Strasbourg.

Lee, C.-T., Huang, C.-C., Lee, J.-F., Pan, K.-L., Lin, M.-L. & Dong, J.-J. (2008). *Statistical approach to earthquake-induced landslide susceptibility.* Engineering Geology **100**: 43–58.

Lee, K. & Rosowsky, D. (2006). *Fragility analysis of woodframe buildings considering combined snow and earthquake loading.* Structural Safety **28**: 289–303.

Lee, S.-J., Chan, Y.-C., Komatitsch, D., Huang, B.-S. & Tromp, J. (2009). *Effects of realistic surface topography on seismic ground motion in the Yangminshan Region of Taiwan based upon the spectral-element method and LiDAR DTM.* Bulletin of the Seismological Society of America **99**: 681–693.

Lin, C.-W., Liu, S.-H., Lee, S.-Y. & Liu, C.-C. (2006). *Impacts of the Chi-Chi earthquake on subsequent rainfall-induced landslides in central Taiwan.* Engineering Geology **86**: 87–101.

Loat, R. (2010). *Risk management of natural hazards in Switzerland.* Tech. rep., Federal Office for the Environment FOEN. URL `http://www.cenat.ch/ressources/planat_product_en_1308.pdf`. Access 23 July 2010.

Loat, R. & Petrascheck, A. (1997). *Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten.* Empfehlungen 1997, Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Raumplanung (BRP) and Bundesamt für Umwelt, Wald und Landschaft (BUWAL).

Luino, F. (2005). *Sequence of instability processes triggered by heavy rainfall in the northern Italy.* Geomorphology **66**: 13–39.

Maggioni, M. (2004). *Avalanche release areas and their influence on uncertainty in avalanche hazard mapping.* Ph.D. thesis, Universität Zürich.

Maggioni, M. & Gruber, U. (2003). *The influence of topographic parameters on avalanche release dimension and frequency.* Cold Regions Science and Technology **37**: 407–419.

Malet, J.-P., Maquaire, O., Locat, J. & Remaître, A. (2004). *Assessing debris flow hazard associated with slow moving landslides: methodology and numerical analyses.* Landslides **1**: 83–90.

Maquaire, O., Malet, J.-P., Ramaître, A., Locat, J., Klotz, S. & Guillon, J. (2003). *Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Basin, South East France.* Engineering Geology **70**: 109–130.

Marzocchi, W. (2007). *Multi-hazard assessment: looking ahead (a "perspective" view).* oral presentation (pdf online) at the 2007 International Geohazards Week. URL `http://earth.esa.int/workshops/2007Geohazards/participants/492/pres_492.pdf`. Access 08 March 2011.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M., Di Ruocco, A. & Novelli, P. (subm.). *Basic principles of multi-risk assessment: a case study in Italy.* Natural Hazards .

Marzocchi, W., Mastellone, M. & Di Ruocco, A. (2009). *Principles of multi-risk assessment: interactions amongst natural and man-induced risks.* Tech. rep., European Commission. URL `http://www.scribd.com/doc/16902233/Principles-of-MultiRisk-Assessment`. Access 19 July 2009.

Mc Clung, D., Maers, A. & Schaerer, P. (1989). *Extreme avalanche run-out: data from four mountain ranges.* Annals of Glaciology **13**: 180–184.

McClung, D. & Schaerer, P. (1993). *The avalanche handbook.* The Mountaineers, Seattle, USA.

MEDD (1999). *Guide méthodologique plans de prévention des risques d'inondations.* Tech. rep., Ministère de l'Écologie et du Développement durable. URL `http://www.prim.net/professionnel/documentation/guide_inond/page01.html`.

MEDD (2007). *Programmes d'études des avalanches.* URL `http://www.avalanches.fr/`. Access 20 October 2009.

Menoni, S. (2006). *Integration of harmonized risk maps with spatial planning decision processes.* Deliverable 5.1, ARMONIA.

Merz, B., Kreibich, H. & Apel, H. (2008). *Flood risk analysis: uncertainties and validation.* Österreichische Wasser- und Abfallwirtschaft **05-06**: 89–94.

Middelmann, M. & Granger, K. (2000). *Community risk in Mackay: a multi-hazard risk assessment.* Tech. rep., Australian Geological Survey Organisation (AGSO). URL `http://www.ga.gov.au/hazards/reports/mackay/`. Access 19 February 2009.

Miles, S. & Keefer, D. (2009). *Evaluation of CAMEL - comprehensive areal model of earthquake-induced landslides.* Engineering Geology **104**: 1–15.

Montgomery, D. & Dietrich, W. (1994). *A physically based model for the topographic control on shallow landsliding.* Water Resources Research **30**: 1153–1171.

Montgomery, D. R., Sullivan, K. & Greenberg, H. M. (1998). *Regional test of a model for shallow landsliding.* Hydrological Processes **12**: 943–955.

Moran, A., Wastl, M., Geitner, C. & Stötter, J. (2004). *A regional scale risk analysis in the community of Ólafsfjödur, Iceland.* In *Internationales Symposium - INTERPRAEVENT.* Riva, Trient.

Müller, M., Vorogushyn, S., Maier, P., Thieken, A., Petrow, T., Kron, A., Büchele, B. & Wächter, J. (2006). *CEDIM Risk Explorer - a map server solution in the project "Risk Map Germany".* Natural Hazards and Earth System Sciences **6**: 711–720.

Munich Re (2000). *Topics 2000: natural catastrophes - the current position.* Tech. rep. URL `http://www.imia.com/downloads/external_papers/EP17_2003.pdf`. Access 23 January 2009.

NADIMPALLI, K., EDWARDS, M. & MULLALY, D. (2007). *National Exposure Information System (Nexis) for Australia: risk assessment opportunities.* In OXLEY, L. & KULASIRI, D. (Eds.), *MODSIM 2007 International Congress on Modelling and Simulation.* 1674–1680.

ODEH ENGINEERS, INC (2001). *Statewide hazard risk and vulnerability assessment for the state of Rhode Island.* Tech. rep., NOAA Coastal Services Center. URL `http://www.csc.noaa.gov/rihazard/pdfs/rhdisl_hazard_report.pdf`. Access 09 March 2010.

ODERREGIO (2006). *Vorsorgender raumordnerischer Hochwasserschutz im Einzugsgebiet der Oder - Transnationales Handlungsprogramm.* Tech. rep., INTERREG III B-Projekt OderRegio. URL `http://www.oderregio.org/download/OR_HP_DE_Web.pdf`. Access 08 November 2010.

OLFERT, A., GREIVING, S. & BATISTA, M. (2006). *Regional multi-risk review, hazard weighting and spatial planning response to risk - results from European case studies.* URL `http://arkisto.gtk.fi/sp/SP42/9_regio.pdf`. Access 10 March 2010.

PAPATHOMA, M. & DOMINEY-HOWES, D. (2003). *Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece.* Natural Hazards and Earth System Sciences **3**: 733–747.

PAPATHOMA-KÖHLE, M., KAPPES, M., KEILER, M. & GLADE, T. (2011). *Physical vulnerability assessment for Alpine hazards - state of the art and future needs.* Natural Hazards **58**: 645–680.

PAPATHOMA-KÖHLE, M., NEUHÄUSER, B., RATZINGER, K., WENZEL, H. & DOMINEY-HOWES, D. (2007). *Elements at risk as a framework for assessing the vulnerability of communities to landslides.* Natural Hazards and Earth System Sciences **7**: 765–779.

PEGRAM, G. & PARAK, M. (2004). *A review of the regional maximum flood and rational formula using geomorphological information and observed floods.* Water SA **30**: 377–384.

PERLES ROSELLÓ, M. & CANTARERO PRADOS, F. (2010). *Problems and challenges in analyzing multiple territorial risks. Methodological proposals for multi-hazard mapping.* Boletín de la Asociación de Geógrafos Españoles **52**: 399–404.

PERUCCA, L. & ESPER ANGILLIERI, M. (2009). *Evolution of a debris-rock slide causing a natural dam: the flash flood of Río Santa Cruz, Province of San Juan.* Natural Hazards **50**: 305–320.

PETSCHKO, H., GLADE, T. & BELL, R. (2010). *Landslide inventories for regional landslide early warning systems.* In MALET, J.-P., GLADE, T. & CASAGLI, N. (Eds.), *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence.* CERG Editions, Strasbourg, 277–282.

Phillips, E., Grubisich, T. & Lyon, B. (Eds.) (2010). *Understanding Risk - Forum.* The World Bank.

Planas, X. (2007). *Landslide hazard assessment and risk management experience in the Principality of Andorra.* Presentation at the Mountain Risks Stakeholder Workshop 1, Ministry of public works, Andorra government, Dortmund, Germany. URL `http://w3.unicaen.fr/mountainrisks/spip/IMG/pdf/09_ES-AD_Corominas-Planas_Stakeholder_Andorra.pdf`. Access 20 May 2011.

PLANAT (2004). *Sicherheit vor Naturgefahren - Vision und Strategie.* Tech. rep., Nationale Plattform für Naturgefahren.

Puissant, A., Malet, J.-P. & Maquaire, O. (2006). *Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure.* In *SAGEO 2006.* Strasbourg, France.

Reese, S., Bell, R. & King, A. (2007a). *RiskScape: a new tool for comparing risk from natural hazards.* Water & Atmosphere **15**: 24–25.

Reese, S., King, A., Bell, R. & Schmidt, J. (2007b). *Regional RiskScape: a multi-hazard loss modelling tool.* In Oxley, L. & Kulasiri, D. (Eds.), *MODSIM 2007 International Congress on Modelling and Simulation.* 1681–1687.

Remaître, A. (2006). *Morphologie et dynamique des laves torrentielles: applications aux torrents des Terres Noires du bassin de Barcelonnette (Alpes du Sud).* Ph.D. thesis, Université de Caen/Basse-Normandie.

Remaître, A. & Malet, J.-P. (2010). *The effectiveness of torrent check dams to control channel instability: example of debris flow events in clay shales.* In Conesa García, C. & Lenzi, M. (Eds.), *Check dams, morphological adjustments and erosion control in torrential streams.* Nova Science Publications, 211–237.

Remaître, A., Malet, J.-P. & Cepeda, J. (2010). *Landslides and debris flows triggered by rainfall: the Barcelonnette basin case study, South French Alps.* In Malet, J.-P., Glade, T. & Casagli, N. (Eds.), *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence.* CERG Editions, 141–145.

Ritchey, T. (2006). *Modeling multi-hazard disaster reduction strategies with computer-aided morphological analysis.* In *Proceedings of the 3rd international ISCRAM Conference.* Newark, USA.

RTM (2000a). *Plan de prévention des risques naturals prévisibles - Department des Alpes de Haute-Provence, Commune de Jausiers.* Tech. rep., Service departamental de restauration des terrains en montagne.

RTM (2000b). *Plan de prévention des risques naturals prévisibles - Department des Alpes de Haute-Provence, Commune d'Enchastrayes.* Tech. rep., Service departamental de restauration des terrains en montagne.

RTM (2002). *Plan de prévention des risques naturels prévisibles - Departement des Alpes de Haute-Provence, Commune de Faucon de Barcelonnette.* Tech. rep., Service departamental de restauration des terrains en montagne.

RTM (2008). *Commune de Barcelonnette: Plan de Prévention des Risques Naturels Prévisibles - Reglement.* Tech. rep., Service departamental de restauration des terrains en montagne. Provisoire.

Ruiz Rodriguez + Zeisler, geomer GmbH, PlanEVAL & HASKONING (2001). *Übersichtskarten der Überschwemmungsgefährdung der möglichen Vermögensschäden am Rhein - Abschlussbericht: Vorgehensweise zur Ermittlung der hochwassergefährdeten Flächen, Vorgehensweise zur Ermittlung der möglichen Vermögensschäden.* Tech. rep., Internationale Kommission zum Schutz des Rheines (IKSR).

Rural Alaska Mitigation Planning (2009). *Multi-hazard mitigation plan.* Tech. rep., Lake and Peninsula Borough. URL `http://www.commerce.state.ak.us/dca/planning/nfip/Hazard_Mitigation_Plans/Lake_Pen_Boro_MJ_HMP.pdf`. Access 04 March 2011.

Salvati, P., Balducci, V., Bianchi, C., Guzzetti, F. & Tonelli, G. (2009). *A WebGIS for the dissemination of information on historical landslides and floods in Umbria, Italy.* GeoInformatica **13**: 305–322. 10.1007/s10707-008-0072-1.

Schick, A. (1988). *Hydrologic aspects of floods in extreme arid environments.* In Baker, V., Kochel, R. & Patton, P. (Eds.), *Flood geomorphology.* Wiley & Sons, New York, USA, 189–204.

Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Smart, G., Cousins, J., Smith, W. & Heron, D. (2011). *Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling.* Natural Hazards **online first**.

Schneiderbauer, S. & Ehrlich, D. (2006). *Social levels and hazard (in)dependence in determining vulnerability.* In Birkmann, J. (Ed.), *Measuring vulnerability to natural hazards - towards disaster resilient societies.* TERI Press, New Delhi, India, 78–102.

Schumm, S. (1979). *Geomorphic thresholds: the concept and its applications.* Transaction of the Institute of British Geographers **4**: 485–515.

SHAFIQUE, M., VAN DER MEIJDE, M., KERLE, N., VAN DER MEER, F. & KHAN, M. (2008). *Predicting topographic aggravation of seismic ground shaking by applying geospatial tools.* Journal of Himalayan Earth Sciences **41**: 33–43.

SHI, P. (2002). *Theory on disaster science and disaster dynamics.* Journal of Natural Disasters **11**: 1–9.

SIVAN, O. (2000). *Torrents de l'Ubaye.* Sabenca, Association de la Valeia, Barcelonnette, France.

SLAYMAKER, O. & EMBLETON-HAMANN, C. (2009). *Mountains.* In SLAYMAKER, O., SPENCER, T. & EMBLETON-HAMANN, C. (Eds.), *Geomorphology and Global Environmental Change.* Cambridge University Press, Cambridge, UK, 37–70.

SLF (1984). *Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten.* Tech. rep., Eidgenössisches Institut für Schnee- und Lawinenforschung & Bundesamt für Forstwesen.

SPERLING, M., BERGER, E., MAIR, V., BUSSADORI, V. & WEBER, F. (2007). *Richtlinien zur Erstellung der Gefahrenzonenpläne (GZP) und zur Klassifizierung des spezifischen Risikos (KSR).* Tech. rep., Autonome Provinz Bozen.

STÖTTER, J., BELITZ, K., FRISCH, U., GEIST, T., MAIER, M. & MAUKISCH, M. (1999). *Konzeptvorschlag zum Umgang mit Naturgefahren in der Gefahrenzonenplanung - Herausforderung an Praxis und Wissenschaft zur interdisziplinären Zusammenarbeit.* Innsbrucker Geographische Gesellschaft - Jahresbericht : 30–59.

SWISS RE (2011). *Natural catastrophes and man-made disasters in 2010: a year of devastating and costly events.* Tech. Rep. 1/2011. URL `http://media.swissre.com/documents/sigma1_2011_en.pdf`. Access 17 June 2011.

SWISS VIRTUAL CAMPUS (2008). *NAHRIS - dealing with natural hazards and risks.* URL `www.nahris.ch`. Access 11 November 2008.

TARVAINEN, T., JARVA, J. & GREIVING, S. (2006). *Spatial pattern of hazards and hazard interactions in Europe.* URL `http://arkisto.gtk.fi/sp/SP42/6_spa_patt.pdf`. Access 10 March 2010.

TATE, E., CUTTER, S. & BERRY, M. (2010). *Integrated multihazard mapping.* Environment and Planning B: Planning and Design **37**: 646–663.

THE WORLD BANK (2010). *World development report 2010: development and climate change.* Washington, DC, USA.

Thierry, P., Stieltjes, L., Kouokam, E., Nguya, P. & Salley, P. M. (2008). *Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon.* Natural Hazards **45**: 429–456.

Thiery, Y. (2007). *Susceptibilité du bassin de Barcelonnette (Alpes du sud, France) aux 'mouvements de versant': cartographie morphodynamique, analyse spatiale et modélisation probabiliste.* Ph.D. thesis, Université de Caen/Basse-Normandie.

Thiery, Y., Malet, J.-P., Sterlacchini, S., Puissant, A. & Maquaire, O. (2007). *Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment.* Geomorphology **92**: 38–59.

Thiery, Y., Puissant, A., Malet, J.-P., Remaître, A., Beck, E., Sterlacchini, S. & Maquaire, O. (2003). *Towards the construction of a spatial database to manage landslides with GIS in mountainous environment.* In *Proceedings of the 6th AGILE Conference on GIScience.* Lyon, France.

Thiery, Y., Sterlacchini, S., Malet, J.-P., Puissant, A., Remaître, A. & Maquaire, O. (2004). *Strategy to reduce subjectivity in landslide susceptibility zonation by GIS in complex mountainous environments.* In *Proceedings of the 7th AGILE Conference on GIScience.* Heraklion, Greece.

Tyagunov, S., Heneka, P., Stempniewski, L., Zschau, J., Ruck, B. & Kottmeier, C. (2005). *CEDIM: From Multi-Hazards to Multi-Risks.* In *Proceedings of the 1st ARMONIA conference.* Barcelona, Spain.

UN (1994). *Yokohama strategy and plan of action for a safer world - guidelines for natural disaster prevention, preparedness and mitigation.* Tech. rep., United Nations, Yokohama, Japan. URL `http://www.undp.org/cpr/disred/documents/miscellanous/yokohamastrategy.pdf`. Access 06 June 2009.

UN (2002). *Johannesburg Plan of implementation of the World Summit on Sustainable Development.* Tech. rep., United Nations. URL `http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf`. Access 03 September 2009.

UN-ISDR (2005). *Hyogo Framework for Action 2005-1015: Building the Resilience of Nations and Communities to Disasters.* In *World Conference on Disaster Reduction.* Kobe, Hyogo, Japan.

UN-ISDR (2009a). *Global assessment report on disaster risk reduction.* Tech. rep., United Nations - International Strategy for Disaster Reduction. URL `http://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413`. Access 1 September 2009.

UN-ISDR (2009b). *UNISDR terminology on disaster risk reduction.* Tech. rep., United Nations - International Strategy for Disaster Reduction. URL `http://www.undp.org.ge/new/files/24_619_762164_UNISDR-terminology-2009-eng.pdf`. Access 18 November 2009.

UNEP (1992). *Agenda 21.* Tech. rep., United Nations Environment Programme. URL `http://www.un.org/esa/dsd/agenda21/res_agenda21_07.shtml`. Access 03 September 2009.

University of Delaware (2005). *GIS@UD Documentation - getting started with programming and scripting in ArcGIS.* online. URL `http://maps.rdms.udel.edu/gis/howtopages/progarcgis.php`.

USGS (2009). *Soil type and shaking hazard in the San Francisco Bay area.* online. URL `http://earthquake.usgs.gov/regional/nca/soiltype/`. Access 05 July 2011.

UVM (2005). *Hochwassergefahrenkarten in Baden-Württemberg.* Tech. rep., Ministerium für Umwelt, Naturschutz und Verkehr. URL `http://www.uvm.baden-wuerttemberg.de/servlet/is/1253/HWGK_Leitfaden_DEU.pdf`. Access 08 November 2010.

vanWesten, C. (2004). *Geo-Information tools for landslide risk assessment. An overview of recent developments.* In Lacerda, W., Erlich, M., Fontoura, S. & Sayao, A. (Eds.), *Landslides : evaluation and stabilization - glissement de terrain: Evaluation et Stabilisation : proceedings of the 9th international symposium on landslides.* Balkema, London, UK, Rio de Janeiro, Brazil, 39–56.

vanWesten, C. (2010). *GIS for the assessment of risk from geomorphological hazards.* In Alcántara-Ayala, I. & Goudie, A. (Eds.), *Geomorphological hazards and disaster prevention.* Camebridge University Press, Cambridge, UK, 205–219.

vanWesten, C., van Asch, T. & Soeters, R. (2006). *Landslide hazard and risk zonation - why is it still so difficult?* Bulletin of Engineering Geology and the Environment **65**: 167–184.

vanWesten, C., Montoya, A., Boerboom, L. & Badilla Coto, E. (2002). *Multi-hazard risk assessment using GIS in urban areas : a case study for the city of Turrialba, Costa Rica.* In *Proceedings of the regional workshop on best practices in disaster mitigation: lessons learned from the Asian urban disaster mitigation program and other initiatives.* Bali, Indonesia, 120–136.

vanWesten, C., Quan Luna, B., Vargas Franco, R., Malet, J., Jaboyedoff, M. & Kappes, M. (2010). *Development of training materials on the use of Geo-information for Multi-Hazard Risk Assessment in a Mountainous Environment.* In

Malet, J.-P., Glade, T. & Casagli, N. (Eds.), *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence.* CERG Editions, Strasbourg, 469–475.

vanWesten, C. J. (2002). *Remote sensing and geographic information systems for natural disaster management.* In Skidmore, A. (Ed.), *Environmental modelling with GIS and remote sensing.* Taylor & Francis, London, UK, 200–226.

Varnes, D. J. (1984). *Landslide hazard zonation: a review of principles and practice.* United Nations Educational, Scientific and Cultural Organisation, Paris, France.

Wald, D. & Allen, T. (2007). *Topographic slope as a proxy for seismic site conditions and amplification.* Bulletin of the Seismological Society of America **97**: 1379–1395.

Walker, G., Whittle, R., Medd, W. & Watson, N. (2010). *Risk governance and natural hazards.* Deliverable D2.1, CapHaz-Net. URL `http://caphaz-net.org/outcomes-results/CapHaz-Net_WP2_Risk-Governance.pdf`. Access 17 August 2010.

Wanczura, S. (2006). *Assessment of spatial planning approaches to natural hazards in selected EU member states.* In Fleischhauer, M., Greiving, S. & Wanczura, S. (Eds.), *Natural hazards and spatial planning in Europe.* ARMONIA, 173–184.

Wastl, M., Stötter, J., Schöberl, F. & Kleindienst, H. (2008). *Risk assessment for mountain roads - a case study from Iceland.* In *Internationales Symposium - INTERPRAEVENT.*

Weber, D. (1994). *Temporal occurrence and forecasting of landslides in the European Community*, vol. I, final report, contract epoch Research into earth movements in the Barcelonnette basin. European Commission, Brussels, 321–336.

White, G., Kates, R. & Burton, I. (2001). *Knowing better and losing even more: the use of knowledge in hazards management.* Environmental Hazards **3**: 81–92.

Wichmann, V. & Becht, M. (2003). *Modelling of geomorphic processes in an alpine catchment.* In *7th International Conference on GeoComputation.* Southampton, UK.

Wichmann, V., Heckmann, T., Haas, F. & Becht, M. (2009). *A new modelling approach to delineate the spatial extent of alpine sediment cascades.* Geomorphology **111**: 70–78.

WMO (1999). *Comprehensive risk assessment for natural hazards.* Technical document 955, World Meteorological Organisation. URL `http://www.planat.ch/ressources/planat_product_en_198.pdf`. Access 05 May 2010.

Zezere, J., Garcia, R., Oliveira, S. & Reis, E. (2008). *Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal).* Geomorphology **94**: 467–495.

Zimmermann, M., Mani, P. & Gamma, P. (1997). *Murganggefahr und Klimaänderung - ein GIS-basierter Ansatz.* vdf Hochschulverlag AG, ETH Zürich.

Zischg, A., Fuchs, S., Keiler, M. & Stötter, J. (2005). *Temporal variability of damage potential on roads as a conceptual contribution towards a short-term avalanche risk simulation.* Natural Hazards and Earth System Science **5**: 235–242.

Zuccaro, G., Cacace, F., Spence, R. & Baxter, P. (2008). *Impact of explosive eruption scenarios at Vesuvius.* Journal of Volcanology and Geothermal Research **178**: 416–453.

Zuccaro, G. & Leone, M. (2011). *Volcanic crisis management and mitigation strategies: a multi-risk framework case study.* Earthzine **4**.

A. Articles

A.1. Challenges of dealing with multi-hazard risk: a review

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Challenges of dealing with multi-hazard risk: a review

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Abstract

Risk analyses are an important component of risk management and thus risk reduction since they provide the basis for decision making. However, to reduce the overall risk proactively and effectively all hazards threatening the area of concern have to be studied. Such so-called Multi-Hazard Risk Analyses (MHRA) are rather multipartite procedures consisting, as single-hazard risk analyses, of the three parts hazard, vulnerability and risk investigation. Though, they pose a range of additional challenges due to the multitude of processes involved as the need for comparability of the single-hazard results, an equivalent vulnerability assessment towards multiple hazards, an overall analysis scheme for the multi-hazard risk or the visualization of the multi-dimensional results. The aim of this contribution is to give an outline of the steps of a Multi-Hazard (Risk) Analysis (MH(R)A), to present a review how multi-hazard (risk) analyses are addressed in various studies and to indicate the inherent challenges.

KEY WORDS: Multi-hazard risk, hazard, vulnerability, risk, hazard cascades, hazard chains

Introduction

The term “multi-hazard” emerged in the international political environment with one of the first references in the Agenda 21 for sustainable development (UNEP 1992). In this document “complete multi-hazard research” was called for as a part of human settlement planning and management in disaster-prone areas (UNEP 1992, paragraph 7.61). The term appears again in the Johannesburg Plan concerning “protecting and managing the natural resource base of economic and social development” (UN 2002, p. 14), aiming for an “integrated, multi-hazard, inclusive approach” as “essential element of a safer world” (UN 2002, p. 20). The aspect to implement an “integrated, multi-hazard approach for disaster risk reduction [...] into policies, planning and programming related to sustainable development, relief, rehabilitation, and recovery activities in post-disaster and post-conflict situations in disaster-prone countries” was taken over by the Hyogo Framework of Action (UN-ISDR 2005, p. 4).

The term multi-hazard is thus used by the UN in the context of risk management and with the focus on overall risk reduction. This indicates that the need is seen to conflate and jointly investigate the whole range of threatening hazards, resulting in an integrated multi-hazard risk output. Consequently, the term multi-hazard risk can be interpreted as the consideration of multiple (if possible all relevant) hazards posing risk to a certain area under observation. In contrast to many scientific studies no significant emphasis is put on the hazardous processes themselves, as their investigation is only one component of the overall risk assessment.

Hazard and risk analysis methods are already well-established for many (if not most) single processes (e.g. Hutter et al. 1996, Aleotti and Chowdhury 1999, Dorren 2003, Ancey et al. 2004, Jonkman et al. 2008). However, a multi-hazard risk output is not just the sum of single-hazard risk results as major differences exist between:

1) hazard characteristics,
2) methods to describe vulnerability,
3) assessment of exposed elements at risk including direct and indirect consequences,
4) modeling methods to compute hazards and risks,
5) hazards and risks classification schemes, and
6) visualization of results.

These process-specific differences are a major challenge for the analysis of multi-hazard risks. In order to compute the overall risk, (1) comparable single-hazard risk components have to be calculated which (2) can be combined to a comprehensive risk. In countries such as Switzerland, France or Liechtenstein, multi-hazard (risk) maps and reports are already elaborated for some time, although the term "multi-hazard (risk)" is still rarely used. In these reports the risk for the communities posed by natural processes is analyzed.

The aim of this contribution is to give an outline of the steps of a Multi-Hazard (Risk) Analysis (MH(R)A), to present a review how multi-hazard (risk) analyses are addressed in various studies and to indicate the inherent challenges.

Although this review focuses on the methodology of multi-hazard (risk) analyses, it also includes studies which are not explicitly working on multi-hazard but consider "more-than-one-hazard" and multiple hazards, respectively. These descriptions refer to studies not aiming at a whole multi-hazard (risk) analysis or not intending to include all relevant processes for a certain area and work only on a distinct part of the whole procedure. These studies were included since they often provide profound insight in a certain aspect which might be neglected in studies doing the overall procedures due to the high difficulty and complexity.

To meet the objective of this paper, the three main steps of a multi-hazard risk analysis are presented, namely the hazard, vulnerability and risk assessment, and the challenges of each step are discussed. Additionally, in a final section, methods for multi-hazard (risk) visualization are outlined. This transfer of the results to the users is important to contribute for a successful risk management and ultimately risk reduction. However, due to the multi-dimensionality of the output, it is indeed a challenging task.

The authors do not claim completeness of the presented review but aim to give a comprehensive introduction into the field of multi-hazard risk analyses and its specificities.

The terms hazard, vulnerability and risk exhibit multiple definitions and are described by various authors and institutions (e.g. Varnes 1984, UNDHA 1992). To avoid confusion, the definition of the main terms used in this paper are highlighted at the beginning of each chapter. Furthermore, we classify the described concepts in qualitative, semi-quantitative and quantitative approaches using the definition of Borter (1999) and Altenbach (1995) as follows:

Qualitative: Description in words (e.g. high, medium and low) which relate to, or involve quality or kind. Qualitative judgments rank in higher and lower without the information how much higher or lower. Such classifications are highly dependent on the experience of the involved personnel.

Semi-quantitative: Description by means of a scale which consists of words or numbers. This scale allows a relative ranking and provides a measure how much more one scenario contributes over the next. This scale is a combination of expert opinion and objective calculations.
Quantitative: Relates to or can be expressed in terms of quantities or amounts. It allows the determination of absolute information on whatever scale of units is chosen.

Multi-hazard risk analysis

According to Varnes (1984, p. 10) hazard is defined as the "probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon". Risk includes, apart from the hazard aspect, also the vulnerability of the elements at risk and is established as the "expected degree of loss due to a particular natural phenomenon", the product of vulnerability and hazard (Varnes 1984, p.10). In this section we focus on the three steps of a multi-hazard risk analysis, namely the analysis of (1) multi-hazard, (2) vulnerability towards multiple processes and (3) multi-hazard risk. Examples of existing methods to cope with difficulties due to the joint investigation of multiple hazards are presented.

Multi-Hazard Analyses

Hazards "differ by their nature, intensity, return period and by the effects they may have on exposed elements. […] Their magnitudes are also measured in different ways, using different units of reference, for example, discharge or inundation depth for floods, ground motion or macro-seismic intensity for seism" (Carpignano et al. 2009, p. 515). This statement summarizes the main reasons why different types of hazards are not directly comparable and why standardization of a common measure is most important to enable a comparison.

Comparability of hazards types

Reviewing numerous studies (e.g. Heinimann et al. 1998, Delmonaco et al. 2006b, Thierry et al. 2008, Odeh Engineers, Inc 2001, El Abidine El Morjani et al. 2007, Bartel and Muller 2007) regarding the used standardization of hazard types two major methods could be determined: (1) the classification of hazards (qualitative approach), and (2) the development of indices as continuous technique (semi-quantitative approach). Both main approaches are exemplified and discussed in the following.
(1) Standardization by means of classification is the most often used approach to allow the comparison of different hazards. A framework of common objectives or criteria has to be established, according to which a coherent classification scheme adjusted to each hazard can be defined. According to Delmonaco et al. (2006a) this is the only way to assure an equivalence and comparability of 'high' earthquake and 'high' flood hazard. Therefore the comparison of data received from different sources without any collaboration is very difficult or even impossible since most probably different criteria were applied. In the following we present a number of studies employing diverse classification schemes.
Moran et al. (2004) (based on Heinimann et al. 1998; Fuchs et al. 2001) used a worst-case scenario for the modeling of avalanches and rock fall in order to

estimate the risk potential at regional scale. Due to the common basis (worst-case scenario), the modeling results can be compared and visualized in a single map. By overlay with elements at risk, the number of endangered buildings or affected road kilometers could be determined and results directly compared between the two processes.

Within the ARMONIA project a classification scheme was proposed for hazard intensities at a regional scale (Delmonaco et al. 2006b). This matrix with regard to spatial planning classifies the process intensities using hazard-specific thresholds for low, medium and high intensities (Table 1). Subsequently the importance of hazards can be compared and consequences for the spatial planning process can be defined.

Table 1 ARMONIA hazard intensity classification matrix for a regional scale (Menoni 2006)

Natural Hazard	Intensity Scales			
	Low	Medium	High	Parameters
Flood	< 0.25	0.2 - 1.25	> 1.25	Flood depth (m)
Forest Fire	< 350	350 - 1750	> 1750 - 3500	Predicted Fire-line Intensity (*)(kW/m)
Forest Fire	< 1.2	1.2 - 2.5	> 2.5 - 3.5	Approximate Flame length (m)
Volcanoes	< 5	5 - 10	> 10	Intensity = Volcanic Explosive Index $\log_{10}$(mass eruption rate, kg/s) + 3
Landslide (fast and slow movements)	< 5	5 - 15	> 15	Percentage of landslide surface (m^2, km^2, …) vs. stable surface (%)
Seismic	< 10	10 - 30	> 30	Peak Ground Horizontal Acceleration (%g)

In Switzerland, the classification for the production of hazard maps used in land use planning is also defined by hazard-specific thresholds determining high, medium and low hazard classes (Heinimann et al. 1998). The thresholds were established according to the possible effect on buildings and humans:

- High hazard (red zone): persons in- and outside of buildings are at risk and the destruction of buildings is possible, or events with a lower intensity occur but with higher frequency and persons outside of buildings are at risk. Further construction of buildings is prohibited.

- Medium hazard (blue zone): people inside of buildings are slightly endangered, damages of buildings are possible, but destruction is seldom. Further construction of buildings is allowed with constraints.
- Low hazard (yellow zone): people are slightly endangered, small damages and interferences are possible.
- Residual hazard (yellow white striped): hazards of very low frequency and high intensity are possible.

The hazard classes are technically defined by their constellation of intensity and probability (Fig. 1).

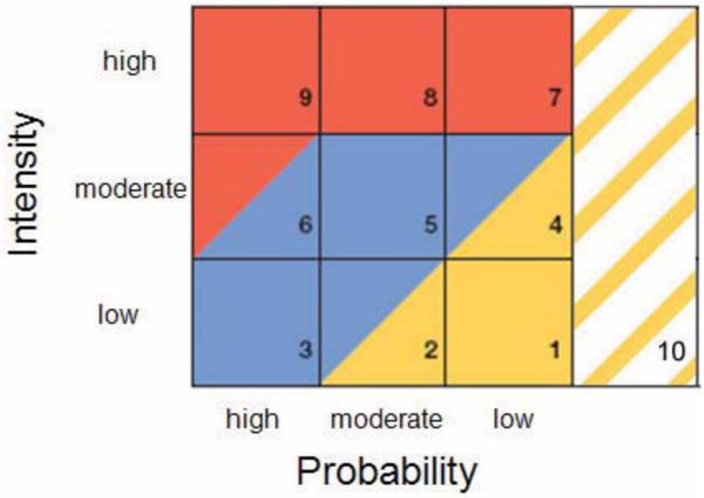

Fig. 1 Swiss intensity-probability matrix after Kunz and Hurni (2008)

Frequency thresholds are the same for all processes divided in 1-30 years for the high, 30-100 years for the medium and 100-300 years for the low class, respectively. The intensity classification is primarily based on the effects on humans and buildings as described in the characterization of the hazard zones and is translated to certain intensity thresholds for each process (for avalanches in SLF (1984), for landslides in Lateltin (1997), for floods in Loat and Petraschek (1997) and all summarized in Loat (2010, Table 2).

Table 2 Swiss hazard intensity classification matrix according to Loat (2010)

Process	**Low intensity**	**Average intensity**	**High intensity**
Rock fall	$E < 30kJ$	$20kJ < E < 300kJ$	$E > 300kJ$
Landslide	Vs < 2cm/year	Vs: dm/year	Vs > dm/day; displacement > 1m per event
Debris flow	--	D < 1m and V < 1m/s	D > 1m and v > 1m/s
Static flooding	$h < 0.5m$	$0.5 < h < 2m$	$h > 2m$
Dynamic flooding	$q < 0.5\ m^2/s$	$0.5 < q < 2m^2/s$	$q > 2m^2/s$
Bank erosion	$t < 0.5m$	$0.5 < t < 2m$	$t > 2m$
Snow avalanche	$P < 3\ kN/m^2$	$3\ kN/m^2 < P < 30\ kN/m^2$	$P > 30\ kN/m^2$
E = kinetic energy; Vs = mean annual velocity of landslide; D = thickness of debris front; v = flow velocity (flood or debris flow); h = flow depth; q = specific discharge ($m^3/s/m$) = h x v; t = extent of lateral erosion; P = avalanche pressure exerted on an obstacle			

An overall hazard map is derived by overlay of all classified hazards. For the overlapping of different hazard scenarios of the same process the highest hazard class is adopted. In case of overlapping of different hazards also the highest hazard class is assumed but hazards of an equal or lower hazard class can be indicated by an additional index letter (Heinimann et al. 1998).

A very similar approach was used by Thierry et al. (2008) for the active volcano Mount Cameroon: six volcanic hazards, two slope instability incidents, and one tectonic phenomenon were included and for each of them a separate intensity classification scheme was developed. The five intensity classes were determined for each process according to the expected damage level (≤5% very low, 5-10% low, 10-50% moderate, 50-80% high and ≥80% very high) by means of expert knowledge following the proposal of Stiltje (1997), cited in Thierry et al. (2008). Seven frequency classes were established from 1-10 years quasi-permanent, 10-50 years very frequent, 50-100 years high, 100-500 years moderate, 500-1000 years low, 1000-5000 years very low and 5000-10000 years very low to negligible. Opposing frequencies and intensities five hazard classes ranging from negligible to very high hazard were computed. The classified hazards were finally superimposed and the locally determined maximum hazard class was retained.

Chiesa et al. (2003) use in their study on earthquakes and tropical storms in the Asia Pacific region a classification scheme as well. However, the overall multi-hazard is not the maximum of overlapping hazards but defined by means of a matrix (Table 3). In comparison with the previous two studies where the maximum class was adopted, this leads to dissent results for very different classes of earthquake and storm threat. E.g. high and low/none hazard results in moderate, and extremely high and low/no hazard results in high overall hazard.

Table 3 Matrix for the determination of the multi-hazard (Chiesa et al. 2003)

		Tropical storm hazard			
		Low/none	*Mod.*	*High*	*Ext. high*
Eq. hazard	*Low/none*	Low/none	Mod.	Mod.	High
	Mod.	Mod.	Mod.	High	High
	High	Mod.	High	High	Ext. high
	Ext. high	High	High	Ext. high	Ext. high

In France, the elaboration of risk prevention plans (Plan de Prévention des Risques naturels prévisibles, PPR), likewise focusing on spatial planning, is obligatory in endangered areas (Delattre et al. 2002). A range of guides is available to support a harmonized preparation of PPRs (e.g. Cariam 2006 or Garry et al. 1997). Hazard modeling is supported and a general instruction how to establish thresholds for the hazard classification is given, but no immovable thresholds are provided - each municipality can determine them according to their specific needs and has to present them in its PPR (Liévois 2003; Besson et al. 1999; MEDD 2002; MEDD 1999).

Although all methods presented in this paragraph use classification schemes, the significant variations between each approach become already obvious. These variations are based on the constellation of hazards taken into account, but also regarding hazard indicators used to quantify intensities. The classification schemes of ARMONIA and Switzerland are not even comparable concerning landslides due to the differing measures used to quantify the processes – annual displacement of the landslide per time versus percentage of landslide surface compared to stable surface. Likewise, large differences become obvious for the frequency classification in the Swiss approach ranging between 1 year and above 300 years versus the scheme of Thierry et al. (2008) ranging between 1 year and 5000-10000 years. Finally, also the methods to assess the overall hazard from overlapping threats vary from the adoption of the maximum hazard class (e.g. Heinimann et al. 1998) to an intermediate rating (e.g. Chiesa et al. 2003). Although classification schemes offer a simple way to compare hazards directly and well understandably, they are specifically developed for a certain situation, application or study and are thus restricted to the use in these frameworks. Since relative assessments were made in order to categorize, the result is a) subjectively influenced, b) adjusted to the purpose it was elaborated for, and c) all additional information between the defined threshold values is lost.

(2) In contrast to classification, indices offer a continuous standardization of very different and not directly comparable parameters and the possibility to relatively rank the results (semi-quantitative method). Some studies using indices for standardization are highlighted in the following.

Odeh Engineers, Inc (2001) compute the continuous "Hazard Scores" (HS) for communities as a whole (instead of modeling hazards in a distributed way, pixel by pixel):

$$HS = FS \cdot AIS \cdot IS$$

With:

FS	Frequency Scores: measuring how often a given hazard occurs [events per year, classified in five levels],
AIS	Area Impact Score: measuring how much geographical area will be affected by a hazard event [gross or relative area, classified in five levels] and
IS	Intensity Score: measuring the intensity level of a hazard [hazard specific units, classified in five levels].

Due to multiplication of the classified input scores (FS, AIS and IS) the resulting HS is a continuous measure. The specificity of an analysis at community level is that it enables the comparison of different hazard indices in one community indicating the importance of each hazard and the comparison between communities. However, due to the choice of the study unit (community) no information is given on the location of the hazards.

The World Bank initiated a global risk analysis to identify natural disaster hotspots and especially areas affected by several hazards, and in a further step to estimate the mortality and economic loss risk (Dilley et al. 2005). The hazard processes were investigated by combining information on past events from inventories and modeling. For the definition of the classification thresholds, the total number of pixels affected by a certain hazard was divided into ten approximately equally sized groups, the so-called deciles. In a next step, based on a histogram the corresponding threshold intensity values were determined. The first to fourth deciles indicate low, the fifth to seventh a medium and the eighth to tenth deciles high hazard. For an overall hazard indication the "Simple Multihazard Index" was calculated, only taking the high hazard class (eighth to tenth deciles) into account and adding up the values of all hazards overlapping in a pixel. The result is given as number of hazards affecting each pixel.

El Abidine El Morjani et al. (2007, p. 20) pursue the goal to "identify potential hotspots where the population might be exposed to several hazards at the same time". Separately modeled and classified hazards are weighted with the impact on humans and economics (numbers of people killed, injured, homeless or affected and total damage expressed in US) caused in the past by these hazards (reported in the EM-DAT[1]). These weights (Table 4) are based on regional averages and are used as a measure of the importance of each process.

Table 4: "Normalised weights applied to the different hazards when calculating multihazard" (El Abidine El Morjani et al. 2007, p. 22)

Hazard	Normalized weight
Seismic	0.41
Flood	0.36
Wind speed	0.09
Heat	0.08
Landslide	0.06
Sum	1

The weighted indices are added up and are presented in the "multi hazard index distribution map" and are subsequently classified in five "intensity level[s] of multihazard" (El Abidine El Morjani et al. 2007, p. 20, p.23).

Another semi-quantitative approach which is not based on an index scheme was elaborated by Bartel and Muller (2007, p.1). They calculated the probability that "a given natural disaster will develop in a given area of the HOA in within a given year" (HOA - Horn of Africa). Bartel and Muller took into account moderate to severe drought and floods above a certain threshold, and locust infestations defined as "outbreaks of gregarious swarms of hoppers and adults" (Bartel and Muller 2007, p.4). The analyses resulted in an estimation of the annual probability of each process, the probability that any of these hazards would occur, the so-called joint probability, and the most probable hazard for each pixel. The earthquake hazard was not taken into account since it is "due to the relative infrequency of large damaging earthquakes in the HOA [...] not an annual concern like the other hazard types" (Bartel and Muller 2007, p. 1 et seq.).

Most of the studies presented so far remain with a completely separate analysis of single hazards within a joint analysis scheme which are combined in a last step to the overall hazard. However, "[n]atural processes are components of systems (ecosystems, geosystems etc.) and only certain characteristics possibly pose a threat to elements at risk convert them into hazards. As components of complex systems these processes are not independent and separated from each other but are linked and connected" (Kappes et al. subm.). Thus, these components influence each other, interact also nonlinearly which can result in changes of the system state and hazard patterns may emerge which differ from the sum of all single hazards. The negligence of these relations between processes might thus lead to under- or misestimation of the actual hazard.

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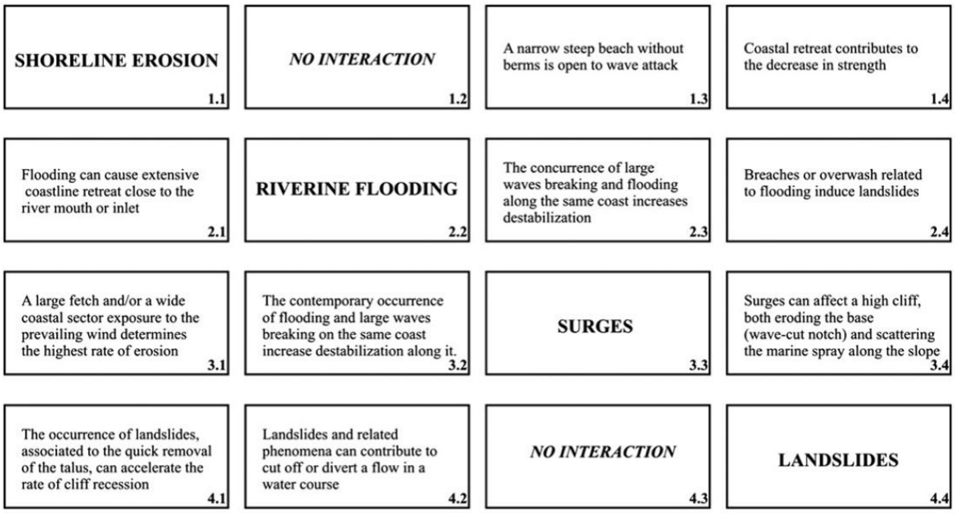
[1] EM-DAT is the Emergency Disaster Data Base maintained by CRED, the Centre for Research on the Epidemiology of Disasters. It contains essential core data on the occurrence and effects of over 18,000 mass disasters in the world from 1900 to present (CRED).

Dealing with relations between hazard types

Interacting or coupled processes are a main challenge in multi-hazard analysis. Reviewing the described studies from this perspective we were able to identify two types of relations between processes:
(1) The "domino effect or cascading failure" (Delmonaco et al. 2006a), i.e. direct triggering of one process by another. Delmonaco et al. (2006a) define this process relation as "failure in a system of interconnected parts, where the service provided depends on the operation of a preceding part, and the failure of a preceding part can trigger the failure of successive parts". These cascading failures cause effects and pose risks which are not captured by means of separate single-hazard analyses which are merged together. Thus, their negligence is problematic.
(2) Processes modify the disposition of each other which results in frequency and/or magnitude. An example is the removal of protective forest by avalanches in winter and the higher frequency and magnitude of rock falls in this area in the following spring.
Although the inclusion of the interaction of several processes within one eco/geosystem (or region) might be the ultimate aim of multi-hazard risk research our understanding of process interactions and cascades is still very limited, and so is the number of respective research studies.
1) According to Delmonaco et al. (2006a, p. 10) "basically two ways of how to assess the coupled hazards" exist: "[w]e can investigate the individual possible chains of hazardous events – one triggering another – and try to assess probability values in order to transfer these phenomena into risk maps [… or we] assess the risk for coincidences of different hazards, even without supposing any direct linkage among them." While the first is extremely data-demanding and the complexity of the hazard chains can be overwhelming, the second method is more robust and less data-intensive.
The studies of Tarvainen et al. (2006) and de Pippo et al. (2008) are very good examples for the "second way" to investigate the hazard coincidences. In both studies a matrix was used for the identification of possible hazard cascades and interactions by opposing all processes taken into account towards each other (Fig. 2). The possibility of an influence of one hazard on another is identified; the relation is either simply marked as in the case of Tarvainen et al. (2006) or the possible effect is shortly described (Fig. 2) as done by de Pippo et al. (2008). An example is given in the following: Surges (Fig. 2, cell 3.3) may influence the occurrence of landslides (cell 4.4) as surges "affect a high cliff, both eroding the base (wave-cut notch) and scattering the marine spray along the slope" (cell 3.4 - the intersecting cell between 3.3 and 4.4 in Fig. 2).



SHORELINE EROSION 1.1	*NO INTERACTION* 1.2	A narrow steep beach without berms is open to wave attack 1.3	Coastal retreat contributes to the decrease in strength 1.4
Flooding can cause extensive coastline retreat close to the river mouth or inlet 2.1	**RIVERINE FLOODING** 2.2	The concurrence of large waves breaking and flooding along the same coast increases destabilization 2.3	Breaches or overwash related to flooding induce landslides 2.4
A large fetch and/or a wide coastal sector exposure to the prevailing wind determines the highest rate of erosion 3.1	The contemporary occurrence of flooding and large waves breaking on the same coast increase destabilization along it. 3.2	**SURGES** 3.3	Surges can affect a high cliff, both eroding the base (wave-cut notch) and scattering the marine spray along the slope 3.4
The occurrence of landslides, associated to the quick removal of the talus, can accelerate the rate of cliff recession 4.1	Landslides and related phenomena can contribute to cut off or divert a flow in a water course 4.2	*NO INTERACTION* 4.3	**LANDSLIDES** 4.4

Fig. 2 “Descriptive matrix of the interaction of each hazard with one another” after de Pippo et al. (2008, p. 459). In the dialog are the four leading processes located and in the cells between them their possible interaction. The process situated in the same line as the cell describing the relation indicates the causing, the process in the same column the affected process.

The general identification of possible relations between hazards under investigation by means of the matrix is followed by the determination of the spatial position of these interactions in the studied area. Tarvainen et al. (2006) determine the locations of possible interactions by identification of areas (NUTS 3 units) in Europe where the interacting hazard pairs occur in a significant magnitude. De Pippo et al. (2008) work with geomorphic units of a coastal area and detect on basis of the matrix those units which exhibit certain hazard combinations possibly leading to interactions.

While with an interaction matrix general interactions and cascades within a set of considered processes can be identified and by overlay determined in the field, Egli (1996) and Marzocchi et al. (2009) propose a methodology on local level (type one approach investigating the individual possible chains of hazardous events according to Delmonaco et al. (2006a) constructing complete cascade scenarios. By means of an event tree all possible scenarios following one initial event are identified and their probabilities quantified (Marzocchi et al. 2009). The event trees are constructed in four steps (Egli 1996): the triggering event is determined, the possible following effects are identified, probabilities are assigned to each step and the probabilities of the possible final states of the complete system are computed. Furthermore, Egli (1996) proposes the use of fault trees. The fault trees enable the logical relation of possible partial scenarios which might lead to an unwanted ‘top-event’ (Fig. 3).

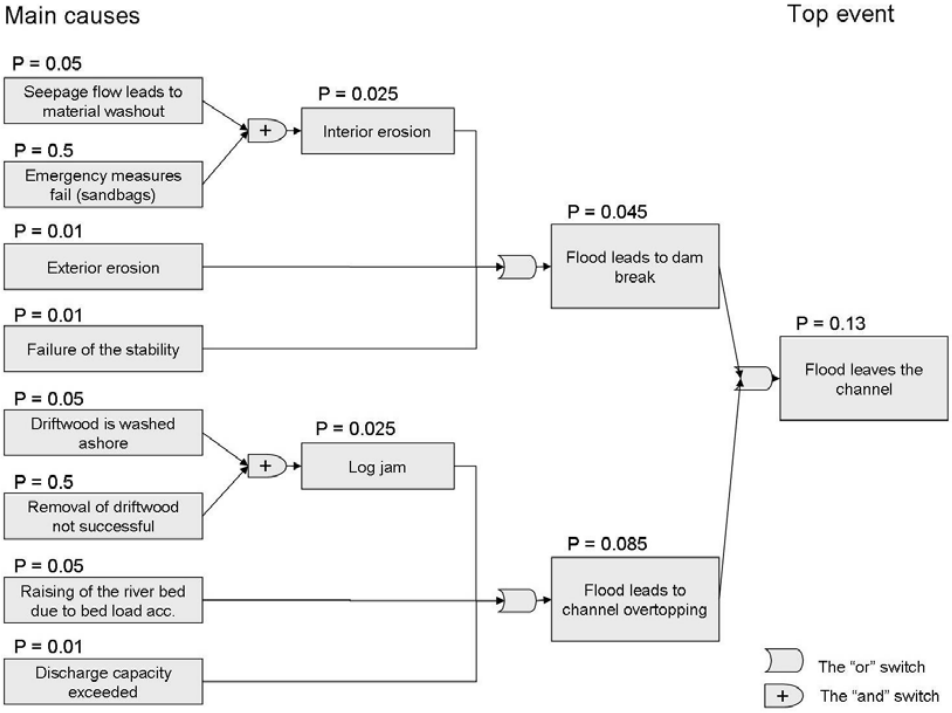


Fig. 3 The example of a fault tree after Egli (1996)

Apart from general methods applicable to a variety of processes, a range of studies focuses on cascades between two specific hazards and develop respective procedures. For example, Carrasco et al. (2003) developed a GIS-based methodology to identify areas of cascades including floods and landslides. Herein, the results of an undercutting of slopes or a damming of torrents by displaced material resulting in a channeled debris flow or a torrential flood are considered. In a first step, the general landslide susceptibility is calculated and displayed. In a second step, gorges (narrow streams and torrents) are identified and by overlying with the susceptibility map slopes connected to narrow streams and torrents are determined. The delineated areas do not only show "intrinsic" susceptibility, but furthermore "the possibility of external contribution by undercutting has been added" (Carrasco et al. 2003, p. 377). Finally, the possibility that displaced material converts into a debris flow or torrential flood and continues its movement along the stream has been considered.

Huggel et al. (2004) investigated the triggering of lake-outbursts by ice avalanches and periglacial debris flows. The target was to indicate those areas where critical situations may emerge; however, detailed scenarios were not elaborated. Only those ice avalanches and debris flows were considered which are large enough to cause an overtopping or even a complete emptying of the lake. Using a simple model based on the angle of reach concept the run out was estimated (Huggel et al. 2002).

One of the most prominent cascades is the triggering of landslides by earthquakes. Meyenfeld (2008) worked on the determination of a minimum earthquake magnitude for landslide initiation and for the general stability of slopes under earthquake influence. ARMAGEDOM, a French tool developed for earthquake modeling, is able to integrate possible slope instabilities after having computed the earthquake hazard (Sedan and Mirgon 2003).

2) Besides the direct triggering of secondary hazards we already mentioned the modification of conditioning factors. Regarding this type or relation, this means that an effect is not immediately caused by a specific event but that this event changes boundary conditions. Hence, a triggering event is still needed to initiate the process (the matrices after Marzocchi et al. 2009 and de Pippo et al. 2008 enable in fact the consideration of both, cascades and alteration of disposition). Cannon and DeGraff (2009) give a good example on changed preparatory factors with their research on increased flood and debris flow frequency due to forest fires. They investigated recurrence intervals and rainfall threshold intensities for the initiation of debris flows and floods shortly after fires and in time steps during the recovery phase and compared them with thresholds of unburned settings. The thresholds of recently burned catchments were significantly lower than most identified for unburned settings. Already after one year of vegetation recovery and sediment removal the threshold increased again. The authors emphasize the need of fast post-fire identification of the most critical locations to avoid damages and losses.

Bovolo et al. (2009) investigated a similar case, firstly modeling possible forest fire scenarios resulting from four different ignition points, and secondly estimating the effect on hydrology, sediment yield and erosion with the SHETRAN approach (Ewen et al. 2000).

Wichmann et al. (2009) present the SEDAG project (SEDiment cascades in Alpine Geosystems) which touches the geomorphic aspects of several natural hazards. Within SEDAG, the sediment pathways in high mountain areas were investigated, including the processes hill slope and channel fluvial processes, debris flows, full-depth snow avalanches, rock fall, landslides and slow mass movements (Wichmann and Becht 2003; Wichmann et al. 2009). The processes were modeled independently, and respective geomorphic process units (erosion, transport and deposition) were subsequently delineated. Linkages between two or more process such as the deposition by rock fall in debris flow erosion area units were identified by overlaying. Thus, the chain of sediment transport can be determined qualitatively.

Garcin et al. (2008) developed a forecast of future (around the year 2100) marine submersion of coastal areas due to storm surges and tsunamis. They superimposed the effect of tsunamis and storm surges on the risen sea level due to climate change.

Evidently, the consideration of interactions and linkages between hazardous processes is a challenging task. Although two main approaches, the investigation of hazard coincidence and thus risk of interactions and the development of detailed hazard chains exist, their rigorous implementation is still seldom done and, especially in case of the chains, very difficult.

To summarize the section of multi-hazard analyses, the comparison of hazards is difficult due to their very different characteristics. Although classification and index schemes help to overcome this problem, they are specifically elaborated for one purpose/stakeholder and only in this framework they can be used. Menoni (2006, p.10) expresses this circumstance as follows: “[i]t is hard to find common units of measures” which would serve for emergency managers and urban and regional planners since they “face specific problems provoked by hazards in a given context.” Furthermore, no actually quantitative approach for multi-hazard investigation could be identified which restricts the comparison of multiple hazards to relative rankings. An option to evade this problem is to move from multi-hazard to multi-hazard risk.

Risks, although emerging from different hazards, are directly comparable since they quantify the possible consequences as numbers or probabilities of loss of life, injury, damages etc. For the analysis of risks, the possible impact of hazards has to be related to the vulnerability of e.g. people, buildings and infrastructure. Risk is, as highlighted in the definition by Varnes (1984), a function of hazard and vulnerability. Therefore, vulnerability is one key element in risk analysis and we will review vulnerability in the context of a multi-hazard framework in the next section.

Analyses of the Vulnerability towards Multiple Hazards

Vulnerability is a multi-dimensional term with very different definitions in social and natural sciences, respectively (e.g. Birkmann 2006; Bohle and Glade 2008; Fuchs 2009; Papathoma-Köhle et al. subm.).

In social sciences, vulnerability mostly represents “the characteristics of a person or a group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard” (Wisner et al. 2004 p. 11). Social vulnerability analyses often merely estimate special characteristics of the society, while the hazard-specific nature of vulnerability is not taken into account (Kumpulainen 2006, also cf. e.g. Ferrier and Haque 2003; Kumpulainen 2006). Hence, these studies have not to be adapted to multi-hazard approaches as they are already dealing with hazards in general. However, “factors that make people vulnerable to earthquakes are not necessarily the same as those that make people vulnerable to floods or cyclones” (UNDP 2004 p. 32). Therefore, from a multi-hazard point of view, social vulnerability should also include the influence of hazard characteristics.

Natural sciences choose a completely different approach to vulnerability. Here, it is mostly expressed as “[d]egree of loss (from 0% to 100% [or dimensionless 0 to 1]) resulting from a potentially damaging phenomenon” (UNDHA 1992, p. 77). As opposed to social vulnerability studies, physical vulnerability investigated by engineers and natural scientists is in most cases hazard-dependent. However, the approaches used for the various hazard types differ strongly (Douglas 2007). Thus, it is not only very difficult to use results from social sciences in natural sciences approaches and vice versa, but even within the engineering and natural sciences.

In the following, we will present some hazard-specific approaches from the social and the natural sciences, respectively.

Approaches dealing with the vulnerability towards multiple hazards in social sciences

An example for a hazard-specific concept considering social vulnerability is the global study of Dilley et al. (2005). They present ‘vulnerability coefficients’ which are derived from historical data on mortality and economic losses due to a specific hazard type as recorded in the EM-DAT database. These hazard specific coefficients represent an “aggregate index of relative losses within each region and country wealth class for each hazard” (Dilley et al. 2005, p. 55). The mortality coefficient is applied as weight to the population exposure resulting in mortality risk, and the economic loss coefficient weights the gross domestic product leading to economic loss risk towards each hazard. Furthermore, the coefficients can be compared for different hazards and/or regions and thus show the relative significance of every single hazard in a given region.

A similar approach was presented by UNDP (2004) introducing the disaster risk index (DRI). The index is also based on data of the EM-DAT database, but is restricted to the estimation of risk of loss of life. In a first step, the “relative vulnerability of a country to a given hazard by dividing the number of people killed by the number exposed” is calculated (UNDP 2004, p. 32). In a second step, the relative vulnerability is linked as dependent parameters in a statistical analysis to a set of 26 socio-economic and environmental parameters to identify possible indicators of vulnerability. Thus, those parameters which are most associated are determined for each hazard type and are used as indicators for risk.

The two hazard-dependent social vulnerability approaches are both based on the consequences of past events. We could not find analyses in which hazard characteristics of multiple processes were investigated with respect to the effects they cause in society or the like. Whilst there are more approaches in the natural sciences which are hazard-dependent the major challenge of physical vulnerability analyses is the development of a common methodology. This problem will be discussed in detail in the next section.

Approaches dealing with the vulnerability towards multiple hazards in natural sciences

A variety of approaches dealing with the vulnerability towards multiple hazards in natural sciences exists which can be broadly distinguished in qualitative and quantitative methods.

A qualitative approach was proposed by Granger et al. (1999) for the identification of shelters. Granger and colleagues investigated in their study the question to what extent buildings are suitable to serve as shelters including their response characteristics towards natural threats in this region. A simple matrix depicts the building characteristics and reveals the relative contribution of these characteristics to the building's vulnerability towards a set of hazards (Table 5).

Table 5 Relative contribution of building characteristics to vulnerability (Granger et al. 1999). The number of stars reflects the significance of the contribution.

Characteristic	Flood	Wind	Hail	Fire	Quake
Building age	***	*****	**	*****	*****
Floor height or vertical regularity	*****	*		****	*****
Wall material	***	***	*****	****	****
Roof material		****	*****	****	***
Roof pitch		****	***	*	
Large unprotected windows	**	*****	****	*****	**
Unlined eaves		***		*****	
Number of stories	****	**		*	*****
Plan regularity	**	**		***	*****
Topography	*****	****		****	***

Another example for a qualitative approach are the risk matrices of the ARMONIA project. Originally in the proposed ARMONIA project a general quantitative concept for multi-hazard risk analyses using vulnerability curves (Fig.

4) for all hazards and building types was planned (Delmonaco et al. 2006b). Quite soon it became obvious that this approach was not feasible as only for floods and earthquakes vulnerability curves and methodologies were available while they were missing for other processes (Walker and Deeming 2006). The qualitative approach adopted instead consists of four vulnerability classes for different elements at risk (e.g. buildings or people). To obtain finally a joint vulnerability index (including e.g. vulnerability of buildings or people), each type of vulnerability is weighted in the framework of a Multi-Criteria Evaluation by the distribution of 20 points. While the weighting with one point assigns the lowest importance to a certain type of vulnerability, 19 points show the highest significance (Walker and Deeming 2006).

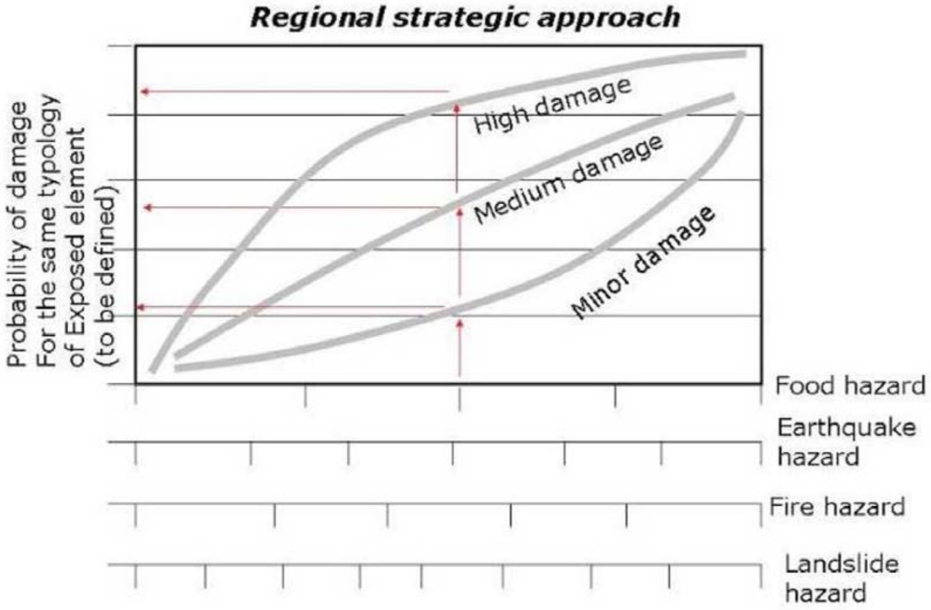


Fig. 4 Vulnerability function for different hazard types (hazard intensities on the x-axis) indicating the probability of damage for different categories of exposed elements (y-axis) according to Delmonaco et al. (2006b)

The tool HAZUS (HAZard United States) developed by the Federal Agency Management Agency utilizes a quantitative approach and is entirely based on vulnerability curves: depth-damage curves and velocity-depth damage functions indicating the collapse potential for floods (FEMA 2007a), fragility (displacement) and building capacity (force) curves for earthquakes (FEMA 2003) and building damage, building loss, building loss of use and building debris functions for hurricanes (FEMA 2007b). However, for the processes floods, earthquakes and hurricanes vulnerability curves are a commonly used method wherefore the problems ARMONIA faced do not occur.

Hollenstein (2005) proposes a completely new, generic framework for the analysis of the vulnerability to any process. On the one hand, elements at risk are described in a hazard-independent, general way, i.e. the “Performance”, by a set of components representing its characteristics (e.g. maximum safe speed, maximum admissible load or market value). On the other hand, the hazards are characterized by the impact, a set of general components of each hazard and due to which the method is adjustable to any process (e.g. acceleration, pressure, shear stress or toxicity). So called “wrapper functions” have to be developed for the

conversion from established measures in which hazards are quantified usually to the needed impact parameters. Finally, the impact parameters are linked to the performance parameters with vulnerability curves (Hollenstein et al. 2002).
Another aspect is brought up in the study of Gibbs (2003), the issue of spatially overlapping hazards. Within this concept, the consequences on the design and construction of buildings in case of exposure towards storms and earthquake are investigated. However, while specific building characteristics may proof favorable for the protection against one hazard, they may proof unfavorable against the other. Thus, an optimization for both hazard types has yet to be achieved.
Ho Lee and Rosowsky (2006) even go a step further. Instead of merely investigating the vulnerability of wood frame buildings towards earthquake or snow loading, they also investigated the vulnerability towards the simultaneous occurrence of both processes. Therefore, they developed a fragility surface in the three dimensional space of snow loading, earthquake loading, and fragility (Fig. 5).

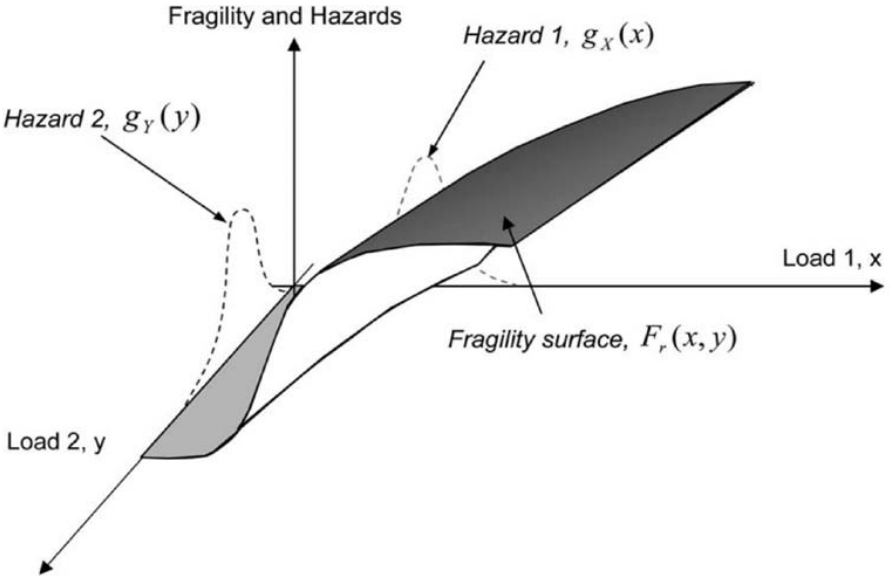


Fig. 5 Fragility surface as function of the combined load of the hazards x and y (snow cover and earthquake impact) after Ho Lee and Rosowsky (2006).

For this section it can be summarized that the available vulnerability assessments are as diverse as the different and specific hazard assessments. The first major challenge for multi-hazard and risk approaches is that most social vulnerability approaches are hazard-independent while natural hazard approaches are “society-independent”. However, the factors which make people/regions/societies vulnerable differ depending on the social context and the kind of hazard with its physical impact. It is exactly these two factors which have to be considered in a multi-hazard risk perspective. Secondly, vulnerability approaches within social and natural sciences cannot be transferred from one to the other. This is especially problematic as multi-hazard risk analyses mostly are (or should be) interdisciplinary in focus. And thirdly, even within the natural sciences no single method applicable for all hazards exists but several approaches which are more or less (or not) transferable to other processes. Although classification schemes might be a solution, they are the lowest common denominator simplifying the result significantly.

To complete the three steps which have to be considered in risk analyses – i.e. hazard, vulnerability, and risk analysis – the following section reviews existing approaches dealing with the computation of multi-hazard risk.

Multi-Hazard Risk Analyses

Risk is a qualitative or quantitative depiction of expected damages or losses and is thus expressed in units which are independent of respective hazard characteristics, e.g. "expected number of lives lost, persons injured, damage to property, or disruption of economic activity" (Varnes 1984, p. 10). This means that the risk posed by several hazards is easier to compare than in the case of a multi-hazard comparison. However, the framework to be computed (e.g. annual loss of life) has to be defined to assure the comparability of the single result and the combination to the overall multi-hazard risk. In this section, we present several approaches which estimate the risk either qualitatively or quantitatively.

Qualitative approaches - classification and indices

Within the Cities Project (National Geohazards Vulnerability of Urban Communities Project), Geoscience Australia developed a semi-quantitative method which ranks suburbs pertaining to one city environment according to their contribution to the city's risk (e.g. Granger et al. 1999, or Middelmann and Granger 2000). The hazard exposure is separately calculated for multiple hazards, and the suburbs are ranked according to their contribution to the city's exposure. The vulnerability is then assessed based on the 'five esses' (shelter, sustenance, security, society and setting), and the suburbs are ranked according to their contribution to the city's vulnerability. Finally, both lists of ranks are classified in either high (top 50% of ranks) or low (bottom 50% of ranks) exposure or vulnerability, and with the matrix shown in Table 6 the total risk posed by each single-hazard risk for each suburb is calculated.

Table 6: Total risk (TR) classes concerning a specific hazard type resulting from contribution of vulnerability (CtV) and exposure (E)

	Low exposure	High exposure
Low Contribution of Vulnerability	Low Total Risk	Significant Total Risk
High Contribution of Vulnerability	Moderate Total Risk	High Total Risk

This final result can be used for several evaluations: For each suburb the hazard posing the highest risk can be identified, the level of risk can be compared between suburbs and the process performing the highest risk for the whole community can be identified.

In the province of Bolzano, Sperling et al. (2007) apply a qualitative method as well. Hazard zone plans are derived according to the Swiss method (Heinimann et al. 1998) and vulnerabilities are assigned depending on the land use type (e.g. built-up area, roads, recreation area). The classified hazard (three classes) and the classified vulnerability (four classes) are combined in a matrix leading to four levels of classified specific risk. The result is not only, as in the case of the Cities Project, a comparison of single risks but the derivation of the overall risk shown in a map. Although it is not explicitly mentioned, it seems likely that in case of overlapping risks as well as in the case of overlapping hazards the highest class is adopted.

Dilley et al. (2005) computed hazard and vulnerability as described in the two previous sections and weight the hazard with the vulnerability index to calculate risk. For the derivation of the multi-hazard risk, the risks posed by the single hazards were added up.

Greiving (2006) presents the qualitative Integrated Risk Index (IRI) as basis for spatial planning decisions which also results in the overall risk posed by several processes: all hazards relevant for spatial planning are analyzed, classified in five intensity classes, and the resulting maps are added up to the integrated hazard map (Fig. 6).

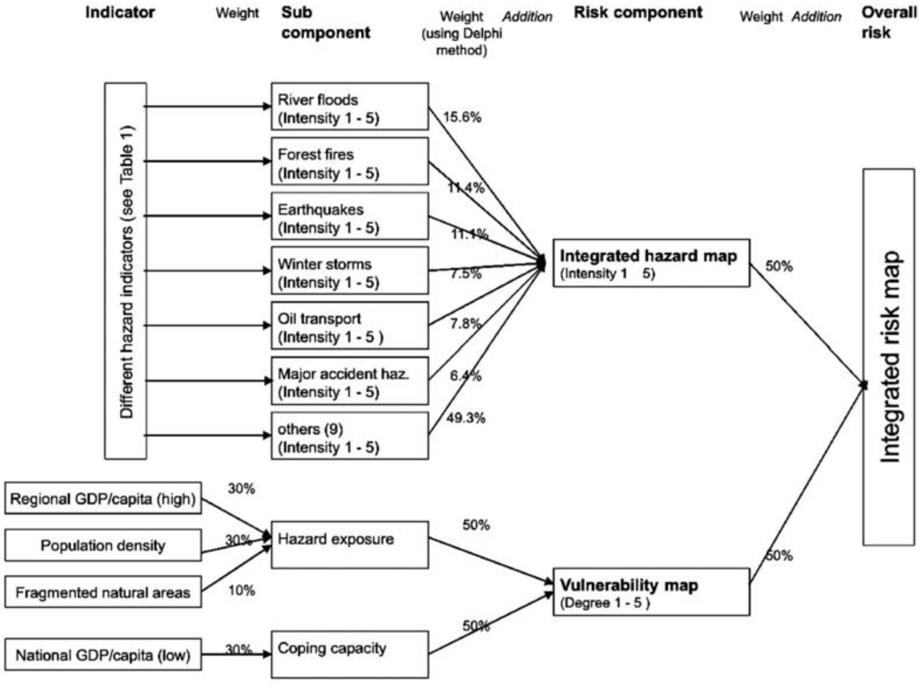


Fig. 6 Calculation scheme of the Integrated Risk Index (Greiving 2006)

In contrast to the previously characterized method, weights can be assigned to the single processes according to their importance in the particular area. Greiving (2006) proposes the elaboration of the weights with the main stakeholders by means of a Delphi process (Helmer 1966). The vulnerability map originates from two indicators, i.e. hazard exposure and coping capacity, which are weighted, added and subdivided in five classes. The integrated risk matrix then opposes the overall hazard intensity (1-5) to the degree of vulnerability (1-5). Finally, the values are added leading to the resulting integrated risk (2-10).

In comparison to the qualitative and semi-quantitative multi-hazard approaches multi-hazard risk analyses already take the vulnerability component of elements at risk into consideration. However, the classification and index schemes exhibit still the disadvantage of being subjective (e.g. the definition of the class thresholds) and limited to the application they were developed for. Quantitative methods present a less subjective alternative and thus a broader applicability since class thresholds and index ranges do not have to be defined.

Quantitative approaches - risk as potential monetary loss

Quantitative approaches to calculate multi-hazard risk, as e.g. a potential monetary loss, meet the objectives of different stakeholders, especially in the (re-)insurance sector regarding their global distributed business or mostly scientific case studies on regional and local levels. Regarding the different main objectives and proposes of the stakeholders these quantitative approaches differ.

Due to the development of various cat-models (catastrophe models), the (re-)insurance business probably is most experienced in risk quantification methods. The MRCatPMLService is a tool for accumulation loss potential analyses (of probable maximum losses) based on the models MRQuake, MRStorm and MRFlood (Munich Re 2000). Furthermore, scenarios of historical or hypothetical events can be simulated; the effect on individual portfolios derived by deterministic analyses and probabilistic evaluations carried out calculating loss occurrence probabilities (Munich Re 1998).

Risk Management Solutions (RMS) is a company providing products, services and expertise for the quantification and management of catastrophe risk to (re-)insurers and catastrophe management professionals (RMS). They offer several products as the Simulation Platform, the RiskLink-ALM (Aggregate Loss Module) and the RiskLink-DLM (Detailed Loss Mode) and provide for their smooth integration of RMS products in (re-)insurers' applications RiskTools.

The Australian Risk Frontiers developed the models FloodAUS (river floods), FireAUS (bushfires), HailAUS (hail), QuakeAUS (earthquakes) and CyclAUS (tropical cyclone winds) for risk analyses (partly probabilistic) and relative risk ratings for (re-)insurers (Risk Frontiers). The risk is rated by classification of each hazard in a five-point scale, and multi-criteria can be purchased at a range of spatial scales: urban areas, postcodes/CRESTA zones, census collection districts, and company specific portfolios.

However, the knowledge and experience of (re-)insurers is difficult to access: The development of cat-models is very costly and due to their value as intellectual property the source codes are mostly unavailable and model licenses are expensive (Porter and Scawthorn 2007). On the one hand, this results in insufficient transparency, result-dependency of the clients to a model, and changes of the analyses with new releases. On the other hand, the input of (re-)insurance companies to the multi-hazard risk modeling community is just as limited as the knowledge transfer. Hence, the models and tools of the (re-) insurance groups cannot be explained in detail.

Beside re-insurance solutions, on a global business perspective three big platforms exist for the automated computation of multi-hazard risks for the governmental risk management on a national level: HAZUS, RiskScape and CAPRA. The software packages offer guided step-by-step analyses.

HAZUS (HAZard United States) is a software tool developed by FEMA (US Federal Emergency Management Agency, (FEMA) for the standardized estimation of losses resulting from several hazards (Baker et al. 1997). HAZUS provides different modeling options for the processes earthquakes, floods and hurricanes: scenario and probabilistic investigations as well as models to calculate the annualized losses of all three processes (Schneider and Schauer 2006).

In New Zealand, the tool Regional RiskScape has been developed for the modeling of potential multi-hazard losses (Reese et al. 2007a). Direct and indirect losses can be quantified, and the impact on people's lives from river floods, earthquakes, volcanic activity (ash), tsunamis and wind storms can also be considered (Reese et al. 2007b, GNS & NIWA).

CAPRA (CEPREDENAC et al.), the Central American Probabilistic Risk Assessment, is a methodology for probabilistic analyses as basis for risk management. The processes considered are earthquakes, hurricanes, volcanic activity, floods, tsunamis and landslides. Products derived by CAPRA are reports on the risk situation (annual expected losses, pure risk premium, loss exceedance curve and probable maximum loss) for spatial planning, cost-benefit analyses and studies on insurance premiums. CAPRA is planned as platform for communication, understanding and cooperation, focusing on the interactive aspect between stakeholders. This becomes clear by the integration of Web 2.0 technologies which allow mass collaboration on the tool and analyses. Implementation of innovations is favored by its modular, extensible and open structure to enable an ever-evolving and sustainable "living tool" (GFDRR).

Focusing the regional/locally level Marzocchi et al. (2009) present a method for the quantification and comparison of risks to identify the most dangerous hazard for a certain area. First, a common definition of the boundary conditions for the single hazard risk analyses (the timeframe and the specific kind of damage) has to be established. In this presented case study they investigate the risk of human life loss in the timeframe of one year in the Casalnova municipality (Italy). Thereupon the single risks are quantified for each process. For example, the formula for the seismic risk for human life is:

$$R_{seis} = P \cdot N \cdot K$$

With

P probability of occurrence of an event above a certain magnitude threshold,

N proportion of buildings with an expected damage above a certain threshold and

K proportion of people killed inside a building with damages above the specific threshold.

The resulting annual risks for human life can be compared to identify the most threatening ones and by adding up the single risks, the overall risk to die caused by one of the investigated processes is quantified.

Bell (2002) calculated the individual risk to life [probability of loss of life per year], object risk to life [probability of loss of life per year] and the economic risk [Icelandic Krona/m^2/a, EUR/m^2/a] emerging from multiple hazards. In contrast to Marzocchi et al. (2009), he used a distributed raster-based approach with the underlying formula for the raster calculation of e.g. individual risk to people in buildings:

$$R_{ipe} = (H \cdot P_s \cdot P_t \cdot V_p \cdot V_{pe} \cdot P_{so}) \cdot E_{ipe}$$

with

R_{ipe} Individual risk to people in buildings (annual probability of loss of life to an individual)

H Annual probability of the hazardous event

Ps Probability of spatial impact (i.e. of the hazardous event impacting a building)

P_t Probability of temporal impact (i.e. of the building being occupied)

V_p Vulnerability of the building
V_{pe} Vulnerability of the people
P_{so} Probability of seasonal occurrence (i.e. snow avalanches only in winter)
E_{ipe} Individual person

For the derivation of the overall risk emerging from the multiple hazards, the single risks are summed up in a distributed way. This means, technically the raster of the single individual risks to life are overlaid and added up to the overall individual risk to life. Thus, it is possible to compare the results of multiple hazards, to identify the processes posing the most serious threats with their distribution and to get an overview on the overall risk (Bell and Glade 2004).
Grünthal et al. (2006) propose the use of risk curves in addition to maps showing hazards, vulnerability and risks in a distributed way. This approach shall enable the user to better capture the characteristics of different processes, understand their significance and prevent from ignorance of the potential damage of extreme events with low probability. For the risk curves the total direct monetary losses for buildings and their contents in the city of Cologne were plotted against their exceedance probability (Fig. 7).

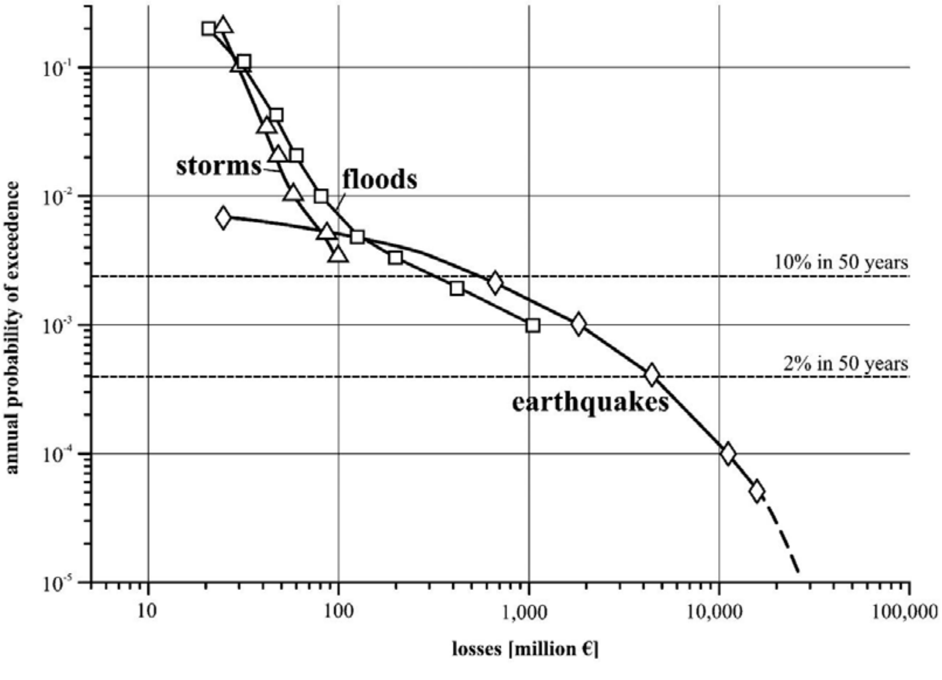


Fig. 7 Risk curve after Grünthal et al. (2006)

Within the framework of RiskCity, a training course developed by ITC, risk curves were created for the case study of Turialba (van Westen et al. 2002). The authors assume that the area under the curve represents the total expected annual damage for the specific type of hazard (Fig. 8).

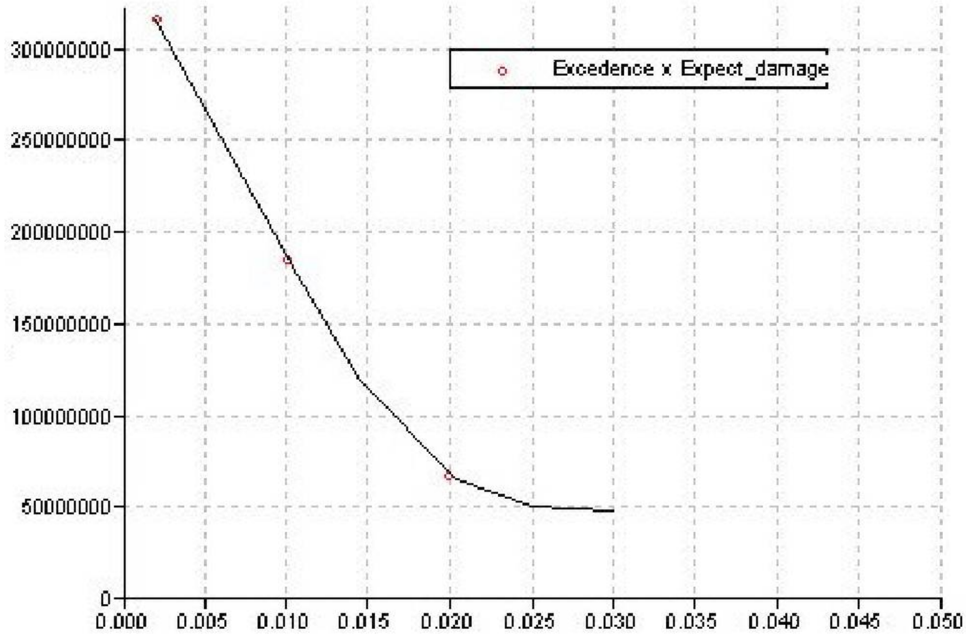


Fig. 8 Specific risk curve for seismic risk. Annual exceedance probability (x-axis) is opposed to the estimated damage in Costa Rican currency (y-axis) (van Westen et al. 2002)

The comparison of the total expected annual losses of different hazards supports a ranking of the risks they pose. Combining the curves of various hazards the total risk curve was derived, representing the annual expected losses to buildings and contents in general.

On the one hand, multi-hazard risk is, in comparison to multi-hazard, easier to compute since the single risks can be easily combined due to matching units. On the other hand, the data needs, especially for quantitative analyses, are very high and the procedure poses not only the challenge of interacting hazards but depends also on a coherent overall vulnerability analysis.

After the calculation of the required hazard or risk product the final and important step is the communication of the results. In most cases, the principal way is a graphical visualization since descriptions and explanations are usually not sufficient to transfer the information.

Visualization

One of the principal products of multi-hazard risk studies are maps since they enable the communication of the spatial aspect of this multi-dimensional problem very well. However, a key question is how to display simultaneously each of the other dimensions (namely the multiple hazards) ensuring that not only the single-hazard patterns are clearly distinguishable, but also their overlapping and coincidences are graspable. Three mapping approaches could be identified within the multi-hazard risk framework: First, the visualization of each single hazard/risk separately, second, the reduction of the multi-dimensionality to only one hazard/risk variable being visualized, and third, the presentation of more than one process displayed in one map as e.g. the overall hazard or risk. An alternative visualization approach are web-mapping applications which offer an interactive definition of the visible layers and gain more and more importance.

Single-hazard visualization

Maps of this category show each hazard or risk separately and are often only the first part of the result, giving the reader the possibility to interpret the patterns separately and in detail. They are mostly followed by the visualization of merged or joined hazards or risks (e.g. Dilley et al. 2005; Bell 2002; Odeh Engineers, Inc 2001). To overcome at least partly the separation of information the method of small multiples introduced by Tufte (2001) can be applied. Small images are arranged side by side which enables the observer the comparison of attributes although not shown in one map. Bartel and Muller (2007) applied this method, juxtaposing the annual occurrence probability of any of the investigated hazards and the most probable hazard type. This provides the information for the reader on the hazard presumably most responsible for e.g. threat hotspots.

Visualization of a joint variable

Maps of this category show summed, multiplied, counted or maximum hazards or risks, and thus the multi-dimensionality is reduced to one parameter. Examples are maps showing the number of relevant processes per pixel (Dilley et al. 2005) or the joint vulnerability, i.e. the annual probability that any of the hazards would occur (Bartel and Muller 2007). Odeh Engineers, Inc (2001) depict a combined hazard map, resulting from the sum of all single hazard scores and according to Heinimann et al. (1998) the highest hazard class is adopted for a hazard zone map. For multi-hazard risk, examples include the global distribution of multiple hazards' mortality risk classified from low to high (UN-ISDR 2009), and Bell (2002) visualizes the individual risk to life, object risk to life and the economic risk emerging from multiple hazards calculated by summing the single risks.

Simultaneous visualization of several variables

Maps visualizing multiple hazards or risks provide on the one hand the possibility to get simultaneously information on their individual patterns and on the spatial coincidence but raise on the other hand the questions of readability and clearness of the maps. The rule of thumb is herein: The more components are included, the more difficult it is to find enough different colors, patterns or sizes still allowing a differentiation. Hazard and risk overlaps aggravate the situation. A number of approaches exist to reduce the problem of readability and benefit from the joint view. One option is to subdivide the whole range of processes considered into hazard type classes. This approach has been followed by the UN-ISDR (2009) where weather-related hazards (floods, tropical cyclones and droughts) and tectonic hazards (tsunamis, landslides and earthquakes) were distinguished. One could argue on the assignment of different processes to the respective class, however, such a procedure reduces the dimensionality from six hazards per map directly to three hazards. Instead of separating hazards, the amount of information per hazard can be reduced alternatively to focus on the most important information to be transmitted. BGR and DESDM (2009, p. 46) show only the high (and eventually moderate) hazard zones in their multi-hazard map to provide "a clearer message" concerning those areas which "deserve most attention for mitigation efforts".

Bell and Glade (2004) depict the outlines of the hazard zones (as lines) within a map showing the total economic risk as areas in raster format (Fig. 9). Thus, apart from the possibility to identify economic risk hotspots, it is possible to determine the contributing processes.

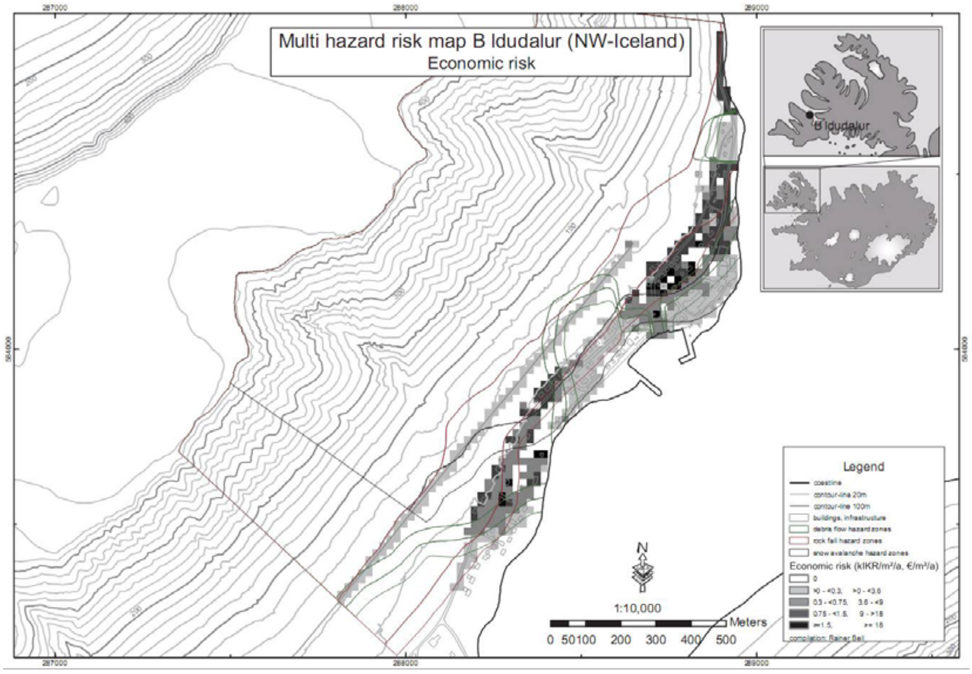
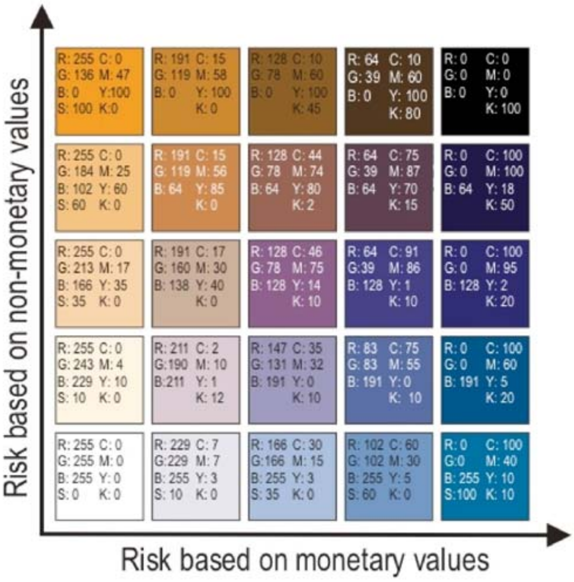


Fig. 9 Multi-hazard risk map after Bell and Glade (2004) showing the outlines of hazard zones and as areas the emerging risks

Within the ARMONIA project a new two-dimensional color scheme was proposed to combine two aspects and thus offer the possibility to show by means of one color in the map simultaneously two aspects. Fig. 10 shows an example opposing risk based on monetary values and risk based on non-monetary values (Klein et al. 2006).



R: 255 C: 0 G: 136 M: 47 B: 0 Y:100 S: 100 K:0	R: 191 C: 15 G: 119 M: 58 B: 0 Y: 100 K: 0	R: 128 C: 10 G: 78 M: 60 B: 0 Y: 100 K: 45	R: 64 C: 10 G: 39 M: 60 B: 0 Y: 100 K: 80	R: 0 C: 0 G: 0 M: 0 B: 0 Y: 0 K: 100
R: 255 C: 0 G: 184 M: 25 B: 102 Y: 60 S: 60 K: 0	R: 191 C: 15 G: 119 M: 56 B: 64 Y: 85 K: 0	R: 128 C: 44 G: 78 M: 74 B: 64 Y: 80 K: 2	R: 64 C: 75 G: 39 M: 87 B: 64 Y: 70 K: 15	R: 0 C: 100 G: 0 M: 100 B: 64 Y: 18 K: 50
R: 255 C: 0 G: 213 M: 17 B: 166 Y: 35 S: 35 K: 0	R: 191 C: 17 G: 160 M: 30 B: 138 Y: 40 K: 0	R: 128 C: 46 G: 78 M: 75 B: 128 Y: 14 K: 10	R: 64 C: 91 G:39 M: 86 B: 128 Y: 1 K: 10	R: 0 C: 100 G: 0 M: 95 B: 128 Y: 2 K: 20
R: 255 C: 0 G: 243 M: 4 B: 229 Y: 10 S: 10 K: 0	R: 211 C: 2 G:190 M: 10 B:211 Y: 1 K: 12	R: 147 C: 35 G: 131 M: 32 B: 191 Y: 0 K: 10	R: 83 C: 75 G: 83 M: 55 B: 191 Y: 0 K: 10	R: 0 C: 100 G: 0 M: 60 B: 191 Y: 5 K: 20
R: 255 C: 0 G: 255 M: 0 B: 255 Y: 0 S: 0 K: 0	R: 229 C: 7 G:229 M: 7 B: 255 Y: 3 S: 10 K: 0	R: 166 C: 30 G:166 M: 15 B: 255 Y: 3 S: 35 K: 0	R: 102 C: 60 G: 102 M: 30 B: 255 Y: 5 S: 60 K: 0	R: 0 C: 100 G:0 M: 40 B: 255 Y: 10 S:100 K: 10

Fig. 10 Color scheme for simultaneous visualization of two aspects (Klein et al. 2006)

Garcin et al. (2007) use a similar approach for the joint visualization of two parameters by applying a color scheme where each color is defined by two characteristics: high, medium, low or no hazard by the first and the second hazard. In their study, they present the combined sea level rise and tsunami hazard in the so-called ‘composite hazard map’.

Kienholz and Krummenacher (1995) proposed a symbol kit (the “Symbolbaukasten”) for the mapping of phenomena. Basic principles are the general assignation of colors to each hazard and the definition of how to use color nuances: the more intensive, active, deep-seated, younger or more evident the process, the more intense the color.

As already indicated each of the three approaches exhibits different advantages and disadvantages. While single hazard/risk maps allow the interpretation of each hazard/risk pattern, it is very difficult to grasp the relationships. Maps reducing the dimensionality offer exactly this joint view, but consequently lack at the same time the information on the single factors. Finally, multi-dimensional maps composed by several hazards/risks might be able to bridge the gap between the two afore mentioned approaches, however the higher the dimensionality the less readable is the map. Thus, only a limited number of different aspects can be visualized in a cognizable way and the challenge has to be faced, how to arrange and depict them.

Web-mapping applications

In the era of GIS and web-mapping, an alternative to static analog maps are digital interactive and flexible visualizations (e.g. the CEDIM Risk Explorer, Munich Re’s NATHAN or CalEMA’s MyHazards). According to Kunz and Hurni (2008) they provide a solution to the difficulty to deal with large sets of data in one multi-hazard or multi-risk map.

Due to the possibility to provide the whole range of single layer information , no content is lost and the user chooses the to him/her relevant hazard or risk combination, defines a specific area, zooms in and out, and is able to explore stepwise the complex information. However, the advantage of free interactive choice should not lead to the creation of maps not following cartographic standards which might in the consequence result in misinterpretation, confusion and missing readability (Kunz and Hurni 2008). An appropriate graphic user interface can prevent from this effect and especially the supply of further information and suggestions might enhance the comprehensibility.

In the previous sections the topics different components of multi-hazard risk analyses (1) multi-hazard, (2) vulnerability towards multiple processes and (3) multi-hazard risk were reviewed and discussed. Additionally, different approaches for (4) the visualization of the results were presented. A number of challenges became apparent within each of the steps and will be recapitulated in the following section.

Facing the challenges

Multi-hazard risk analyses as important part and basis of risk management consist of a number of steps and pose a variety of challenges. The different methodologies and approaches available to cope with these difficulties have advantages and disadvantages. Thus, the adjustment of the whole framework towards the required result considering the inherent issues is a fundamental necessity. From the beginning several principal choices have to be made:

The first major choice is the definition of the expected outcome: multi-hazard (MH) or multi-hazard risk (MHR). This is not only a question of the objective but also of the data availability and the question if either qualitative or quantitative outcome is needed. While multi-hazard analyses are commonly restricted to qualitative and semi-quantitative approaches, the whole range from qualitative to quantitative methods is available for multi-hazard risk research.

Based on the previous review of different methods and concepts, the following paragraphs summarize the identified difficulties and the related solution approaches:

1) Multi-hazard: a) The computation of the overall hazard due to multiple natural processes is difficult since the single processes are mostly quantified in different units and measures. The approach typically used to overcome this difficulty is the development of a common standardization scheme (classification or indices, qualitative or semi-quantitative). The approach of standardization can mostly be used easily; it is an adaptive method also in case of few input data but only applicable for the aim it was developed for due to the specificity of the scheme.

b) Hazards are parts of geosystems, and thus are not independent from each other and their interactions might lead to hazard patterns not captured by the sum of separate single-hazard analyses. Multi-hazards can be assessed either by identification of coincidences (overlay) or by detailed scenario development.

The next step towards risk is the examination of the vulnerability of elements at risk with its inherent challenges and available solutions:

2) Vulnerability towards multiple hazards: a) Vulnerabilities of elements at risk towards multiple hazards vary just as hazard characteristics vary. Thus, the methods to assess them are likewise differing widely, not only between approaches for social and physical vulnerability, but also towards the single threats. Typical approaches in the natural sciences are vulnerability curves or matrices. The few methods identified for the social sciences refer to the effect of past impacts and assess thereby the hazard-specific vulnerability.

b) In case of simultaneously occurring hazard events, the overall vulnerability might be different from the single vulnerabilities. A possibility to describe this combined vulnerability is the extension of e.g. two dimensional vulnerability curves into three dimensional vulnerability surfaces.

And finally the connection of hazard and vulnerability to risk:

3) Multi-hazard risk: The comparison of risks is much easier than the comparison of hazards since the procedure is carried on from hazard to risk and the single risks can be expressed in hazard-independent and element at risk/ damage / loss specific units. However, still a general analysis framework defining which parameter to compare is needed. This framework can either be qualitative (classification), semi-quantitative (indices) or quantitative (monetary values, probabilities, etc.). And finally, the issue of hazard interactions resulting in amplified risk or differing patterns has to be considered.

4) Visualization: The communication of the multi-dimensional results poses a final major challenge. One single map for all kinds of stakeholders and showing all types of hazards in the area will surely not match the needs of the involved parties. Several options could be identified, each highlighting another aspect: a) separate visualization of single hazards/risks, b) visualization of the overall hazard, risk, probability etc., c) joint visualization of a number of hazards and risks according to a certain criteria and d) the use of web-mapping tools to let the user choose the combination.

In summary, multi-hazard risk analyses are multipartite and pose a lot of challenges. The choice to compute multi-hazard or multi-hazard risk, to use a qualitative, semi-quantitative or quantitative approach, and the selection of the method depend primarily on the objective. However, also practical issues as method availability for the specific set of hazards and the scale as well as data availability complicate the selection. And finally, the decision has to be taken aware of all strengths, weaknesses and inherent generalizations of the method and possible alternatives. A conscious choice is also necessary for the consideration or negligence of hazard interactions and cascading effects, respectively, since their implementation is surely difficult but they obviously pose an additional threat. This article presented a range of possible approaches to deal with the challenges, hopefully serving as basis for the development of further (more) coherent multi-hazard (risk) analysis methods.

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References

Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. B Eng Geol Environ 85:21–44

Altenbach T (1995) A comparison of risk assessment techniques from qualitative to quantitative. In: ASME Pressure and Piping Conference, Honolulu, Hawaii

Ancey C, Gervasoni C, Meunier M (2004) Computing extreme avalanches. Cold Reg Sci Tecnol 39:161–180

Baker M, Little A, Hilson J (1997) Multi hazard: identification and risk assessment - the cornerstone of the national mitigation strategy. Tech. rep., FEMA, available at: http://www.fema.gov/library/viewRecord.do?id=2214

Bartel P, Muller J (2007) Horn of Africa natural hazard probability and risk analysis. Tech. rep., USAID

Bell R (2002) Landslide and snow avalanche risk analysis - methodology and its application in Bíldur, NW-Iceland. Master's thesis, Rheinische Friedrich-Wilhelms-Universität Bonn

Bell R, Glade T (2004) Multi-hazard analysis in natural risk assessments. In: International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation, Brebbia, C.A., Rhodes, Greece, pp 197–206

Besson L, Durville JL, Garry G, Graszk E, Hubert T, Toulement M (1999) Plans de prévention des risques naturels (PPR) - risques de mouvements de terrain: guide méthodologique. Tech. rep., Ministère de l'aménagement du territoire et de l'environnement & Ministère de l'équipement, des transports et du logement

BGR, DESDM (2009) Guidebook for assessing the risks to natural hazards - case study: Province of central java. Tech. rep., Bundesanstalt für Geowissenschaften und Rohstoffe and the Geological Agency of Indonesia

Birkmann J (ed) (2006) Measuring vulnerability to natural hazards. Towards disaster resilient societies. United Nations University Press, New Delhi, India

Bohle HG, Glade T (2008) Naturrisiken und Sozialkatastrophen, Spektrum Akademischer Verlag, Heidelberg, Germany, chap Vulnerabilitätskonzepte in Sozial- und Naturwissenschaften, pp 99–120

Borter P (1999) Risikoanalyse bei gravitativen Naturgefahren - Methode. Umwelt-Materialien 107/I, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland

Bovolo CI, Abele SJ, Bathurst JC, Caballero D, Ciglan M, Eftichidis G, Simo B (2009) A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield. Comput Geosi 35(5):924 – 945

Cannon S, DeGraff J (2009) Landslides - disaster risk reduction, Springer Verlag, Berlin Heidelberg, Germany, chap The increasing wildfire and post-fire debris-flow threat in Western USA, and implications for consequences of climate change, pp 177–190

Cariam (2006) Plans de prévention des risques naturels prévisibles (PPR) - cahier de recommandations sur le contenu des PPR. Tech. rep., Ministère de l'Écologie et du Développement durable

Carpignano A, Golia E, Di Mauro C, Bouchon S, Nordvik JP (2009) A methodological approach for the definition of multi-risk maps at regional level: first application. J Risk Res 12:513–534

Carrasco R, Pedraza J, Martin-Duque J, Mattera M, Sanz M, Bodoque J (2003) Hazard zoning for landslide connected to torrential floods in the Jerte Valley (Spain) by using GIS techniques. Nat Hazards 30:361–381

CEPREDENAC, ISDR, IDB, Worldbank, CAPRA Portal (Central American Probabilistic Risk Assessment). http://www.ecapra.org/en/, access 10 February 2010

Chiesa C, Laben C, Cicone R (2003) An Asia Pacific natural hazards and vulnerabilities atlas. In: 30th International Symposium on Remote Sensing of Environment

CRED, EM-DAT: Emergency Events Database. http://www.emdat.be/, access 15 July 2009 de Pippo T, Donadio C, Pennetta M, Petrosino C, Terlizzi F, Valente A (2008) Costal hazard assessment and mapping in Northern Campania, Italy. Geomorphology 97:451–466

Delattre A, Garancher T, Rozencwajg C, Touret T (2002) Jurisque - prévention des risques naturels. Tech. Rep. 3, Ministere de l'Écologie et du Développement durable

Delmonaco G, Margottini C, Spizzichino D (2006) ARMONIA methodology for multi-risk assessment and the harmonisation of different natural risk maps. Deliverable 3.1.1, ARMONIA

Delmonaco G, Margottini C, Spizzichino D (2006) Report on new methodology for multi-risk assessment and the harmonisation of different natural risk maps. Deliverable 3.1, ARMONIA

Dilley M, Chen U RS Deichmann, Lerner-Lam A, Arnold M (2005) Natural disaster hotspots: a global risk analysis. In: Disaster Risk Management Series, 5, World Bank

Dorren LK (2003) A review of rockfall mechanics and modelling approaches. Nat Hazard Earth Sys 27(1):69–87

Douglas J (2007) Physical vulnerability modelling in natural hazard risk assessment. Nat Hazard Earth Sys 7:283–288

Egli T (1996) Hochwasserschutz und Raumplanung. Schutz vor Naturgefahren mit Instrumenten der Raumplanung - dargestellt am Beispiel von Hochwasser und Murgängen. vdf Hochschulverlag AG, ETH Zürich, oRL-Bericht 100

El Abidine El Morjani Z, Ebner S, Boos J, Abdel Ghaffar E, Musani A (2007) Modelling the spatial distribution of five natural hazards in the context of the WHO/EMRO Atlas of Disaster Risk as a step towards the reduction of the health impact related to disasters. Int J Health Geogr 6

Ewen J, Parkin G, PE O (2000) SHETRAN: distributed river basin flow and transport modeling system. J Hydrol Eng 5:250–258

FEMA, U.S. Department of Homeland Security: FEMA. http://www.fema.gov/, access 19 August 2009

FEMA (2003) Multi-hazard loss estimation methodology: earthquake model. HAZUS-MH MR3. Technical manual, FEMA, available at: http://www.fema.gov/plan/prevent/hazus/

FEMA (2007) Multi-hazard loss estimation methodology: flood model. HAZUS-MH MR3. Technical manual, Department of Homeland Security, Federal Emergency Management Agency

FEMA (2007) Multi-hazard loss estimation methodology: hurricane model. HAZUS-MH MR3. Technical manual - appendices, FEMA

Ferrier N, Haque CE (2003) Hazards risk assessment methodology for emergency managers: a standardized framework for application. Nat Hazards 28:271–290

Fuchs S (2009) Susceptibility versus resilience to mountain hazards in Austria - paradigms of vulnerability revisited. Nat Hazard Earth Sys 9:337–352

Fuchs S, Keiler M, Zischg A (2001) Risikoanalyse - Oberes Suldental, Vinschgau: Konzepte und Methoden zur Erstellung eines Naturgefahrenhinweis-Informationssystems. Innsbrucker Geographische Studien

Garcin M, Prame B, Attanayake N, de Silva U, Desprats J, Fernando S, Fontaine M, Idier D, Lenotre N, Pedreros R, Siriwardana C (2007) A geographic information system for coastal hazards - application to a pilot site in Sri Lanka. Final report BRGM/RP-55553-FR, Bureau de recherches géologiques et minières (BRGM)

Garcin M, Desprats J, Fontaine M, Pedreros R, Attanayake N, Fernando S, Siriwardana C, de Silva U, Poisson B (2008) Integrated approach for coastal hazards and risks in Sri Lanka. Nat Hazard Earth Sys 8:577–586

Garry G, Graszk E, Dupuy JL (1997) Plans de prévention des risques naturels prévisibles (PPR): Guide général. Tech. rep., La documentation francaise

GFDRR, Reducing vulnerability to natural hazards. http://gfdrr.org, access 15 July 2010

Gibbs T (2003) Multi-hazard design - contradictions and synergies. In: Leaders: International course on development and disasters with a special focus on health, St. Ann, Jamaica

GNS & NIWA, Regional RiskScape. http://riskscape.org.nz/home, access 14 August 2009

Granger K, Jones T, Laiba M, Scott G (1999) Community risk in Cairns: a multi-hazards risk assessment. Tech. rep., Australian Geological Survey Organisation (AGSO), available at: http://www.ga.gov.au/hazards/reports/cairns/

Greiving S (2006) Integrated risk assessment of multi-hazards: a new methodology. In: Schmidt-Thomé P (ed) Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, vol 42, Geological Survey of Finland, pp 75–81, available at: http://arkisto.gtk.fi/sp/SP42/1_alkus.pdf

Grünthal G, Thieken A, Schwarz J, Radtke K, Smolka A, Merz B (2006) Comparative risk assessment for the city of cologne - storms, floods, earthquakes. Nat Hazards 38(1-2):21–44

Heinimann H, Hollenstein K, Kienholz H, Krummenacher B, Mani P (1998) Methoden zur Analyse und Bewertung von Naturgefahren. Umwelt-Materialien Nr. 85, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland

Helmer O (1966) The use of the Delphi Technique in problems of educational innovations. Tech. Rep. P-3499, The Rand Corporation, available at: http://www.rand.org/pubs/papers/2006/P3499.pdf

Ho Lee K, Rosowsky D (2006) Fragility analysis of woodframe buildings considering combined snow and earthquake loading. Structural Safety 28:289–303

Hollenstein K (2005) Reconsidering the risk assessment concept: standardizing the impact description as a building block for vulnerability assessment. Nat Hazard Earth Sys 5:301–307

Hollenstein K, Bieri O, Stückelberger J (2002) Modellierung der Vulnerabilität von Schadobjekten gegenüber Naturgefahrenprozessen. Tech. rep., ETH Zürich, Forstliches Ingenieurwesen

Huggel C, Kääb A, Haeberli W, Teysseire P, Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can Geotech J 39:316–330

Huggel C, Kääb A, Salzmann N (2004) GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery. Nor J Geogr 58:61–73

Hutter K, Svendsen B, Rickenmann D (1996) Debris flow modeling: a review. Continuum Mech Therm 8:1–35

Jonkman S, Vrijing J, Vrowenvelder A (2008) Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method. Nat Hazards 46:353–389

Kappes M, Keiler M, Glade T (subm.) From single- to multi-hazard risk analyses: a concept addressing emerging challenges. In: Mountain Risks: Bringing Science to Society, Firenze, Italy

Kienholz H, Krummenacher B (1995) Symbolbaukasten zur Kartierung der Phänomene. Tech. rep., Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bundesamt für Wasser und Geologie (BWG)

Klein J, Greiving S, Jarva J (2006) Integrated natural risk legend and standard for harmonised risk maps for land use planning and management. Deliverable 3.2, ARMONIA

Kumpulainen S (2006) Vulnerability concepts in hazard and risk assessment. In: Schmidt-Thomé P (ed) Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, vol 42, Geological Survey of Finland, pp 65–74, available at: http://arkisto.gtk.fi/sp/SP42/4_vulnera.pdf

Kunz M, Hurni L (2008) Hazard maps in Switzerland: state-of-the-art and potential improvements. In: Proceedings of the 6th ICA Mountain Cartography Workshop, Lenk, Switzerland

Lateltin O (1997) Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten. Tech. rep., Bundesamt für Raumplanung (BRP), Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Umwelt, Wald und Landschaft (BUWAL)

Liévois J (2003) Guide méthodologique plans de prévention des risques d'avalanches. Tech. rep., Ministère de l'Écologie et du Développement et de l'Aménagement, available at: http://www.prim.net/professionnel/documentation/guide_avalanche/page01.html

Loat R (2010) Risk management of natural hazards in Switzerland. Tech. rep., Federal Office for the Environment FOEN, available at: http://www.cenat.ch/ressources/planat_product_en_1308.pdf

Loat R, Petrascheck A (1997) Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten. Empfehlungen 1997, Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Raumplanung (BRP) and Bundesamt für Umwelt, Wald und Landschaft (BUWAL)

Marzocchi W, Mastellone M, Di Ruocco A (2009) Principles of multi-risk assessment: interactions amongst natural and man-induced risks. European Commission

MEDD (1999) Guide méthodologique plans de prévention des risques d'inondations. Tech. rep., Ministère de l'Écologie et du Développement durable

MEDD (2002) Guide méthodologique plans de prévention des risques sismique. Tech. rep., Ministère de l'Écologie et du Développement durable

Menoni S (2006) Integration of harmonized risk maps with spatial planning decision processes. Deliverable 5.1, ARMONIA

Meyenfeld H (2008) Modellierung seismisch ausgelöster gravitativer Massenbewegungen für die Schwäbische Alb und den Raum Bonn und Erstellen von Gefahrenhinweiskarten. Dissertation, University of Vienna

Middelmann M, Granger K (2000) Community risk in Mackay: a multi-hazard risk assessment. Tech. rep., Australian Geological Survey Organisation (AGSO), available at: http://www.ga.gov.au/hazards/reports/mackay/

Moran A, Wastl M, Geitner C, Stötter J (2004) A regional scale risk analysis in the community of Ólafsfjödur, Iceland. In: Internationales Symposium - INTERPRAEVENT, Riva, Trient

Munich Re (1998) Weltkarte der Naturgefahren. Tech. rep., Münchner Rückversicherungs-Gesellschaft

Munich Re (2000) Topics 2000: natural catastrophes - the current position. Tech. rep., available at: http://www.imia.com/downloads/external_papers/EP17_2003.pdf

Odeh Engineers, Inc (2001) Statewide hazard risk and vulnerability assessment for the state of Rhode Island. Tech. rep., NOAA Coastal Services Center, available at: http://www.csc.noaa.gov/rihazard/pdfs/rhdisl_hazard_report.pdf

Papathoma-Köhle M, Kappes M, Keiler M, Glade T (subm.) Physical vulnerability assessment for Alpine hazards - state of the art and future needs. Nat Hazards

Porter K, Scawthorn C (2007) OpenRisk: open-source risk software and access for the insurance industry. In: 1st International Conference on Asian Catastrophe Insurance (ICACI), Kyoto University, Japan

Reese S, Bell R, King A (2007) RiskScape: a new tool for comparing risk from natural hazards. Water Atm 15:24–25

Reese S, King A, Bell R, Schmidt J (2007) Regional RiskScape: a multi-hazard loss modelling tool. In: MODSIM 2007 International Congress on Modelling and Simulation, pp 1681–1687

Risk Frontiers, PerilAUS II - relative risk ratings for postcodes and CRESTA/ICA zones. Website link to a PowerPoint presentation, http://www.riskfrontiers.com/perilaus.html, access 20 August 2008

RMS, Risk management solutions. http://www.rms.com/, access 16 November 2009

Schneider P, Schauer B (2006) HAZUS - its development and its future. Nat Hazards Rev 7:40–44

Sedan O, Mirgon C (2003) Application ARMAGEDOM. Notice utilisateur BRGM/RP-52759-FR, Bureau de recherches géologiques et minières (BRGM)

SLF (1984) Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten. Tech. rep., Eidgenössisches Institut für Schnee- und Lawinenforschung & Bundesamt für Forstwesen

Sperling M, Berger E, Mair V, Bussadori V, Weber F (2007) Richtlinien zur Erstellung der Gefahrenzonenpläne (GZP) und zur Klassifizierung des spezifischen Risikos (KSR). Tech. rep., Autonome Provinz Bozen

Tarvainen T, Jarva J, Greiving S (2006) Spatial pattern of hazards and hazard interactions in Europe. In: Schmidt-Thomé P (ed) Natural and Technological Hazards and Risks Affecting the

Spatial Development of European Regions, vol 42, Geological Survey of Finland, pp 83–91, available at: http://arkisto.gtk.fi/sp/SP42/6_spa_patt.pdf

Thierry P, Stieltjes L, Kouokam E, Nguéya P, Salley PM (2008) Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon. Natural Hazards 45:429–456

Tufte E (2001) Envisioning information. Graphics Press, Cheshire, UK

UN (2002) Johannsburg plan of implementation of the world summit on sustainable development. Tech. rep., United Nations, available at: http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf

UN-ISDR (2005) Hyogo framework for action 2005-1015: Building the resilience of nations and communities to disasters. In: World Conference on Disaster Reduction, Kobe, Hyogo, Japan

UN-ISDR (2009) Global assessment report on disaster risk reduction. Tech. rep., available at: http://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413

UNDHA (1992) Internationally agreed glossary of basic terms related to disaster management. Glossary, United Nations Department of Humanitarian Affairs

UNDP (2004) A global report: reducing disaster risk - a challenge for development. Tech. rep., United Nations Development Programme, available at: http://www.undp.org/cpr/disred/documents/publications/rdr/english/rdr_english.pdf

UNEP (1992) Agenda 21. Tech. rep., United Nations Environment Programme, available at: http://www.un.org/esa/dsd/agenda21/res_agenda21_07.shtml

van Westen C, Montoya A, Boerboom L, Badilla Coto E (2002) Multi-hazard risk assessment using GIS in urban areas : a case study for the city of Turrialba, Costa Rica. In: Proceedings of the regional workshop on best practices in disaster mitigation: lessons learned from the Asian urban disaster mitigation program and other initiatives

Varnes DJ (1984) Landslide hazard zonation: a review of principles and practice. United Nations Educational, Scientific and Cultural Organisation, Paris, France

Walker G, Deeming H (2006) Functional and technical architectural design of a decision-support system for risk informed spatial planning. Deliverable 5.2, ARMONIA

Wichmann V, Becht M (2003) Modelling of geomorphic processes in an alpine catchment. In: 7th Internation Conference on GeoComputation, Southampton, United Kingdom

Wichmann V, Heckmann T, Haas F, Becht M (2009) A new modelling approach to delineate the spatial extent of alpine sediment cascades. Geomorphology 111:70–78

Wisner B, Blaikie P, Cannon T, Davis I (2004) At risk: natural hazards, people’s vulnerability and disasters. Routledge, London, UK

A.2. Physical vulnerability assessment for alpine hazards: state of the art and future needs

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ORIGINAL PAPER

Physical vulnerability assessment for alpine hazards: state of the art and future needs

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Abstract Mountain hazards such as landslides, floods and avalanches pose a serious threat to human lives and development and can cause considerable damage to lifelines, critical infrastructure, agricultural lands, housing, public and private infrastructure and assets. The assessment of the vulnerability of the built environment to these hazards is a topic that is growing in importance due to climate change impacts. A proper understanding of vulnerability will lead to more effective risk assessment, emergency management and to the development of mitigation and preparedness activities all of which are designed to reduce the loss of life and economic costs. In this study, we are reviewing existing methods for vulnerability assessment related to mountain hazards. By analysing the existing approaches, we identify difficulties in their implementation (data availability, time consumption) and differences between them regarding their scale, the consideration of the hazardous phenomenon and its properties, the consideration of important vulnerability indicators and the use of technology such as GIS and remote sensing. Finally, based on these observations, we identify the future needs in the field of vulnerability assessment that include the user-friendliness of the method, the selection of all the relevant indicators, the transferability of the method, the inclusion of information concerning the hazard itself, the use of technology (GIS) and the provision of products such as vulnerability maps and the consideration of the temporal pattern of vulnerability.

Keywords Vulnerability · Landslides · Avalanches · Debris flows · Rock falls · Floods

1 Introduction

The alpine communities have long suffered from natural hazards that have often caused loss of life, agricultural land, infrastructure and buildings in the past. Although alpine communities are threatened by a significant number of hazards, in this study, the focus is on avalanches, floods and landslides including debris flows and rock falls.

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The vast majority of the studies concerning alpine hazards focus on hazard assessment (zoning), hazard modelling, hazard monitoring and risk management. Vulnerability assessment of alpine hazards is a relative new field of research which eventually brings together scientists from different disciplines (Fuchs 2009). As there is no universal definition for vulnerability, all these scientists from different background give their own definition, showing clearly that there is a lack of common language that hinders vulnerability research to move forward (Brooks 2003). In social science, vulnerability is related only to the social context whereas, engineers and natural scientists try to define thresholds in order to determine the acceptable risk and the point from which a society should take measures against a hazard (Bohle and Glade 2007).

In this paper, the physical vulnerability is investigated without taking into consideration the social, legal or cultural setting. The focus is on the physical environment and, particularly, on the impact of natural hazards on the built environment.

In most studies concerning physical vulnerability, assessment vulnerability is perceived as “The degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)” (UNDRO 1984). In this study, vulnerability is considered a pre-existing condition that is related to those characteristics and properties of the elements at risk that increase their susceptibility to the impact of hazards. In a wider sense, “vulnerability is a characteristic of human behaviour, social and physical environments, describing the degree of susceptibility (or resistance) to the impact of e.g. natural hazards” (CENAT 2004). Proper understanding of vulnerability and its assessment is very important since it can lead to more effective emergency management and to the development of mitigation and preparedness activities all of which are designed to reduce the loss of life and economic costs.

The objective of the present study is to identify the gaps and difficulties of existing methodologies and to point out the future needs for vulnerability assessment to alpine hazards, which can serve as a tool for effective emergency and disaster management.

2 The impact of alpine hazards on the built environment

The impacts of natural hazards on elements at risk vary according to their characteristics and properties. In the following section, the natural phenomena and their properties that make them hazardous to the alpine communities are described.

2.1 Landslides, including debris flows and rock falls

Landslides can be defined as the downslope movement of soil, rock, or debris due to gravitational forces that can be triggered by heavy rainfall, rapid snow melting, slope undercutting, etc. (Crozier 1999; Glade and Crozier 2005). In this paper, we categorise the methodologies in three groups according to the type of phenomenon: landslides in a general meaning, debris flow and rock falls. The impact of landslides on the built environment ranges from null or minimum (landslides in remote regions away from inhabited areas or infrastructure) to maximum (collapse or burial of buildings and infrastructure, loss of life and loss of agricultural land). Although large magnitude landslides have a low probability to result in significant loss of human life in Europe, the concentration of property on steep slopes, high standard of living and high population density makes society vulnerable to even small magnitude landslide events (Blöchl and Braun 2005).

Debris flows are rapid gravity-induced mass movements that consist of sediment saturated with water that owe their destructive power to the interaction of solid and fluid forces (Iverson 1997). They can cause extensive damage to buildings, infrastructure, lifelines and critical infrastructure. As far as buildings are concerned, debris flows do not only influence their stability, as most of the mass movements do, but they also enter the building through doors or windows and damage its interior (Holub and Fuchs 2009).

Rock falls pose a continuous threat to the inhabitants of alpine areas. The rolling, bouncing, or falling from rocks put in danger not only the stability of the building but also its interior (Holub and Hübl 2008). Potential hazardous zones can be identified by mapping the presence of detached rock blocks or the presence of unstable rock masses resting on the cliff face (Corominas et al. 2005).

2.2 Avalanches

Avalanches are fast moving mass movements that can contain, apart from snow, rocks, soil and vegetation, or ice (Bründl et al. 2010). Avalanches occur due to topographical (inclination, aspect and roughness of ground surface), meteorological (temperature, precipitation, wind speed and direction) and snowpack factors (snowpack structure, depth and water content) (McClung and Schaerer 1993). The impact on the objects that are located in the disposition area can be very high. Only in Austria, since 1950 avalanches have claimed more than 1,600 lives, which are 30 fatalities on an annual basis (Höller 2007). The elements at risk are influenced by two major processes: the air pressure plume in front of the avalanche and the high impact pressure of the snow in motion. The debris or vegetation that can be transported within an avalanche increases its impact on buildings, infrastructure and individuals (Bründl et al. 2010).

2.3 Floods

River and flash floods pose a serious threat to Alpine communities. They are caused by heavy or prolonged rainfall and rapid snowmelt, ice jams or ice break-up, damming of river valleys by landslides or avalanches, and failure of natural or man-made dams (WMO 1999).

BWW et al. (1997) suggest two categories of river flooding: static and dynamic. Static flooding occurs in areas with relatively plane topography. Water level is rising slowly and flow velocity is very slow if the water is moving at all. The damage they cause is attributed to the influence of the water on the building structure. In dynamic floods the water movement is higher and affects the elements at risk due to erosion or direct impact (Hollenstein et al. 2002). On the other hand, flash floods originate in steep basins and show an extremely sudden onset (Barredo 2007). They are not always connected with bodies of water since also ditches can turn into torrents where water may reach high flow velocities. UNDHA (1992) defines this phenomenon as floods "of short duration with a relatively high peak discharge".

The frequent occurrence of natural hazards in Alpine regions leads to a high impact potential to the exposed societies. Therefore, the role of vulnerability assessment needs to be addressed. A working report from PLANAT (Swiss National Platform for Natural Hazards) provides a thorough list of national and international efforts from scientists or projects to assess vulnerability to alpine hazards having a focus on vulnerability functions (Spichtig and Bründl 2008). Moreover, vulnerability studies regarding landslides are reviewed by Glade (2003). Various methods to assess vulnerability are compared and some examples of applications are given (Glade 2003). The present review expands the analysis to more recent studies concerning not only landslides but also snow avalanches and floods focusing on Alpine regions.

3 Literature review of existing vulnerability assessment methods for alpine natural hazards

After conducting a review of existing vulnerability assessment methods regarding various disaster types, Hollenstein (2005) suggests that vulnerability assessment studies concerning mass-movements related disasters are limited. The difference to other types of disaster is striking: Hollenstein (2005) recorded more than 100 studies about earthquake vulnerability models, more than 100 studies regarding wind-related vulnerability models and less than 20 vulnerability models involving gravitational hazards (landslides, debris flows, snow avalanches) and floods. He assumes that a potential reason for this is that gravitational processes are usually accurately delimited and the most common strategy of the authorities and other stakeholders is to simply avoid the potentially affected areas. Another potential reason is that the institutions that are responsible for the management of these risks have enough empirical knowledge and they do not need theoretical models.

Each study addresses vulnerability in a different way and the result is a wide range of different vulnerability assessment methods. Engineers focus on the reaction of individual buildings to the impact of a natural process (e.g. landslide, snow avalanche). Some scientists design vulnerability curves showing the relationship of the vulnerability and the phenomenon intensity as well as others, having a disaster management or emergency planning background, provide vulnerability maps in order to support the local authorities with a decision-making tool. Some studies focus exclusively on vulnerability assessment, whereas others deal with vulnerability as part of a risk assessment. A review of some vulnerability assessment methods regarding alpine hazards is given in the following paragraphs without claiming completeness.

3.1 Landslides

One of the first studies dealing with the vulnerability assessment of geological hazards was the one of Mejia-Navarro et al. (1994), which assessed the vulnerability and risk of geological hazards (subsidence, rock falls, debris flows and floods) in the Glenwood Springs area, Colorado. In this vulnerability analysis, the following aspects were considered: ecosystem, economic and social structure vulnerability. The result was a map with 14 land use suitability classes, which incorporated hazards, vulnerability and risk parameters. The first seven classes are, or may become, suitable for urban infrastructure while the last seven classes are reserved for environmental protection, contingency occasions, or avoided because of a high hazard level (Mejia-Navarro et al. 1994). According to the same study, vulnerability is a function of population density, land use and lifelines. This function is expressed by the following equation.

$$\text{Vuln} = (\text{Density} \times 10 + \text{Lusevuln} \times 7 + \text{Lifelines} \times 2)/19.$$

with:

Vuln	Vulnerability
Density	Population density (higher weight to higher human concentration per hectare)
Lusevuln	Land use vulnerability (schools have the highest score (10) and farms the lowest)
Lifelines	Highways, city roads, service lines such as phone and electricity

Leone et al. (1996) also worked on the vulnerability assessment of elements exposed to mass movements, by investigating the interaction between landslides and exposed elements. They produced damage matrices for elements exposed to mass movements that provide a correlation, in terms of loss rate, between the landslides and the exposed elements. Finally, they developed a classification of the types and levels of damage of the main elements exposed to mass movements, without linking them to the intensity of the phenomenon based on historic data. Zezere et al. (2008), on the other hand, connect the vulnerability values of the elements at risk to the types of landslide that the element is exposed to (shallow translational landslides, translational landslides and rotational slides). Through a case study in Portugal, they assessed the vulnerability of buildings and roads, based on the age and material of buildings, their use and the number of floors. As far as roads were concerned, they used data concerning the type of road (motorway, national road, county road, rural road).

A number of vulnerability indicators, as far as the buildings were concerned, were also used by Bell and Glade (2004). They recognised the gap in vulnerability assessment of elements at risk subject to landslides and made an attempt to assess vulnerability to landslides in Iceland using a heuristic approach within the framework of a quantitative risk analysis. In this effort, they used general information on houses within the endangered areas, based on expert judgement, noting that some of the houses were made of timber and had large windows built towards the mountain slope. The vulnerability of the people in buildings is expressed as the product of the vulnerability of buildings and the vulnerability of people. The vulnerability of buildings and people is determined depending on the process and its magnitude. As final product, they provided an “elements at risk map” based on number of residents and employees and a “risk map” as a function of hazard and consequences including elements at risk, damage potential and vulnerability.

Some studies aim at the production of a final map that demonstrates the spatial pattern of vulnerability. For example, Papathoma-Köhle et al. (2007) introduce a framework to undertake an assessment of the vulnerability of buildings to landslide, based on the development of an “elements at risk database” that takes into consideration the characteristics and use of the buildings, their importance for the local economy and the characteristics of the inhabitants (population density, age, etc.). The established GIS database contains attributes that affect vulnerability, and it is used for the visualisation of physical, human and economic vulnerability (Fig. 1). The vulnerability assessment is based on a landslide susceptibility map demonstrating the probability of landslide occurrence; however, it does not take into consideration the frequency, magnitude and run out of potential landslides. The result of the study can contribute to effective disaster management and emergency planning and the database produced may be used by various end-users and stakeholders, such as insurance companies, emergency planners, local authorities.

Apart from Papathoma-Köhle et al. (2007), GIS and remote sensing data were also used in a study of Macquarie et al. (2004). The main idea of the approach of Macquarie et al. (2004) is to identify vulnerable zones for landslide risk assessment at large scales (1:5,000 to 1:10,000) through the aggregation of elements at risk sharing identical attributes. Based on aerial photography, statistical analysis and GIS technology, the urban fabric is divided in three vulnerability categories (low, medium and high) according to criteria such as number of inhabitants, type of buildings, type of activities, land use and lifelines.

Vulnerability maps were also produced by Uzielli et al. (2008) and Kaynia et al. (2008). Uzielli et al. (2008) used a method for scenario-based, quantitative estimation of physical vulnerability of the built environment to landslides and introduced a methodology of probabilistic estimation for vulnerability to landslides. Based on a first-order second-moment approach, they estimate the vulnerability for susceptible categories of structures and people for prescribed study areas, finally quantifying the uncertainties.

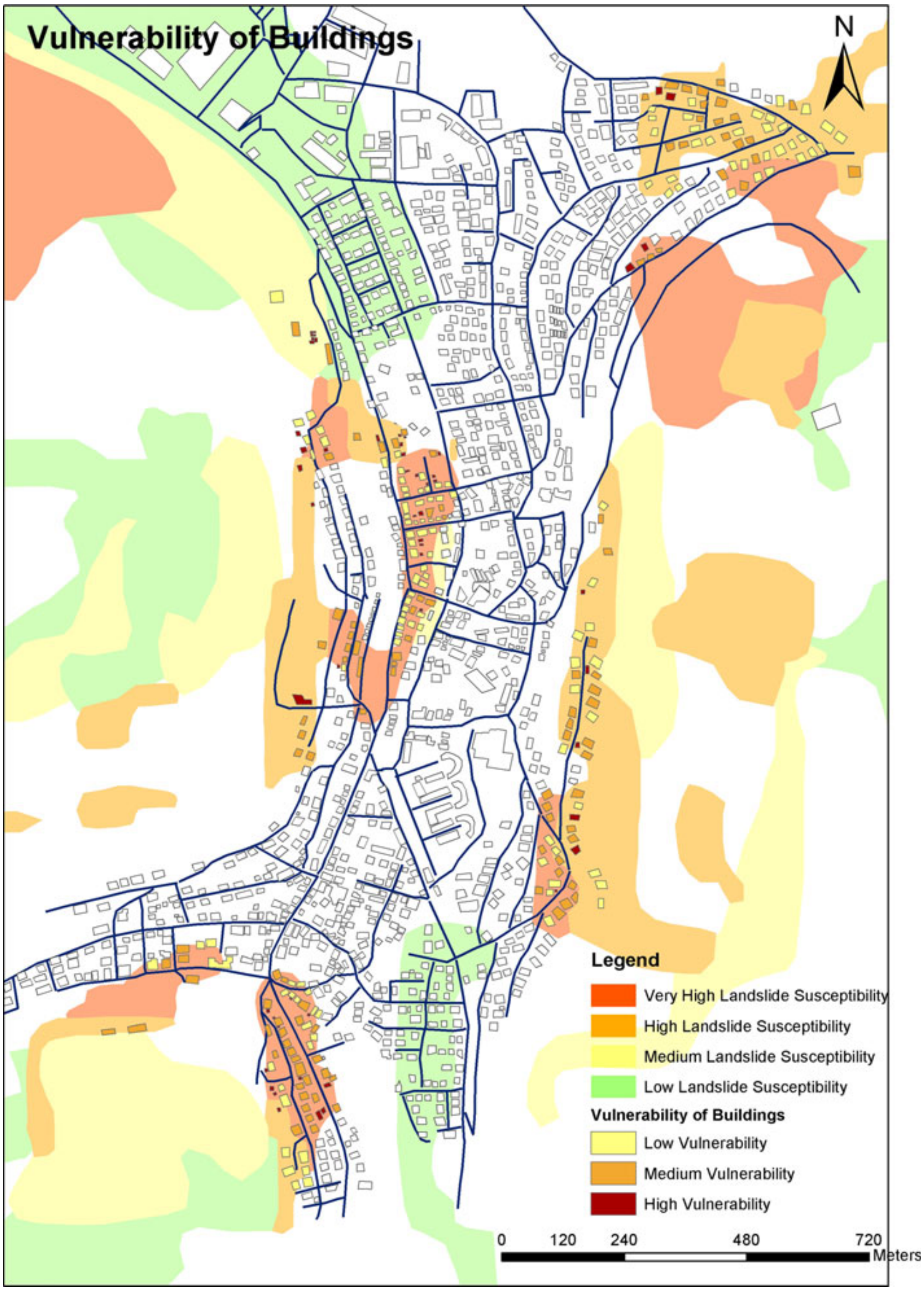


Fig. 1 Map showing the landslide susceptible areas of Lichtenstein (Germany) and the vulnerability of the buildings that are found within them (Papathoma-Köhle et al. 2007)

Some studies investigated also the impact of landslides on people and not only on buildings. For example, Bell and Glade (2004) and Glade and Crozier (2005) determine the vulnerability of a person affected by a landslide according to his location (open spaces, vehicles, buildings). Santos (2003) has included a vulnerability assessment study for landslides within a QRA (quantitative risk analysis), which is based on a weighting of elements at risk giving the highest priority to the human life. In this study, the criteria used included presence, frequency and absolute number of human lives, infrastructures (public, residential, etc.) and productive function and activities (industry, agriculture, etc.). However, the construction type or the condition of the buildings in the study area are not taken into consideration. The vulnerability assessment was used for the production of a risk map. There was no map demonstrating the vulnerability pattern (Santos 2003).

Another study has been carried out by the Department of Hydrology and Meteorology for Nepal for the Advance Institute on Vulnerability to Global Environmental Change (Shrestha 2005). This study includes physical and social vulnerability for both landslides and floods. Total vulnerability is also assessed based on hazard, physical exposure and adaptive capacity. In parts of the study area, although the hazard has decreased, the total vulnerability has risen due to higher physical exposure and the lower adaptive capabilities of the community (Shrestha 2005). Similar findings have been reported in New Zealand (Hufschmidt et al. 2005).

Galli and Guzzetti (2007) map vulnerability of buildings and roads to landslides, in Umbria (Italy) by using the existing landslide inventory and established vulnerability curves. Based on information on the damage caused by 103 landslides, they establish dependencies between the area of the landslide and the vulnerability of buildings and roads.

Finally, a vulnerability assessment method for landslides was introduced by Alexander (2005) based on the vulnerability of buildings and structures, human lives and socio-economic activities. The methodology can be used in three scales: single asset method (vulnerability is assessed for each element at risk of the area), summed asset method (vulnerability is assessed as an average vulnerability of assets in a hazard area) and generalised asset method (a general level of vulnerability for all assets in the hazard area is estimated). The vulnerability classes of the assets are assigned on the basis of the likely degree of loss. Vulnerability estimated in this way can be mapped, and, in combination with a hazard map, can lead to the production of a risk map.

3.2 Debris flow

In the study of debris flow vulnerability, there are significantly more efforts in the production of vulnerability curves. BUWAL (1999a), focusing on gravitational mass movements in Switzerland, presents vulnerability curves that are integrated in a 3-step methodology for the vulnerability of communities at risk.

1. Step 1: By combining a hazard and a land use map and comparing with the protection objectives potential ‘protection deficits’ are deducted.
2. Step 2: The vulnerability of object categories is quantified by taking into consideration the loss of life, assets and agricultural land, and rebuilding and clean-up costs.
3. Step 3: The vulnerability of each object is assessed using vulnerability curves and detailed information on elements at risk to estimate the death risk in buildings, on the street and in the train, as well as the monetary loss as far as buildings, business interruption and loss of farm animals are concerned.

The methodology is illustrated by case studies from Switzerland for debris flow, rock falls, landslides and avalanches. It is based on vulnerability curves related to the intensity of the phenomenon and its impact (degree of loss) on the buildings (green line in Fig. 2 for debris flow).

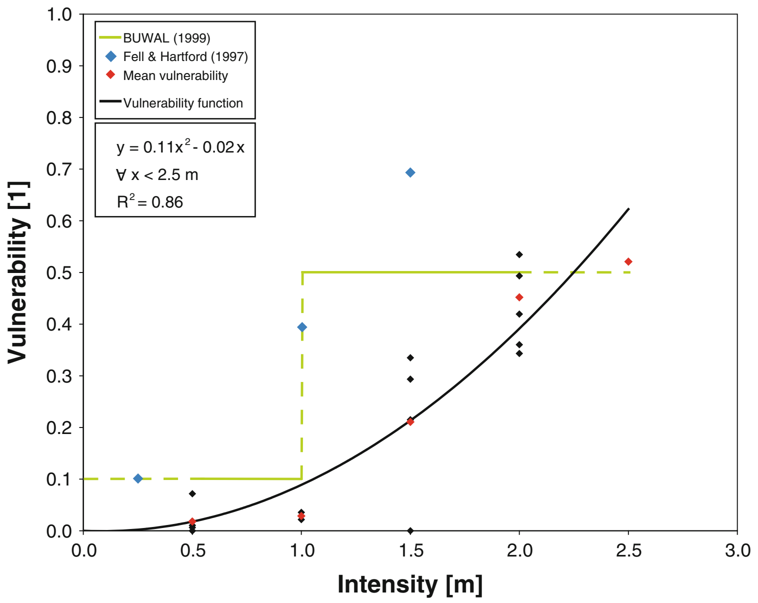


Fig. 2 The generalised relationship between debris flow intensity and vulnerability is represented by the black curve (refer to Fuchs et al. 2007). Mean vulnerability values published by BUWAL (1999b) and Fell and Hartford (1997) (refer to *green line* and *blue dots*, respectively)

Moreover, Romang (2004) in a study related to the effectiveness of protection measures for flooding and debris flow events in Switzerland recognised that the vulnerability of buildings is a critical parameter not only within risk analysis but also for the planning of protection measures. There, the vulnerability of buildings was expressed as the ratio of effective damage and the value of the object, by using data provided by insurance companies. The vulnerability of buildings was calculated according to different water depth (0.5–1, 1–2, >2 m). According to Fuchs et al. (2007), the resulting curves were in accordance with BUWAL (1999a) as far as medium debris flow intensities are concerned. However, for high intensities, the values provided by Romang (2004) were considerably higher than the ones provided by BUWAL (1999a).

Fuchs et al. (2007) using a well-documented event, which occurred in the Austrian Alps (August 1997), obtained a vulnerability curve for buildings of the dominant type (brick masonry and concrete) located on the fan of the torrent, based on the damage ratio and the intensity of the phenomenon. The relationship between debris flow intensity and vulnerability is expressed by a second polynomial function (Fig. 2). The intensity is expressed by deposit height and the curve concerns intensities lower than 2.5-m deposit height. In Fig. 2, the curve produced by Fuchs et al. (2007) is shown together with existing curves for comparison.

Akbas et al. (2009) use data from the 2008 debris flow event in Selvetta (Italian Alps) in order to develop an empirical vulnerability function based on the relationship between vulnerability of buildings and deposition height. The authors suggest that there is a difference in the results between the developed vulnerability function and other vulnerability functions that can be found in the literature. In more detail, although the obtained vulnerability values are similar to the ones resulting from some studies (Fell and Hartford 1997; Bell and Glade 2004), they appear to be higher when compared with those of Fuchs et al. (2007). To obtain results of high confidence level, future studies should include both characteristics related to the intensity of the event (velocity, deposition height) and description of outcoming damage.

Cardinali et al. (2002) have also discussed the issue of vulnerability through a risk assessment. In order to conduct a landslide risk assessment, they provided a table with the vulnerability of the elements at risk, expressed as expected damage (superficial, functional and structural) caused by different types of landslides having different intensities, but they never went any further by mapping this vulnerability. Michael-Leiba et al. (2003) assessed the vulnerability of elements as risk (people, buildings and roads), as part of a landslide risk assessment for the community of Cairns, Australia. They consider vulnerability as the probability of an element at risk to be destroyed by a landslide and produced a table showing how the vulnerability of the elements at risk can change according to the type of slide.

Other studies show a wider focus, not being limited to the assessment of the vulnerability of buildings. Liu and Lei (2003) presented a vulnerability assessment model through the assessment of debris flow risk in China, based on a more holistic approach taking into consideration all the factors that influence vulnerability. According to the authors, vulnerability depends on physical, economic, environmental and social factors. In order to assess vulnerability on a regional scale, the following characteristics were taking into consideration:

- Physical vulnerability, defined by fixed asset values;
- Economic vulnerability, assessed through Gross Domestic Product (GDP);
- Environmental vulnerability, including baseline prices of different types of land;
- Social vulnerability, based on size, density, age, education and wealth of people.

Sterlacchini et al. (2007) include a vulnerability assessment of an Italian community susceptible to debris flow within a multi-disciplinary landslide risk analysis. The vulnerability assessment of the elements at risk is based on the physical effects that the elements could suffer because of the disastrous event, assessed basing on damage scenarios of similar past events. Finally, the authors estimate the social and economic consequences by producing a vulnerability scenario for built-up areas and infrastructure (buildings, road network and waterlines and penstocks) described in terms of aesthetical, functional and structural damage.

3.3 Rock falls

As far as rock falls are concerned, attempts for vulnerability assessment of elements at risk of rock falls are limited, perhaps due to the limited impact of the phenomenon (it can affect individual buildings rather than settlements, and rarely it causes casualties). BUWAL (1999b) proposed vulnerability curves for rock falls as far as five building categories are concerned. The curves express the relationship between the vulnerability of the buildings and the intensity of the rock fall (kJ). Corominas et al. (2005) worked within the framework of a quantitative risk assessment (QRA) in Andorra. Although they suggest that the intensity of the event and the nature of the element are the two factors controlling the amount of damage that can be produced by the rock fall in order to assign vulnerability values to elements at risk, they only take into account the intensity of the event. Mavrouli and Corominas (2008) make a step further, by analysing the vulnerability of buildings to rock falls for three representative structural typologies: (1) reinforced concrete structure with column and beam frames, (2) reinforced concrete structure with additional reinforced concrete walls on the exposed facade and (3) bearing brick masonry. Finally, other landslide vulnerability studies included vulnerability to rock falls as part of a wider vulnerability assessment focused on landslides (Bell and Glade 2004).

3.4 Avalanches

Studies focusing on the vulnerability assessment of communities and buildings to avalanches are significantly less than similar studies regarding other disaster types, probably due to lack of sufficient data on avalanche damages to exposed elements (Cappabianca et al. 2008).

Wilhelm (1997) determines the vulnerability functions for different construction types of buildings related to avalanche impact pressure (kPa) based on different avalanche events beginning with the avalanche event in Voralberg in 1954. He introduces four vulnerability thresholds, as shown in Fig. 3, in which:

- p_u is the general damage level: mentionable damage (e.g. destroyed windows and doors)
- p_{ui} is he specific damage level: damage on the building structure (according to construction type)
- p_{oi} is the destruction level: maximum loss within each building category.
- p_{ai} is the detached limit: demolition and reconstruction is necessary.

Keiler (2004) investigates the damage potential of avalanche events in Austria. Within this study, the value of buildings and number of exposed people that are located within every hazard zone and the changes through the time for the period 1950–2000 are calculated. In a later study (Keiler et al. 2006), which includes the vulnerability curves introduced by Wilhelm (1997), she assesses potential building damage based on the building value, the construction type and the existence of avalanche deflectors and reinforced structures at the exposed side of buildings. The results showed that the potential building damage has decreased during the last 50 years, due to changes in the type of building construction, which influence highly the vulnerability of buildings.

For the three stage-methodology of BUWAL (1999b), the main input is represented by hazard maps for three scenarios (30, 100 and 300-year return period) and a related intensity map for each obtained scenario according to the Swiss guidelines (BFF and SLF 1984;

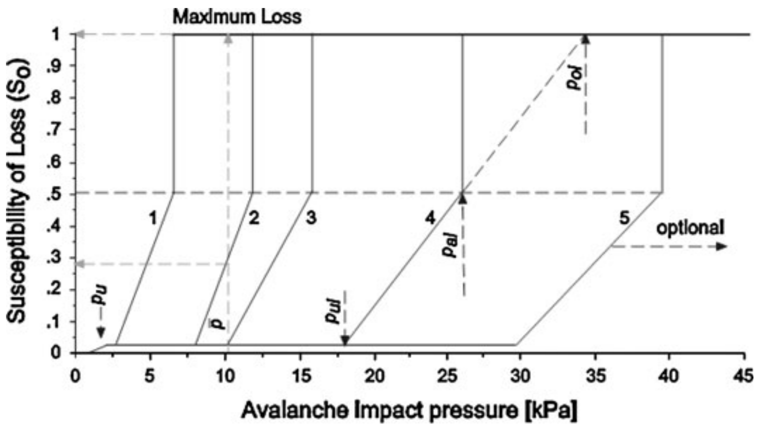


Fig. 3 The relationship between the avalanche impact pressure and the vulnerability of the buildings (expressed here as the susceptibility of loss) is determined for 5 building types: (1): lightweight construction, (2): mixed construction, (3): massive construction, (4): concrete reinforced construction, (5): reinforced construction (Keiler et al. 2006 after Wilhelm 1997)

BWW et al. 1997; BUWAL et al. 1997). The intensity classification is derived as an example for avalanches from impact pressure on large obstacles, and divided into low ($<$3 kPa), medium (3 kPa $<$ 30 kPa) and high ($>$30 kPa). For the first two stages, the vulnerability of elements at risk is neglected or included as general assumptions with regard to the probability of lethality according to the intensity class and the land use category (e.g. settlement area, industrial area, dense developed area). In the third stage, the potential damage for buildings and infrastructure is calculated depending on the value of the element at risk and the degree (or susceptibility) of loss related to the impact pressure and intensity classes, respectively (BUWAL 1999b). The latter includes the construction type of the buildings and the related resistance, the building height and the presence of local structural protection. Furthermore, a degree of loss is estimated for traffic lines, infrastructure and different agricultural uses. Also the vulnerability curve of BUWAL (1999b) is strongly related to the approach of Wilhelm (1997) but differs because the degree of loss is only given for three aggregated intensity classes and the related impact pressure and no general damage level (p_u) is included.

Keylock and Barbolini (2001) studied the impact of snow avalanches on buildings, introducing a methodology for deriving vulnerability values as a function of position downslope for a range of avalanche sizes. The same concept was used later by Barbolini et al. (2004) in order to assess the vulnerability of buildings and people. Barbolini et al. (2004) suggest that for buildings this loss is the value of the property and for people the loss can be expressed as the probability that a particular life will be lost. Based on data from two well-documented events in Tyrol (Austria) for different impact pressure they produced three vulnerability curves for: buildings, people inside buildings and people outside buildings. The vulnerability is expressed as a function of avalanche dynamical parameters (impact pressure and flow depth). The vulnerability of buildings is defined in this study by Barbolini et al. (2004) as the ratio between the cost of repair and the building value. On the other hand, the vulnerability of people inside buildings is defined as the probability of being killed by an avalanche if one stays inside a building when the avalanche occurs. Moreover, the vulnerability of people outside buildings is defined as the degree of burial, which depends on the flow depth of the avalanche.

Bertrand et al. (2010) presented a methodology for vulnerability assessment of unreinforced masonry buildings exposed to snow avalanches. They accept that vulnerability is the degree of loss of a given element at risk within the threatened area. Therefore, the vulnerability of the structures is expressed as damage level. In more detail, they use a numerical approach in order to simulate the displacements of blocks that constitute the structure under threat. The damage of the structure is estimated by the number of broken joints.

Finally, one of the most recent studies on vulnerability for snow avalanches is the one of Cappabianca et al. (2008) who are proposing a vulnerability curve for people inside buildings affected by dense avalanches based on Wilhelm (1997) making possible the inclusion of these vulnerable elements in the calculation of the total risk at the valley bottom. In a similar way, Jonasson et al. (1999) related the probability of people surviving an avalanche to the avalanche velocity based on data from Iceland. The results concern Icelandic type of housing, thus, the method is not transferable to other parts of the world without adaptation.

3.5 Floods

Most of the current state-of-the-art flood loss analyses focus on the estimation of direct, tangible damages (Messner and Meyer 2005). The most frequently applied approach concerns the linkage of inundation depth to estimated damages. Hooijer et al. (2001) developed classes of severity of flood and for each class (serious (<1.5 m), disastrous (1.5–4 m) and catastrophic (>4 m)) the percentage of total potential damage for households, industrial assets, infrastructure, etc. and number of inhabitants, respectively, is determined.

The stage-damage curves are widely used, tracing back to White (1945), who linked inundation depth to expected losses expressed as percentage or total damage (monetary value). The use of stage-damage curves is restricted to gently flowing water (<1 m/s) since faster flows cause with increasing likelihood damages due to the dynamic load (Greenaway and Smith 1983 in Middelmann-Fernandes 2010). NZIER (2004) limit their applicability even further to slow-rising, low-silt and low-flow floods. Kang et al. (2005), for example, developed curves for single and multiple family dwellings interrelating flow depth with total damage, while Grünthal et al. (2006) worked with relative stage-damage curves estimating the damage ratio of buildings and contents for various economic sectors as private housing, commerce, services, public infrastructure. The total economic value per grid cell was assessed according to the economic sector to which it belonged based on unit values per land area and after linkage to the stage-damage curves total losses were derived for various flood scenarios. Meyer et al. (2009) used relative stage-damage curves for potential damage assessment for various asset categories as residential, agriculture, industry or service for the river Mulde in Saxony (Germany). Apart from the economic assessment, Meyer et al. (2009) considered also ecological (erosion, accumulation and inundation of oligotrophic biotopes) and social (spatial distribution of affected population, location of social hot spots as hospitals, schools, etc. and inundation) consequences. By means of multi-criteria analysis, the single sub-criteria and criteria were combined and the spatial allocation of these monetary and non-monetary consequences was visualised in separate maps or as final standardised multi-criteria risk.

Dutta et al. (2003) produced relative stage-damage curves for residential wooden structures, residential concrete structures, residential content, non-residential property and non-residential stocks. Additionally, they developed relative damage curves for crops relating flood duration to relative damages for three inundation depth classes (Fig. 4).

Merz et al. (2010) include a review of damage functions for floods in a wider review of assessment methods for economic flood damage. They distinguish the various functions in relative (used in the HAZUS-MH model) and absolute (used in the UK and Australia), and they summarise their advantages and disadvantages.

For static floods, the depth may indeed be the dominating factor and sufficient for an analysis but Merz et al. (2004) criticise the limitation to this hazard indicator as too simplistic since still a big variety of further parameters may influence the quantity of losses. The Deutsche Rück (1999) found for the flood in May 1999 in Germany a triplication of damages for buildings with filled oil tanks due to oil spill and Thieken et al.

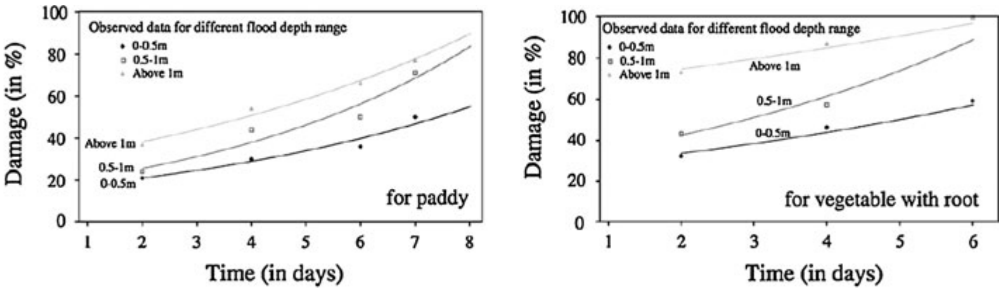


Fig. 4 Stage-damage curves for agriculture product damage estimation (Dutta et al. 2003)

Table 1 Loading factors for different levels of contamination and precautionary measures (Büchele et al. 2006)

Consequence and measures	Loading factors for damage ratios	
	Buildings	Contents
No contamination and no precautionary measures	0.92	0.90
No contamination and medium precautionary measures	0.64	0.85
No contamination and very good precautionary measures	0.41	0.64
Medium contamination and no precautionary measures	1.20	1.11
Medium contamination and medium precautionary measures	0.86	0.99
Medium contamination and very good precautionary measures	0.71	0.73
High contamination and no precautionary measures	1.58	1.44

(2005) identified for the Elbe flood of 2002 contamination and flood duration as important factors. Büchele et al. (2006) identified contamination and the application of precautionary measures as important variables in their study. They complemented the stage-damage curve by these two parameters by means of so-called loading factors (Table 1), which are multiplied with the damage predicted by the stage-damage curve.

Büchele et al. (2006) collected a list of further influencing factors as “duration of inundation, sediment concentration, availability and information content of flood warning and the quality of external response in a flood situation”, but very few studies consider them quantitatively.

For dynamic floods flow velocity is an important parameter, but still only few studies are available which include it into damage estimations. De Lotto and Testa (2000) analysed the effect of dam-break at a test site in an alpine valley basing their analysis on water depth and flow velocity. By that time no velocity-damage function could be found thus, they adopted the pressure used as threshold of complete destruction of structures due to snow avalanches (30 kN/m^2). Since for the elements at risk (1 storey, 2 storey and 3 storey houses and the content) two damage values were obtained—one for depth and one for velocity, always the highest value was used and interactions were not taken into account. In HAZUS-MH (FEMA 2007) a velocity–depth function is included indicating whether building collapse has to be assumed. If the threshold for collapse is reached or exceeded, the damage is set to 100% while below this threshold the damage is estimated based on inundation levels only. Furthermore, the effect of warning and associated damage reduction can be considered and assessed by a so-called day curve. Based on the time of the warning before the event a maximum percentage of 35% damage reduction can be achieved if a public response rate of 100% can be assumed.

The Swiss risk concept from PLANAT (Nationale Plattform Naturgefahren) defines three intensity classes for an effect analysis, based on flood depth and velocity (Table 2), which are used as basis for spatial planning regulations (BWW et al. 1997; Bründl 2009).

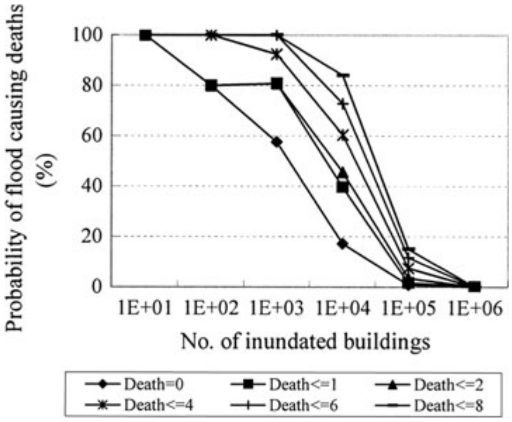
The intensity classes are established according to their effect on human beings and buildings (BWW et al. 1997):

- High: persons inside and outside of buildings are at risk and the destruction of buildings is possible or events with a lower intensity occur but with higher frequency and persons outside of buildings are at risk.
- Middle: persons outside of buildings are at risk and damage to buildings can occur while persons in buildings are quite safe and sudden destruction of buildings is improbable.

Table 2 Intensity classes based on flood depth and velocity from PLANAT (Bründl et al. 2009)

Intensity class	Criteria
Low	$h < 0.5$ m or $v \times h < 0.5$ m^2/s
Middle	2 m $> h >$ 0.5 m or 2 m^2/s $> v \times h >$ 0.5 m^2/s
High	$h > 2$ m or $v \times h > 2$ m^2/s

Fig. 5 Probability of a flood causing a certain number of deaths versus the number of inundated buildings (Zhai et al. 2006)



- Low: persons are barely at risk and only low damages at buildings or disruptions have to be expected.

Zhai et al. (2006) proposes an indirect method by assessing the probability of fatality or injury as a function of the number of inundated buildings without considering any flood characteristics (Fig. 5).

Obviously, a variety of empirical approaches is available, mostly focused on the predominant hazard characteristic (static or dynamic floods) of the particular event, linking the corresponding hazard indicator (e.g. inundation depth) to the expected damage. On the contrary, Kelman and Spence (2004) give a very detailed and more theoretical overview of flood actions referring to them as “acts which a flood could do to a building, potentially causing damage or failure” instead of flood indicators:

(a) hydrostatic actions (resulting from water’s presence) which are lateral pressure on the building structure and capillary rise
(b) hydrodynamic actions (resulting from water’s motion) as e.g. velocity and turbulence (irregular fluctuations in velocity in magnitude and direction)
(c) erosion actions (water moving soil)
(d) buoyancy action (tendency to float)
(e) debris actions (actions from solids in the water) are composed by static (e.g. sediment accumulation in or outside of buildings creating forces), dynamic (impact of debris moved by water on a building) and erosion actions
(f) non-physical actions which are chemical (e.g. rusting or contaminations, conducting of electricity), nuclear and biological actions (e.g. micro organisms).

Although for most of the parameters they list no current techniques including them into vulnerability assessments exist yet, this collection might serve as first step for a more coherent approach.

In order to address the various concepts of vulnerability assessment and to determine the similarities and the differences between them, a project funded by the European Commission has been launched. In the MOVE project (Methodologies for Vulnerability Assessment in Europe), existing vulnerability assessment methods were reviewed based on a series of criteria. Information such as, the location of the study, the type of hazard and the research domain of the scientific team that undertook the study are important for the review. However, information regarding the way vulnerability is perceived by each author, the gaps and difficulties of the methods and the potential end-users that can also demonstrate the applicability of each method is considered as essential. Moreover, by scale we do not mean the extend of the case study area but the units that have been used for the vulnerability assessment that, for example, in the case of “local” are the individual houses. The reviewed vulnerability assessment methods and their scores according to the MOVE criteria are listed in the Appendix.

4 Discussion: Identifications of gaps

In this paper, 41 vulnerability assessment methods for alpine hazards are reviewed (some of them referring to more than one type of hazard). As far as the landslide-related hazards are concerned, the majority of vulnerability assessment methodologies have been designed for earth flow and debris flow-related hazards, whereas for rock fall hazards we have the smallest number of methodologies. Most of the reviewed methods consider vulnerability to be “the degree of loss of a specific element at risk to a hazard of a given magnitude”. The vast majority of the vulnerability assessment methods are quantitative, assigning vulnerability values from 0 to 1 to the elements at risk (e.g. Michael-Leiba et al. 2003; Fuchs et al. 2007), whereas, only a small percentage of them are qualitative describing vulnerability as low, medium and high (e.g. Cardinali et al. 2002; Santos 2003; Macquarie et al. 2004; Sterlacchini et al. 2007). This “degree of loss” is often expressed as monetary loss (reconstruction costs, building value, etc.) (e.g. Barbolini et al. 2004; Keylock and Barbolini 2001; Romang 2004; Fuchs et al. 2007; Cappabianca et al. 2008), in other cases it is expressed as damages (aesthetic, functional, structural, etc.) (e.g. Corominas et al. 2005; Sterlacchini et al. 2007; Mavrouli and Corominas 2008). Finally, in some studies (e.g. Mejia-Navarro et al. 1994; Liu and Lei 2003; Papathoma-Köhle et al. 2007; Sterlacchini et al. 2007), vulnerability is a combination of all these factors that contribute to the susceptibility of the building or the given element at risk. Moreover, for studies with a focus on human life, vulnerability is the probability of a life to be lost (e.g. Jonasson et al. 1999; Santos 2003; Barbolini et al. 2004; Keylock and Barbolini 2001; Zhai et al. 2006).

From the 41 reviewed methods, 21 use existing (12) or introduce new vulnerability curves (9). In the case of floods, almost all of the studies are based on vulnerability curves which holds only for a few studies related to gravitational hazards. As Douglas (2007) suggests, there are more vulnerability curves for other geohazards, such as earthquakes, rather than for landslides and snow avalanches. Moreover, in the cases where vulnerability curves are used the expected damages to the built environment are not always expressed in relationship to the same characteristic of the hazardous phenomenon. For example, in the case of debris flows, vulnerability is presented in relationship to the intensity of the debris flow, which is expressed as deposit height. Other properties of the phenomenon (e.g. flow velocity) are not taken into consideration (Fuchs et al. 2007). For snow avalanches, the vulnerability curves that are available express the relationship between potential loss and the impact pressure of the snow avalanche, expressed as kPa, without taking into consideration other avalanche characteristics such as flow density (Wilhelm 1997; Keiler et al. 2006). On the other hand, for floods there is a variety of vulnerability curves available in the literature. The majority of the studies use vulnerability curves that demonstrate the relationship between expected damage and inundation depth. The large number of vulnerability curves in flood studies can be explained by the fact that floods (just like earthquakes and storms which are also hazards with very well developed vulnerability curves) damage more buildings in a single event than other hazard types (Douglas 2007). Additionally, these hazards occur frequently and are in society's recent memory. Finally, most of the methodologies have been applied in Europe or in countries with similar level of development, such as America and Australia. However, the curves that are produced are mostly for a specific construction type that is common in the study area. Therefore, they cannot be used in another part of the world where the dominant construction type is different or where there is diversity in the quality or types of buildings.

The focus of the methodologies varies significantly. The majority of the methodologies focus on buildings, whereas, others include also potential victims, infrastructure and lifelines such as the road network. Very few studies focus on the vulnerability of the environment or the agricultural land, or the economic vulnerability of the affected community that can include the vulnerability of businesses, employment, tourism, etc. A very limited number of the reviewed studies address the multi-dimensional nature of vulnerability (Leone et al. 1996; Liu and Lei 2003; Sterlacchini et al. 2007). As far as the scale of the study is concerned, the majority of the studies, especially the ones involving landslides, concern methodologies designed to be applied only on a local level, whereas only a few (Liu and Lei 2003; Galli and Guzzetti 2007) are applied on a regional scale. In the case of studies concerning floods, the majority of them are carried out on a regional scale (Hooijer et al. 2001; Grünthal et al. 2006; Meyer et al. 2009; Zhai et al. 2006, etc.). The regional vulnerability assessment is important for the central or the regional government in order to make decisions regarding funding allocations. However, as far as on-site emergency management and disaster planning is concerned in particular local vulnerability assessment can provide the decision makers with useful information.

There are many difficulties in implementing the methodologies. The most common setback is the data availability (Barbolini et al. 2004; Büchele et al. 2006; Papathoma-Köhle et al. 2007; Kaynia et al. 2008; Uzielli et al. 2008; Akbas et al. 2009) and the fact that some methods are time-consuming (Papathoma-Köhle et al. 2007; Kaynia et al. 2008; Uzielli et al. 2008) due to extensive field work and the detailed data that are required. Many studies focus only on the vulnerability of individual buildings (Corominas et al. 2005; Bertrand et al. 2010; Mavrouli and Corominas 2008). In the case of rock falls (Corominas et al. 2005; Mavrouli and Corominas 2008), this is widely understood since the specific type of disaster affects individual buildings rather than settlements. As far as other alpine hazards are concerned, usually the studies focus on settlements rather than individual buildings. Vulnerability maps, which could give an overview of the vulnerability pattern, are often not provided (Leone et al. 1996; Sterlacchini et al. 2007; Zezere et al. 2008). Although due to the goal of the study vulnerability maps are not always necessary, they may be a valuable tool for emergency planning and decision making in disaster management. In many cases the authors provide an inventory of the elements at risk but they do not provide information regarding their properties which is essential for a vulnerability assessment (Fuchs et al. 2007). In other cases, the indicators of vulnerability are explicitly explained (Sterlacchini et al. 2007) and in many cases, only one vulnerability indicator is taken into consideration, e.g. building type (Keylock and Barbolini 2001;

Büchele et al. 2006; Fuchs et al. 2007; Zezere et al. 2008). Moreover, vulnerability in most cases is considered hazard dependant, in other words, characteristics of the hazardous phenomenon, such as its intensity or magnitude, are also taken into consideration (Mejia-Navarro et al. 1994; Macquarie et al. 2004; Keiler et al. 2006; Fuchs et al. 2007; Bründl 2009; Kaynia et al. 2008; Bründl et al. 2009). However, some studies do not take into consideration the hazardous phenomenon (Leone et al. 1996; Liu and Lei 2003; Papathoma-Köhle et al. 2007). In general, most of the vulnerability assessment methods reviewed here are static: they refer to a state of vulnerability for given elements at risk within a certain time period. However, vulnerability is a dynamic phenomenon which is changing through time. Therefore, the temporal evolution of vulnerability should be taken into consideration in future vulnerability assessment studies.

5 Conclusion: future needs

The diversity in the way physical vulnerability to alpine hazards is assessed by different scientists is remarkable. It is understood that a common vulnerability assessment method that satisfies all would be impossible. However, following this detailed review of the existing vulnerability assessment methods for alpine hazards, a series of aspects regarding future needs in the field of vulnerability assessment are outlined.

The absence of a common definition and conceptual framework of vulnerability can obstruct efficient risk reduction. Sometimes, the different approaches confuse potential end-users, leading to the exclusion of vulnerability assessment from the decision-making process. For this reason, a common language not only between scientists of different disciplines but also between scientists sharing a similar background is essential. Since vulnerability can have many dimensions (physical, economic, social, etc.) a multi-dimensional approach is necessary which would enable the collaboration between scientists from various disciplines. Even if we focus on one dimension only in the respective research, the other dimensions are still there and they might influence unintentionally the results of the specific research. According to Fuchs (2009), integrating the contributions of the different disciplines in a holistic way would not result in an individual integral method which would be generally applicable; however, they could be combined in a concept offering complementary results that can lead to a deeper understanding of hazard and risk. In order to improve the physical vulnerability assessment, as a part of a future multi-dimensional vulnerability assessment method, we would like to outline the following:

1. The aim of the vulnerability assessment and its end-users should be identified before the development of the methodology. This holds not just for vulnerability assessment but our analysis of existing methods shows that this is mostly missing. A vulnerability assessment which will be used as a tool for decision making or emergency planning will take into consideration different parameters than a vulnerability assessment that will be used for funding allocation in national or international level. In case the method is targeting a number of end-users then it should be user friendly and comprehensible for a wide range of people and not only for specialists. The end-users will also influence the scale of the assessment (local/regional/national).
2. All the relevant vulnerability indicators should be considered. Indicators can be identified by looking at records of previous events, as far as every different type of disaster is concerned. The construction type is a very important indicator of vulnerability but there are other indicators that play a major role in the interaction

between a building and a hazardous phenomenon such as the design and shape of the building, its foundation, its surrounding, the existence of vegetation or protection measures, and the static characteristics of the building. As far as floods and torrent processes are concerned the opening of the buildings and the use of the ground floor are also very important indicators. Birkmann (2006) suggests a number of steps for such an indicator development, and a series of quality criteria.

3. It would be of great value if a vulnerability assessment method could be transferred to other places of the world. However, due to the different housing materials and architecture this is very difficult. Although the transferability of a method is hard to be secured it should not be neglected where possible. For example, more than one building type could be considered. These would eventually lead to more than one vulnerability curve for the study area that could also enable the transferability of the method to other parts of the world with a diversity of building and construction types. Moreover, the uncertainties of the vulnerability functions should be also considered.
4. It can be of great use when vulnerability assessment is accompanied by a product (e.g. a map or a GIS database) that shows its spatial pattern. Weichselgartner (2001) also points out the importance of mapping vulnerability as a result of a series of hazard, exposure, preparedness and prevention maps. Available technology such as remote sensing and GIS should be used not only for the provision of quality maps but also in order to reduce time-consuming fieldwork as much as possible. Although the necessity of such technology (remote sensing and GIS) is highly dependent on the goal and scale of the study, recent remote sensing data can provide the most up to date picture of the study area and the inventory of the elements at risk together with their properties avoiding time-consuming field work. Following, the up to date information can be contained in a GIS database for fast data retrieval, easy weight allocation for the various vulnerability indicators, better visualisation (understanding of the spatial pattern of vulnerability) of the results and continuous updating.
5. The fact that vulnerability is hazard dependant should not be ignored. Information regarding the properties of the hazardous phenomenon should be collected as well as information regarding the impact of past events on the built environment. Moreover, the vulnerability assessment method differs with the type of disaster as characteristics regarding its frequency and extend should be taken into consideration.
6. A static vulnerability assessment method does not cover the needs of the end-users and the development of risk management strategies under the consideration of complex interaction between natural systems and social systems (global change) (Keiler et al. 2006, 2010). Vulnerability is a dynamic phenomenon that changes through time, especially as much as people are concerned. A dynamic perspective of vulnerability and the resulting consequents should be also taken into consideration in the development of new methodologies.

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Appendix

See Table 3.

Table 3

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
1	Akbas et al. (2009)	Type of disaster: Debris flow Scale: Local Location: Selvetta (Italian Alps) Research domain: Natural science Focus: Buildings, infrastructure, population Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Local authorities, planning agencies, engineers	Vulnerability is considered to be the expected degree of loss to a given element at risk resulting from the occurrence of a hazard of a given magnitude. It is defined as the ratio between the loss and the individual reconstruction value	The authors suggest that, in order to reach a higher confidence level, there is a need for more data concerning not only the resulting damage to buildings but also intensity measures if the event such as deposition height and velocity
2	Alexander (2005)	Type of disaster: Landslides Scale: local (multi-scale) Location: N/A Research domain: disaster management Focus: Buildings, human lives, socio-economic activities Type of assessment: qualitative Hazard dependant: NO Vulnerability curves: NO Possible end-users: Local authorities, disaster managers	"….with respect to the elements at risk vulnerability can be considered either as susceptibility to damage in mass movements of given types and sizes or in terms of value…"	Required data should be mainly collected by time-consuming field survey
3	Barbolini et al. (2004)	Type of disaster: Snow avalanches Scale: Local Location: Italy Research domain: Natural science Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Civil engineers, local authorities, city planners	Vulnerability is defined as the degree of loss, and it is expressed on a scale of 0 (no loss) to 1 (total loss). For buildings, the loss is the value of the property and for people it is the probability that a particular life will be lost. In more detail, the vulnerability of buildings is defined as the ratio between the cost of repair and the building value (SL: specific loss)	More data are necessary in order to assess the validity of the method. Moreover, the curves are created for one type of construction (alpine types of buildings), which makes the methodology difficult to be applied in an area with different types of buildings. Finally, the vulnerability of people is based to a limited amount of data and many assumptions

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
4	Bell and Glade (2004)	Type of disaster: Landslides Scale: Local Location: Iceland Research domain: Natural science Focus: Buildings and people Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Local authorities, emergency and civil protection services	No definition of vulnerability is provided	No vulnerability map is provided and no detailed investigations of buildings is carried out
5	Bertrand et al. (2010)	Type of disaster: Snow avalanches Scale: Local Location: - Research domain: Engineering Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Engineers, construction specialists	The vulnerability is the degree of loss (from 0 to 1) of a given element within the threaten area	The methodology is developed only for one type of building (unreinforced masonry structures), and it is time-consuming if it is to be applied to a large number of buildings. Therefore, it is not appropriate for emergency planning and disaster management or vulnerability mapping
6	Bründl (2009)	Type of disaster: Floods, avalanches, debris flows, rock fall, landslides, earthquakes, storms, hail, heat waves Scale: regional Location: Switzerland Research domain: Natural science, engineering Focus: Buildings, infrastructure, people, agricultural land Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Natural hazards experts and decision makers at various administrative levels	Characterisation of the extent of disturbance/damage an object experiences due to a specific process action	Non-continuous approach, well adapted classification thresholds to the specific situation in Switzerland (especially to spatial planning) but transferability to other countries or other applications may be difficult

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
7	Büchele et al. (2006)	Type of disaster: Floods Scale: local Location: Baden-Württemberg, Germany Research domain: Natural science, engineering, reinsurance sector Focus: Buildings and contents Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Public authorities (communities), spatial planners, house owners and insurance agencies	"Stage-damage functions for individual objects"	Very site-specific approach with high amount of data needed
8	BUWAL (1999b)	Type of disaster: Debris flow Scale: Local Location: Switzerland Research domain: Natural science, engineering Focus: Infrastructure, people, agricultural land, farm animals Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Regional and local authorities, civil engineers, insurance companies	The authors do not give any definition of vulnerability. The degree (or susceptibility) of loss (from 0 to 1) is part of the calculation for the damage potential	The degree of loss is more an estimation due to only few detailed event analyses. The damage function is only given for three intensity classes that lead to over- and underestimation, respectively
9	BUWAL (1999b)	Type of disaster: Snow avalanches Scale: Local Location: Switzerland Research domain: Natural science, engineering Focus: Buildings, infrastructure, people, agricultural land Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Regional and local authorities, civil engineers, insurance companies	The authors do not give any definition of vulnerability. The degree (or susceptibility) of loss (from 0 to 1) is part of the calculation for the damage potential	The degree of loss is more an estimation due to only few detailed event analysis. The damage function is only given for three intensity classes that lead to over- and underestimation, respectively

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
10	BUWAL (1999b)	Type of disaster: Rock falls Scale: Local Location: Switzerland Research domain: Natural science, engineering Focus: Buildings, infrastructure, people, agricultural land Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Regional and local authorities, civil engineers, insurance companies	The authors do not give any definition of vulnerability. The degree (or susceptibility) of loss (from 0 to 1) is part of the calculation for the damage potential	The degree of loss is more an estimation due to only few detailed event analysis. The damage function is only given for three intensity classes that lead to over- and underestimation, respectively
11	Cappabianca et al. (2008)	Type of disaster: Snow avalanches Scale: Local Location: Italian Alps (Trento) Research domain: Engineering Focus: Buildings and people Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Decision makers	No definition is given. It is stated that for buildings, vulnerability represents the ratio between the cost of repair and the building value and for people, the probability of being killed inside a building	For buildings, the authors use the vulnerability curve from Wilhelm (1997) only for one type of building (concrete). Other building types and other building characteristics are excluded from the vulnerability assessment
12	Cardinali et al. (2002)	Type of disaster: Landslides, debris flow, rock falls Scale: Local Location: Umbria, Italy Research domain: Natural science Focus: Buildings and people Type of assessment: Qualitative (A,S,F) Hazard dependant: YES Vulnerability curves: NO Possible end-users: Town officials, private consultants involved in land use and city planning	No definition is given. They suggest that a vulnerability assessment should include considerations of the type of failure, the elements at risk and the buildings ability to survive the expected landslide	The authors proposed three different types of damage for different types of landslides and magnitude but they never quantified vulnerability for the elements at risk

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
13	Corominas et al. (2005)	Type of disaster: Rock falls Scale: Local Location: Andorra Research domain: Engineering Focus: Buildings and people Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Engineers, owner of buildings, local authorities	Vulnerability is the degree of loss of an element at risk	A vulnerability score is assigned to the buildings according to the volume of the impact block. The characteristics of the buildings are not taken into consideration
14	De Lotto and Testa (2000)	Type of disaster: Floods Scale: regional Location: Alpine valley in Italy Research domain: Engineering Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Planners, emergency managers and engineers	"A function that relates the percentage of the value of a property that could be lost with the intensity of the event"	Only the highest expected damage value of depth and velocity was used and interactions were neglected
15	Dutta et al. (2003)	Type of disaster: Floods Scale: local and regional Location: Ichinomiya river basin, Japan Research domain: Engineering Focus: Buildings, contents, crops and infrastructure Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Insurance agencies, engineers, authorities and emergency managers	Vulnerability as term not mentioned	Only stage-damage curves are used, other parameters neglected. High errors in urbanised areas hinder the applicability for the real world

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
16	FEMA (2007)	Type of disaster: Floods Scale: local Location: USA Research domain: Natural hazards risk management Focus: buildings, contents, essential/high loss facility, lifelines, vehicles, Human casualties Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Federal, state, regional and local governments, private enterprises, emergency preparedness, response and recovery institutions	The term is not explicitly defined but dealt with as the degree of loss a particular element at risk will suffer due to a certain impact of a hazardous process	The method is mainly based on flow depth, flow velocity is only taken into account with a threshold for building collapse
17	Fuchs et al. (2007)	Type of disaster: Debris flow Scale: Local Location: Austrian Alps Research domain: Natural science Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Local authorities, emergency planners, building owners	The vulnerability was measured using an economic approach. Vulnerability was derived from the quotient between the loss and the individual reinstatement value for each element at risk in the test site	The vulnerability assessment method is designed only for one kind of building which is common in alpine countries but the methodology and the vulnerability curve could not be transferred to areas with different structural characteristics
18	Galli and Guzzetti (2007)	Type of disaster: Landslides Scale: Regional Location: Umbria, Italy Research domain: Natural science disaster management Focus: Buildings and roads Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Local authorities, emergency services	Vulnerability is the probability of total loss to a specific element given the occurrence of the landslide	The resulting map is not easy to read and to use for planning due to the scale (regional)

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
19	Grünthal et al. (2006)	Type of disaster: Floods, storms, earthquakes Scale: regional Location: Cologne, Germany Research domain: Natural science, engineering, reinsurance Focus: Buildings and contents Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Disaster managers, urban planners, insurers, regional and local authorities, etc.	Vulnerability assessment: "evaluation how exposed assets will suffer by various hazard events"	Only inundation depth is taken into account. For concrete planning decisions and emergency strategies still more detailed analyses might be needed
20	Hooijer et al. (2001)	Type of disaster: Floods Scale: regional Location: Hai River Basin, China Research domain: Engineering Focus: Agricultural/industrial production, industrial fixed assets, households and people. Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Decision makers for planning of mitigation measures	Instead of vulnerability the term "loss rate" is used which is defined as the "percentage of total potential damage and number of inhabitants"	Non-continuous approach, only considering flood depth. The data availability was too low for the proposed methodology and thus the results are not sufficient for flood management cost-benefit analyses
21	Jonasson et al. (1999)	Type of disaster: Snow avalanches Scale: local Location: Iceland Research domain: Natural science Focus: people Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Emergency services	The term "vulnerability" is not included in this study; however, the survival probability (which is calculated in this study) could be used as a component of a vulnerability assessment to snow avalanches	The method concerns only Icelandic type of buildings and it cannot be transferred elsewhere

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
22	Kang et al. (2005)	Type of disaster: Floods Scale: local and regional Location: Taipei, Taiwan Research domain: Natural science, engineering Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Risk managers and engineers	The term vulnerability is not used in this article. Focus is put on the damage. Stage-damage curves establish the link between flood depth and total damage	Only flow depth is considered. Absolute damage was calculated, hindering transferability to other locations and usability in the future due to inflation, etc.
23	Kaynia et al. (2008)	Type of disaster: Landslides Scale: Local Location: Germany Research domain: Natural sciences, engineering Focus: Buildings and people Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Emergency planners, local authorities	Vulnerability is defined in terms of both the landslide intensity and of the susceptibility of the elements at risk. $V = I \times S$	The method is too sophisticated and the data difficult to collect especially for larger areas
24	Keiler et al. (2006)	Type of disaster: Snow avalanches Scale: Local Location: Austria Research domain: Natural science Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: A study target audience is not identified in the study. However, the results could be used by local authorities, planners, emergency services and insurance companies	"The vulnerability of the buildings is understood as a degree of loss to a given element within the area affected by natural hazards. A vulnerability function for different construction types of buildings that depends on avalanche pressure was used to assess the degree of loss"	The vulnerability of buildings to avalanche impact pressure has to be further investigated since the present study takes into consideration a method (Wilhelm 1997), which could only serve as a rough estimation

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
25	Keylock and Barbolini (2001)	Type of disaster: Snow avalanches Scale: Local Location: Iceland Research domain: Natural science Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Avalanche experts, engineers, planners, decision makers	Vulnerability is defined as the degree of loss, and it is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the property and for persons the probability that a particular life could be lost	Very simple relation for the estimation of the vulnerability (derived from one event). Different buildings types are not regarded
26	Leone et al. (1996)	Type of disaster: Landslides Scale: Regional/local Location: - Research domain: Natural sciences Focus: Multi-dimensional Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: End-users are not defined but local authorities and emergency planners could use the outcomes of this study	Vulnerability is defined as the level of potential damage (0–1) to a given exposed element which is subject to a possible or real phenomenon of a given intensity	The potential damage level for different elements at risk is given in a table without being explained or connected with different process intensities
27	Liu and Lei (2003)	Type of disaster: Debris flow Scale: Regional Location: China Research domain: Natural science, Disaster management Focus: Multi-dimensional physical, economic, environmental Type of assessment: Quantitative Hazard dependant: NO Vulnerability curves: YES Possible end-users: Regional or central government	Vulnerability is defined as the potential total maximum loss due to a potential damaging phenomenon for a specific area and for a reference period	The approach can be used for funding allocation but due to its regional scale and the difficulty of the data to be collected on a local scale, cannot be used in a local scale

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
28	Macquarie et al. (2004)	Type of disaster: Landslides Scale: Local Location: Barcelonette, Southeast France Research domain: Natural Sciences Focus: Buildings and people Type of assessment: Qualitative Hazard dependant: NO Vulnerability curves: NO Possible end-users: Local authorities	A vulnerability definition is not given. Vulnerability is considered to be related with the interaction between the exposed element and the landslide phenomenon	The methodology has not been validated, and it has been only been tested on a specific built-up environment (ski resort)
29	Mavrouli and Corominas (2008)	Type of disaster: Rock falls Scale: Local Location: Andorra Research domain: Engineering Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Engineers, building owners	No definition for vulnerability is given, it is however considered to be the structural damage of the building following a rock fall	The methodology is designed for individual buildings, it is however difficult to be applied on a larger number of buildings
30	Mejia-Navarro et al. (1994)	Type of disaster: Subsidence, rock falls, debris flows and floods Scale: Local Location: Colorado, USA Research domain: Earth Science Focus: Ecosystem, economic and social structure vulnerability Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Urban planners, local authorities	Vulnerability is defined as the intrinsic predisposition of any element to be at risk of a mental or economic loss upon the occurrence of a hazardous event of intensity *i*	In the calculation of the vulnerability the condition or the construction type of building is not taken into consideration. No final vulnerability map is provided

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
31	Meyer et al. (2009)	Type of disaster: Floods Scale: regional Location: River Mulde, Germany Research domain: Natural science, engineering Focus: Economical, ecological and social risk Type of assessment: Qualitative & quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Local authorities and engineers	Damaged share of the total value of the assets, depending on inundation depth	The results are very dependant on the criteria chosen and the weights given to the different criteria
32	Michael-Leiba et al. (2003)	Type of disaster: Debris flow Scale: Regional Location: Cairns, Australia Research domain: Natural science, disaster management Focus: People, buildings and roads Type of assessment: Quantitative Hazard dependant: YES (type of disaster) Vulnerability curves: NO Possible end-users: Emergency planners, local authorities	The vulnerability is considered the probability of death or destruction given that a landslide hit the residence or road	The methodology assumes that vulnerability is independent of landslide magnitude
33	Papathoma-Köhle et al. (2007)	Type of disaster: Landslides Scale: Local Location: Germany Research domain: Natural sciences, civil protection Focus: Buildings Type of assessment: Quantitative Hazard dependant: NO Vulnerability curves: NO Possible end-users: Local authorities, public, civil protection services, insurance companies	No vulnerability definition is given but vulnerability is considered a dynamic element that should be assessed by taking into consideration temporal and spatial aspects	The methodology is based on pre-existing landslide susceptibility maps that in some cases might be difficult to obtain and in others their quality can be questionable. The method is also time-consuming, as most of the data have to be collected on site for each house. Therefore, the methodology cannot be applied on large areas

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
34	Romang (2004)	Type of disaster: Floods and debris flow Scale: Local Location: Switzerland Research domain: Natural science, engineering Focus: Buildings Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Local authorities	Vulnerability is defined according to the insurance sector as follows: Vulnerability = insured damage/insured value of the building	Only the value of the building is taken into consideration and not its shape, construction material, condition and other indicators that influence its vulnerability
35	Santos (2003)	Type of disaster: Landslides Scale: Local Location: Regua, Portugal Research domain: Physical Geography, land use planning Focus: Human life Type of assessment: Qualitative Hazard dependant: NO Vulnerability curves: NO Possible end-users: Land use planners	Although the author quotes the definition of Varnes (1984), considering vulnerability as the degree of loss, he also quotes IUGS Working Group on Landslides (1997), suggesting that when human life is involved vulnerability should calculated as a function of the probability of loss of human life and where only material damage is considered vulnerability should be the function of the monetary value of the elements at risk	The material or condition of the buildings is not taken into consideration. No final map for vulnerability is provided. A vulnerability zonation map is provided based on categories of functional spaces
36	Shrestha (2005)	Type of disaster: Landslides and floods Scale: Regional Location: Nepal Research domain: Natural and social science Focus: Physical and socio-economic vulnerability Type of assessment: Qualitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Government, public and private organisations, NGOs, the community, insurance companies	Vulnerability is the degree to which a system is likely to experience harm to its exposure to hazard (Turner II et al. 2003). It is determined by the capacity of a system to anticipate, cope with, resist, and recover from the impact of hazard (Blaike et al. 2004)	The indicators used for the physical vulnerability to floods and landslides were not clear. The regional scale of the study is not appropriate to use for emergency management

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
37	Sterlacchini et al. (2007)	Type of disaster: Debris flow Scale: Local Location: Italy Research domain: Natural science Focus: Built-up areas, infrastructure, Socio-economic features of the area Type of assessment: Qualitative Hazard dependant: NO Vulnerability curves: NO Possible end-users: Public administrators, economic planners, building managers and owners, lawmakers, civil protection and emergency services	No definition of vulnerability is given but vulnerability corresponds to the physical effects (aesthetic, functional and structural damage) due to the impact of a damaging event	It is not clear which attributes of the buildings located in the hazardous area have been taken into consideration in order to assess their vulnerability. There is no map showing vulnerability's spatial pattern
38	Uzielli et al. (2008)	Type of disaster: Landslides Scale: Local Location: - Research domain: Natural science, engineering Focus: Built environment Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Emergency planners, local authorities	Vulnerability V is defined in terms of both the landslide intensity I and of the susceptibility S of the elements at risk. $V = I \times S$	The method is too sophisticated and the data difficult to collect especially for larger areas
39	Wilhelm (1997)	Type of disaster: Snow avalanches Scale: Local Location: Switzerland Research domain: Natural science, economics Focus: Buildings, people, traffic lines Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Regional and local authorities, civil engineers, insurance companies	The authors do not give any definition of vulnerability. The degree (or susceptibility) of loss (from 0 to 1) is part of the calculation for the damage potential	The degree of loss is more an estimation due to only few detailed event analyses

Table 3 continued

	Authors (year)	General info	Vulnerability definition used	Gaps and difficulties of the method
40	Zezere et al. (2008)	Type of disaster: Landslides Scale: Local Location: Lisbon, Portugal Research domain: Natural science, geography Focus: Buildings and roads Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: NO Possible end-users: Local authorities, emergency services, insurance companies	Vulnerability is considered as the degree of loss. It depends not only on the structural properties of the exposed elements but also on the type of process and its magnitude, this is why it cannot be defined in absolute terms but only with respect to a specific process	For the vulnerability of the buildings, only the construction type of the building is taken into consideration. The vulnerability to translational and rotational slides is 1 (total loss) for all the types of buildings. No map of vulnerability is provided
41	Zhai et al. (2006)	Type of disaster: Floods Scale: regional Location: Japan Research domain: Natural science, engineering, planning Focus: People Type of assessment: Quantitative Hazard dependant: YES Vulnerability curves: YES Possible end-users: Emergency managers: efficiency of warnings and other emergency response measures	"Social vulnerability refers to population, land use, systems for warning, emergency assistance, preparedness, and so on"	Only the indicator 'inundated buildings' is taken into account for the prediction of the probability of fatality or injury. The effect of evacuation behaviour, natural and socioeconomic characteristics were not yet considered

References

Akbas SO, Blahut J, Sterlacchini S (2009) Critical assessment of existing physical vulnerability estimation approaches for debris flows. In: Malet JP, Remaitre A, Bogaard T (eds) Proceedings of landslide processes: from geomorphologic mapping to dynamic modelling. Strasburg, France, 6–7 February 2009, pp 229–233

Alexander D (2005) Vulnerability to landslides. In: Glade T, Anderson M, Crozier M (eds) Landslide hazard and risk. Wiley, Chichester, UK, pp 175–198

Barbolini M, Cappabianca F, Sailer R (2004) Empirical estimate of vulnerability relations for use in snow avalanche risk assessment. In: Brebbia CA (ed) Risk analysis, IV. WIT Press, Southampton, pp 533–542

Barredo J (2007) Major flood disasters in Europe: 1950–2005. Nat Hazards 42:125–148

Bell R, Glade T (2004) Quantitative risk analysis for landslides - Examples from Bildudalur, NW-Iceland. Nat Hazards Earth Syst Sci 4:117–131

Bertrand D, Naaim M, Brun M (2010) Physical vulnerability of reinforced concrete buildings impacted by snow avalanches. Nat Hazards Earth Syst Sci 10:1531–1545

BFF, SLF (Bundesamt für Forstwesen, Eidgenössisches Institut für Schnee- und Lawinenforschung) (1984) Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten. Bundesamt für Forstwesen, Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos und Bern

Birkmann J (2006) Indicators and criteria for measuring vulnerability: Theoretical bases and requirements. In: Birkmann J (ed) Measuring Vulnerability to Natural Hazards. United Nations University Press, pp 55–77

Blaikie P, Cannon T, Davis I, Wisner B (1994) At Risk, Natural Hazards, People's Vulnerability and Disasters. Routledge Press, London, p 284

Blöchl A, Braun B (2005) Economic assessment of landslide risks in the Schwabian Alb, Germany -research framework and first results of homeowners and experts surveys. Nat Hazards Earth Syst Sci 5:389–396

Bohle HG, Glade T (2007) Vulnerabilitätskonzepte in Sozial- und Naturwissenschaften. In: Felgentreff C, Glade T (eds) Naturrisiken und Sozialkatastrophen, pp 99–119

Brooks N (2003) Vulnerability risk and adaptation: a conceptual framework, Tyndall Centre for Climate Change Research. Working paper 38:1–16

Bründl, M. (Editor), 2009. Risikokonzept für Naturgefahren. Einzelprojekt A1.1: Leitfaden. Nationale Plattform Naturgefahren PLANAT, Bern, p 420. http://www.planat.ch/ressources/planat_product_de_1110.pdf)

Bründl M, Romang HE, Bischof N, Rheinberger CM (2009) The risk concept and its application in natural hazard risk management in Switzerland. Nat Hazards Earth Syst Sci 9(3):801–813

Bründl M, Bartelt P, Schweizer J, Keiler M, Glade T (2010) Snow avalanche risk analysis—review and future challenges. In: Alcantara-Ayla I, Goudie A (eds) Geomorphological hazards and disaster prevention. Cambridge University Press, Cambridge, pp 49–61

Büchele B, Kreibich H, Kron A, Thieken A, Ihringer J, Oberle P, Merz B, Nestmann F (2006) Flood-risk mapping: contributions towards and enhanced assessment of extreme events and associated risks. Nat Hazards Earth Syst Sci 6:485–503

BUWAL (Bundesamt für Umwelt, Wald und Landschaft) (1999a) Risikoanalyse bei gravitative Naturgefahren: Methode, Umweltmaterialen No 107/1 Naturgefahren, p 115

BUWAL (Bundesamt für Umwelt, Wald und Landschaft) (1999b) Risikoanalyse bei gravitative Naturgefahren: Fallbeispiele und Daten, Umweltmaterialen No 107/2 Naturgefahren, p 129

BUWAL, BWW, BRP (Bundesamt für Umwelt, Wald und Landschaft, Bundesamt für Wasserwirtschaft, Bundesamt für Raumplanung) (1997) Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten. Bundesamt für Umwelt, Wald und Landschaft, Bundesamt für Wasserwirtschaft, Bundesamt für Raumplanung, Bern und Biel

BWW, BRP, BUWAL (Bundesamt für Wasserwirtschaft, Bundesamt für Raumplanung, Bundesamt für Umwelt, Wald und Landschaft) (1997) Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten. Bundesamt für Wasserwirtschaft, Bundesamt für Raumplanung, Bundesamt für Umwelt, Wald und Landschaft, Biel und Bern

Cappabianca F, Barbolini M, Natale L (2008) Snow avalanche risk and mapping: a new method based on a combination of statistical analysis, avalanche dynamics simulation and empirically based vulnerability relations integrated in a GIS platform. Cold Reg Sci Technol 54:193–205

Cardinali M, Reinbach P, Guzzetti F, Ardizzone F, Antonini G, Galli M, Cacciano M, Castellani M, Salvati P (2002) A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy. Nat Hazards Earth Syst Sci 2:57–72

CENAT (2004) Monte Verità Workshop 2004, Coping with Risks due to Natural Hazards in the 21st Century, 28 November 2004–03 December 2004, GLOSSARY, http://www.cenat.ch/index.php?navID=824&userhash=41529&I=e

Corominas J, Copons R, Moya J, Vilaplana JM, Altimir J, Amigo J (2005) Quantitative assessment of the residual risk in a rockfall protected area. Landslides 2:343–357

Crozier MJ (1999) Slope instability: landslides. In: Alexander D, Fairbridge RW (eds) Encyclopaedia of environmental science. Dordrecht, pp 561–562

De Lotto P, Testa G (2000) Risk assessment: a simplified approach of flood damage evaluation with the use of GIS. Interpraevent 2:281–291

Deutsche Rück (1999) Das Pfingsthochwasser im Mai 1999. Deutsche Rückversicherung AG

Douglas J (2007) Physical vulnerability modelling in natural hazard risk assessment. Nat Hazards Earth Syst Sci 7:283–288

Dutta D, Herath S, Musiake K (2003) A mathematical model for flood loss estimation. J Hydrol 277:24–49

ER NZI (2004) Economic impacts on New Zealand of climate change-related extreme events. Focus on fresh-water floods. New Zealand Climate Change Office, New Zealand

Fell R, Hartford D (1997) Landslide risk management. In: Dikau R, Brunsden D, Schrott L, Ibsen M-L (eds) Landslide recognition. Identification, movement and causes. Wiley, Chichester p. 251

FEMA (2007) Multi-hazard loss estimation methodology: flood model. HAZUS-MH MR3. Department of Homeland Security, Federal Emergency Management Agency, USA

Fuchs S (2009) Susceptibility versus resilience to mountain hazards in Austria—paradigms of vulnerability revisited. Nat Hazards Earth Syst Sci 9:337–352

Fuchs S, Heiss K, Hübl J (2007) Towards an empirical vulnerability function for use in debris flow risk assessment. Nat Hazards Earth Syst Sci 7:495–506

Galli M, Guzzetti F (2007) Landslide vulnerability criteria: a case study from Umbria, Central Italy. Environ Manage 40:649–664

Glade T (2003) Vulnerability assessment in landslide risk analysis. Die Erde 134:123–146

Glade T, Crozier M (2005) The nature of landslide hazard impact. In: Glade T, Anderson M, Crozier M (eds) Landslide hazard and risk. Wiley, Chichester, pp 43–74

Greenaway MA, Smith DI (1983) ANUFLOOD field guide. Centre of Resource and Environmental Studies, Australian National University, Canberra

Grünthal G, Thieken A, Schwarz J, Radtke K, Smolka A, Merz B (2006) Comparative risk assessment for the city of Cologne—storms, floods, earthquakes. Nat Hazards 38:21–44

Hollenstein K (2005) Reconsidering the risk assessment concept: standardizing the impact description as a building block for vulnerability assessment. Nat Hazards Earth Syst Sci 5:301–307

Hollenstein K, Bieri O, Stückelberger J (2002) Modellierung der Vulnerabilität von Schadobjekten gegenüber Naturgefahrenprozessen. ETH Zürich, Forstliches Ingenieurwesen

Höller P (2007) Avalanche hazards and mitigation in Austria: a review. Nat Hazards 43:81–101

Holub M, Fuchs S (2009) Mitigating mountain hazards in Austria—legislation, risk transfer, and awareness building. Nat Hazard Earth Syst Sci 9:523–537

Holub M, Hübl J (2008) Local protection against mountain hazards—state of the art and future needs. Nat Hazard Earth Syst Sci 8:81–99

Hooijer A, Li Y, Kerssens P, Van der Vat M, Zhang J (2001) Risk assessment as a basis for sustainable flood management. 29th Annual congress of the international-association-of-hydraulic-engineering-and-research (IAHR), Bejing, China, pp 442–449

Hufschmidt G, Crozier M, Glade T (2005) Evolution of natural risk: research framework and perspectives. Nat Hazard Earth Syst Sci 5:375–387

IUGS (1997) Quantitative risk assessment for slopes and landslides-the state of the art. In: Cruden DM, Fell R (eds) Landslide risk assessment. Roterdam, Balkema, pp 3–12

Iverson MR (1997) The physics of debris flows. Rev Geophys 35(3):245–296

Jonasson K, Sigurosson S, Arnalds P (1999) Estimation of avalanche risk. Vedurstofu Islands n. R99001-ur01, p 44

Kang JL, Su MD, Chang LF (2005) Loss functions and framework for regional flood damage estimation in residential area. J Mar Sci Technol 13:193–199

Kaynia AM, Papathoma-Köhle M, Neuhäuser B, Ratzinger K, Wenzel H, Medina-Cetina Z (2008) Probabilistic assessment of vulnerability to landslide: application to the village of Lichtenstein, Baden-Württemberg, Germany. Eng Geol 101:33–48

Keiler M (2004) Development of the damage potential resulting from the avalanche risk in the period 1950–2000, case study, Galtür. Nat Hazard Earth Syst Sci 4:249–256

Keiler M, Sailer R, Jörg P, Weber C, Fuchs S, Zischg A, Sauermoser S (2006) Avalanche risk assessment—a multi-temporal approach, results from Galtür, Austria. Nat Hazard Earth Syst Sci 6:637–651

Keiler M, Knight J, Harrison S (2010) Climate change and geomorphological hazards in the eastern European Alps. Philos Trans R Soc A 368:2461–2479

Kelman I, Spence R (2004) An overview of flood actions on buildings. Eng Geol 73:297–309

Keylock CJ, Barbolini M (2001) Snow avalanche impact pressure-vulnerability relations for use in risk assessment. Can Geotech J 38:227–238

Leone F, Aste JP, Leroi E (1996) Vulnerability assessment of elements exposed to mass-movement: working toward a better risk perception. In: Senneset K (ed) Landslides. Balkema, Rotterdam, pp 263–270

Liu X, Lei J (2003) A method for assessing regional debris flow risk: an application in Zhaotong of Yunnan province (SW China). Geomorphology 52:181–191

Macquarie O, Thiery Y, Malet JP, Weber C, Puissant A, Wania A (2004) Current practices and assessment tools of landslide vulnerability in mountainous basins-identification of exposed elements with a semi-automatic procedure. In: Lacerda WA, Ehrlich M, Fontoura SAB, Sayao ASF (eds) Landslides: evaluation and stabilisation. Taylor and Francis Group, London, pp 171–176

Mavrouli O, Corominas J (2008) Structural response and vulnerability assessment of buildings in front of the rock fall impact, Geophysical Research Abstract 10

McClung D, Schaerer P (1993) The avalanche handbook. The Mountaineers, Seattle, p 271

Mejia-Navarro M, Wohl LEE, Oaks SD (1994) Geological hazards, vulnerability, and risk assessment using GIS: model for Glenwood Springs, Colorado. Geomorphology 10:331–354

Merz B, Kreibich H, Thieken A, Schmidtke R (2004) Estimation uncertainty of direct monetary flood damage to buildings. Nat Hazards Earth Syst Sci 4:153–163

Merz B, Kreibich H, Schwarze R, Thieken A (2010) Review article “Assessment of economic flood damage”. Nat Hazards Earth Syst Sci 10:1697–1724

Messner F, Meyer V (2005) Flood damage, vulnerability and risk perception—challenges for flood damage research. UFZ Discussion Paper. Umweltforschungszentrum Leipzig, Halle

Meyer V, Scheuer S, Haase D (2009) A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany. Nat Hazards 48:17–39

Michael-Leiba, Baynes F, Scott G, Granger K (2003) Regional landslide risk to the cairns community. Nat Hazards 30:233–249

Middelmann-Fernandes M (2010) Flood damage estimation beyond stage-damage functions: an Australian example. J Flood Risk Manage 3:88–96

Papathoma-Köhle M, Neuhäuser B, Ratzinger K, Wenzel H, Dominey-Howes D (2007) Elements at risk as a framework for assessing the vulnerability of communities to landslides. Nat Hazards Earth Syst Sci 7:765–779

Romang H (2004) Wirksamkeit und Kosten von Wildbach-Schutzmassnahmen.Verlag des Geographischen Instituts der Universität Bern, p 212

Santos JG (2003) Landslide susceptibility and risk maps of Regua (Douro basin, NE Portugal). In: Proceeding of the IAG and IGU-C12 Regional Conference “Geomorphic hazards; towards the prevention of disasters”, Mexico City, Mexico

Shrestha A (2005) Vulnerability assessment of weather disasters in Syangja District, Nepal: a case study in Putalibazaar Municipality, Advances Institute on Vulnerability to Global Environmental Change

Spichtig S, Bründl M (2008) Verletzlichkeit bei gravitativen Naturgefahren—eine Situationsanalyse. Projekt B5. Schlussbericht. Nationale Plattform Naturgefahren PLANAT, Bern

Sterlacchini S, Frigerio S, Giacomelli P, Brambilla M (2007) Landslide risk analysis: a multi-disciplinary methodological approach. Nat Hazards Earth Syst Sci 7:657–675

Thieken A, Merz B, Grünthal G, Schwarz J, Radtke K, Smolka A, Gocht M (2005) A comparison of storm, flood and earthquake risk for the city of Cologne, Germany. In: Proceedings of the 1st ARMONIA conference, Barcelona, Spain

Turner II BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003) A framework for vulnerability analysis in sustainability science. In: Proceedings of the national academy of sciences, 100(14)

UNDHA (1992) Internationally agreed glossary of basic terms related to disaster management. United Nations Department of Humanitarian Affairs

UNDRO (1984) Disaster prevention and mitigation—a compendium of current knowledge, vol 11. Preparedness Aspects, New York

Uzielli M, Nadim F, Lacasse S, Kaynia AM (2008) A conceptual framework for quantitative estimation of physical vulnerability to landslides. Eng Geol 102:251–256

Varnes D J (1984) Landslide hazard zonation: a review of principles and practice. Natural Hazards, 3, Paris, UNESCO, p 63

Weichselgartner J (2001) Disaster mitigation: the concept of vulnerability revisited. Disaster Prevent Manage 10(2):85–94

White G (1945) Human adjustment to floods—a geographical approach to the flood problem in the United States. Research Paper No. 29. University of Chicago, USA

Wilhelm C (1997) Wirtschaftlichkeit im Lawinenschutz, Mitteilungen des Eidgenossisches Institut für Schnee- und Lawinenforschung, 54, Davos

WMO (1999) Comprehensive risk assessment for natural hazards. Technical document, no. 955. World Meteorological Organisation

Zezere JL, Garcia RAC, Oliveira SC, Reis E (2008) Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal). Geomorphology 94:467–495

Zhai G, Fukozono T, Ikeda S (2006) An empirical model of fatalities and injuries due to floods in Japan. J Am Water Resour As 42:863–875

A.3. Assessment of debris-flow susceptibility at medium-scale in the Barcelonnette Basin, France

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Natural Hazards and Earth System Sciences

Assessment of debris-flow susceptibility at medium-scale in the Barcelonnette Basin, France

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Abstract. Debris flows are among the most dangerous processes in mountainous areas due to their rapid rate of movement and long runout zone. Sudden and rather unexpected impacts produce not only damages to buildings and infrastructure but also threaten human lives. Medium- to regional-scale susceptibility analyses allow the identification of the most endangered areas and suggest where further detailed studies have to be carried out. Since data availability for larger regions is mostly the key limiting factor, empirical models with low data requirements are suitable for first overviews. In this study a susceptibility analysis was carried out for the Barcelonnette Basin, situated in the southern French Alps. By means of a methodology based on empirical rules for source identification and the empirical angle of reach concept for the 2-D runout computation, a worst-case scenario was first modelled. In a second step, scenarios for high, medium and low frequency events were developed. A comparison with the footprints of a few mapped events indicates reasonable results but suggests a high dependency on the quality of the digital elevation model. This fact emphasises the need for a careful interpretation of the results while remaining conscious of the inherent assumptions of the model used and quality of the input data.

1 Introduction

"Debris flows are churning, water-saturated masses of fine sediment, rocks and assorted detritus that originate on mountain slopes and course down-stream channels when they reach valley floors" (Iverson and Denlinger, 2001, p. 1). They flow "as a single-phase system" and "look like mudslides and landslides except that their velocity and the distances they travel are much larger" (Ancey, 2001, p. 529). According to the origin of the material, debris flows can be classified into slope and gully debris flows (Glade, 2005). Their velocity, the frequently long distances between the source area and the deposition zone and the often apparent insignificance of the source volume, which increases manifold during the runout, make them one of the most dangerous natural hazards occurring in the mountainous environment. They affect not only built-up areas and infrastructure but also threat human lives (Hofmeister et al., 2002). For the management and reduction of risk posed by debris flows, analyses identifying the areas at hazard by debris flows and describing the threat play an important role. According to the purpose of the analyses, the extent of the studied area and the data availability, the analysis scale is chosen (Aleotti and Chowdhury, 1999): regional, medium or local (single slope). Medium-scale analyses, which include according to van Westen et al. (2006) the range between 1:10 000 and 1:50 000, provide an initial overview of a certain area identifying all potentially unstable areas as far as possible and the down-slope regions probably affected by the flow. Usually they are not used as the basis for final decisions but rather serve, as in the case of Hofmeister and Miller (2003), as initial screens for potential impacts and they offer an indication where further local studies should be carried out. Debris-flow analyses are often split into two steps, (a) the identification of potential sources and (b) the estimation of the runout. For both steps a variety of methods is available:

(a) Heuristically potential sources can be identified as in Benda and Cundy (1990) or Chau and Lo (2004) in the field and on aerial photographs. Statistical

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methods linking a variety of environmental factors contributing to possible instabilities to an inventory of past events are very well-established for the source identification at smaller scales (van Westen et al., 2006). The models are either based on bivariate (Guinau et al., 2007; Blahut et al., 2010; Melelli and Taramelli, 2004) or multivariate statistics (Carrara et al., 2008). Horton et al. (2008) use a methodology for the source identification based on empirical rules. By means of a combination of environmental parameters chosen on the basis of experience, primarily slope angle, upslope area and planar curvature, the debris-flow susceptibility is computed. For physically-based source identification a common option is to couple hydraulic models with the calculation of the safety factor (Delmonaco et al., 2003; Carrara et al., 2008).

(b) While for the source identification statistical models play a dominant role, empirical relationships and formulae are well-established for the runout computation: the *Fahrböschung* (Heim, 1932) translated to *angle of reach* (Corominas, 1996) describes the angle between the horizontal and a line connecting the most distal point of deposition with the upper limit of the source area, along the path. This concept enables the estimation of the maximum runout distance if the source area is known. In many cases the angle of reach is expressed as a function of the debris-flow volume (Hürlimann et al., 2008) as in the formulas proposed by Corominas (1996) and Rickenmann (1999). Prochaska et al. (2008) developed the average channel slope model predicting the *runout angle*, which is the angle between the horizontal and a line between the vertical midpoint of the elevation difference between source area and fan apex and the most distal deposition. Rickenmann (1999) presents a formula predicting the runout distance on the fan as a function of the debris-flow volume. Several other studies associate the volume with the deposition area of the flow as Iverson et al. (1998) or Scheidl and Rickenmann (2010). So far, only a few physically-based runout models have been applied on a medium-scale due to calibration difficulties. Chau and Lo (2004) adjusted a physically-based runout model to one recorded event including friction and erosion and computed the potential runout of several unstable areas on the basis of this adjustment.

While deterministic approaches are very well transferable to basically any site since they consider the physical characteristics of the process, they are characterised by rather high data requirements for the calibration. Statistical models are based on extensive inventories of past events and are, apart from the reliance on good records, only transferable to a very limited extent. This is a consequence of frequent inclusion of indirect parameters as elevation, aspect etc. since these parameters cause very different effects in distinct areas. Empirical models offer an alternative in the case of general low data availability. Empirical models in this study are understood as general rules and relations which are established once on the basis of large datasets and are afterwards usable without the high data needs for calibration deterministic models have. An example is the concept of *Fahrböschung* according to (Heim, 1932), for more detail refer to the description at the end of the Sect. 3.1. In contrast to statistical models, empirical rules and relations are not based on indirect parameters but on parameters directly linked to physical characteristics. Due to the degree of generalisation from the data on which empirical models were created, they are rather well transferable. If quite similar environmental conditions can be assumed, even calibration parameters can be transferred to a certain extent. A first overview over a relatively unknown area can thus be conducted without many records of past events and detailed environmental information for the model calibration. The simplicity of empirical models is their major advantage and disadvantage, since specific characteristics in single cases cannot be accounted for (Hürlimann et al., 2008). For a debris-flow susceptibility analysis of the Barcelonnette Basin, located in the southern French Alps, an empirical methodology after Horton et al. (2008) was used.

The Barcelonnette Basin is prone to debris-flows. One of the recent damaging events was the debris flow in the Faucon torrent in 2003 which affected six houses as well as the main road crossing the valley (R.D. 900) and led to its closure for several hours (Remaître, 2006; Remaître and Malet, 2010). Even though information on a number of events may exist, records indicating source areas are missing and impede the calibration of a statistical model. Likewise, in-depth information on environmental parameters, indispensible for the calibration of regional deterministic models, is missing and leads to the selection of an empirical model. The methodology applied in this study, consists of empirical rules for source identification and empirical relations for the modelling of the runout on a medium to regional scale. Runout refers in this article to the complete 2-D pathway of the debris flow from source to deposition area. An analysis aiming at a preliminary worst-case[1] debris-flow susceptibility identification was carried out. In a further step the applicability of the methodology for scenario analyses was also investigated, estimating areas of high, medium and low susceptibility. Both analysis-types, worst-case and qualitative scenarios, were evaluated qualitatively on the basis of a set of recorded events.

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[1] Worst-case scenario refers to a very low-frequency and rather high-magnitude event.

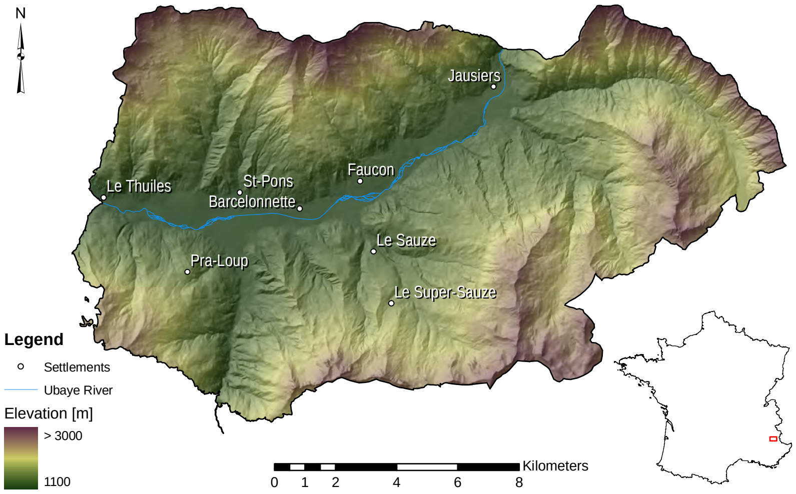

Fig. 1. Hillshade of the Barcelonnette Basin (Southern French Alps) with the location of the most important human settlements and the Ubaye River.

2 The Barcelonnette Basin

The Barcelonnette Basin is located in the dry intra-Alpine zone and extends from 1100 to 3000 m a.s.l. (Fig. 1). It is characterised by (1) a mountain climate with a marked inter-annual rainfall variability (735 ± 400 mm over the period 1928–2004) and 130 days of freezing per year, (2) a continental influence with significant daily thermal amplitudes ($> 20°$) and numerous freeze-thaw cycles and (3) a Mediterranean influence with summer rainstorms yielding more than 50 mm h^{-1} on occasion (Maquaire et al., 2003; Flageollet et al., 1999). Heavy spring rains on melting thick snow layers also lead to high discharges (Flageollet et al., 1999). Meso-climatic differences on a small scale emerge due to the east-west orientation of the valley (Remaître, 2006).

The valley is drained by the Ubaye River which is fed by several torrents on the north- and south-facing slopes. It constitutes a geological window, baring the autochthonous Callovo-Oxfordian black marls, also called 'Terres Noires', under the allochthonous Autapie and Parpaillon flysch (Maquaire et al., 2003). Local slopes are characterised by a specific morphology due to the geological setting:

(a) In the upper part (1900–3000 m a.s.l.), slopes are steeper than 45° and consist of thrust sheets of cataclastic calcareous sandstones. These slopes are often covered by non-consolidated debris varying in thickness between 0.5 and 5 m. Several debris tracks are affecting these slopes.

(b) The gentle slopes (10–30°) of the lower part (1100–1900 m a.s.l.) consist of Callovo-Oxfordian black marls, mainly composed of fragile plates and flakes packed in a clayey matrix. Slopes are covered by various Quaternary deposits: thick talus slopes of poorly sorted debris, moraine deposits and landslide debris. The high erosion susceptibility of the black marls promotes badland formation.

This geological, structural and climatological setting gives rise to mass movements (Flageollet et al., 1999), active torrential streams and debris tracks (Remaître et al., 2005, 2008; Remaître and Malet, 2010). Moreover, the region suffered nearly complete deforestation during the 18th and 19th centuries, which increased the torrent activity. Reforestation and construction of check-dams was initiated in 1864 and since then, forest cover has been rising (Remaître and Malet, 2010). The collection of historical data in catalogues, newspapers, monographs, technical reports, bulletins and scientific papers for the period between 1850 and 2004 provides evidence of 561 torrential events. The type and quality of information collected, and the methodologies used to analyse the data are detailed in Flageollet et al. (1999) and Remaître (2006). The analysis indicates a dominance of flash floods with 461 recorded events while only 100 debris-flows (slope and gully) have been registered. The spatial distribution of historical debris-flows shows that they have occurred mainly in the torrents located on the south-facing slope of the Barcelonnette Basin. Indeed, about 75% of the debris-flow events were recorded in four torrents: Riou-Bourdoux, Sanières, Faucon and

Bourget. This has to be ascribed (1) to the location of springs in the transition between the permeable, coarse material of the Autapie thrust sheet and the Callovo-Oxfordian black marls below, (2) to the higher slope angle and (3) to the thicker morainic coverage on the south-facing slopes which gives rise to a higher material availability.

Further possible sources for debris flows are the three big mudslides of La Valette, Super-Sauze and Poche which have developed in the black marls. Having already produced several mudflows and debris-flow events in recent years, they pose a serious menace due to their high sediment volumes and mobility (Malet et al., 2004).

3 Method

3.1 The debris-flow modelling

The debris-flow modelling was carried out in two steps: (1) the identification of potential source areas and (2) the calculation of the runout. According to Takahashi (1981) and Rickenmann and Zimmermann (1993) the critical factors for debris-flow occurrence are sediment availability, water input and slope gradient. While sediment availability and slope gradient refer to the general disposition, the water input from precipitation and snow melt acts as a triggering factor. To represent these factors by area-wide available data the following inputs were chosen: the sediment availability is linked to the lithology since the debris production depends on the material characteristics and furthermore the slope shape influences the accumulation of material – the parameters lithology and planar curvature were included. The water input is strongly related to the upslope area in which precipitation and water from melting snow accumulate and so the parameter flow accumulation was implemented. The third factor, the slope gradient, is critical due to its influence on the shear strength of the soil and debris, respectively. Therefore, the parameter slope angle was integrated. Furthermore the land use/cover was considered since according to Ancey (2001) "[v]egetation reduces the initiation potential to a certain extent". Thus, the parameter land use/cover was incorporated. Each input parameter is entered as a raster into the modelling procedure. User-defined thresholds classify the pixels of the continuous data (e.g. slope, flow accumulation and planar curvature) as favourable for mobilisation (the pixels are marked *included* which indicates them as possible source) or inhibiting (the pixels are *excluded* from being a possible source) debris flow initiation. In the case of slope angle and upslope area a combined approach is applied as for example proposed in Rickenmann and Zimmermann (1993) or Heinimann et al. (1998): below a certain upslope area size threshold the slope angle is a function of the upslope area size and above the threshold the angle is constant (Fig. 2). Horton et al. (2008) propose two curves, the rare and the extreme fitting (Fig. 2). For upslope areas bigger than 2.5 km^2 both curves set the slope threshold at 15° (Takahashi, 1981) while smaller catchments are only considered as possible sources if the slope angle lies above the threshold function. The two equations are the following (Horton et al., 2008):

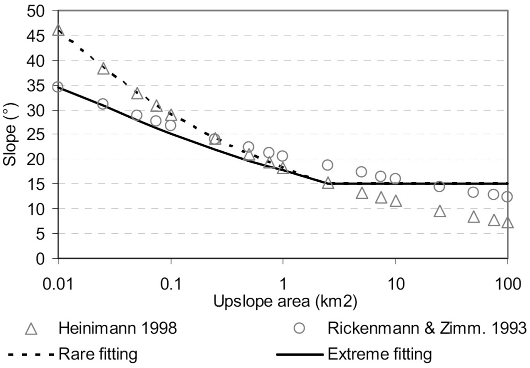

Fig. 2. Extreme and rare slope thresholds for debris-flow triggering with regard to the upslope area after Horton et al. (2008), considering Heinimann et al. (1998) and Rickenmann and Zimmermann (1993).

Rare events

$$\begin{cases} \tan\beta_{\text{lim}} = 0.32 \cdot S_{\text{UA}}^{-0.2} & \text{if} \quad S_{\text{UA}} < 2.5\,\text{km}^2 \\ \tan\beta_{\text{lim}} = 0.26 & \text{if} \quad S_{\text{UA}} \geq 2.5\,\text{km}^2 \end{cases} \tag{1}$$

Extreme events

$$\begin{cases} \tan\beta_{\text{lim}} = 0.31 \cdot S_{\text{UA}}^{-0.15} & \text{if} \quad S_{\text{UA}} < 2.5\,\text{km}^2 \\ \tan\beta_{\text{lim}} = 0.26 & \text{if} \quad S_{\text{UA}} \geq 2.5\,\text{km}^2 \end{cases} \tag{2}$$

with the slope gradient β_{lim} and the surface of the upslope contributing area S_{UA}. For the classified datasets land use/cover and lithology those classes prone to debris flows are designated as included as e.g. moranic deposits or excluded as possible source, such as built-up areas. Finally all classified spatial input parameters are combined and pixels being at least once determined as possible debris-flow source (included) and never excluded are assigned as sources.

In a second step the probabilitistic runout is calculated, starting from the previously determined sources and using two types of functions: flow direction and runout distance algorithms. It is a probabilistic propagation as it aims to incorporate every possible path with a notion of probability. Thus, it does not intend to process the spreading of a unique event, but to include all possible events. The flow direction algorithm defines the propagation of the flow from one cell to the surrounding neighbours starting with a source cell (Horton et al., 2008). A variety of algorithms is available: the D8 and D∞ algorithm of O'Callaghan and Mark (1984) and Tarboton (1997), respectively, which are restricted to one flow direction following the steepest downward slope. The multiple flow direction method (Quinn et al., 1991) and its modification (Holmgren, 1994) which spread the flow on a percentage basis over several neighbouring downslope pixels are more realistic. The modified multiple flow direction method after Holmgren (1994) is expressed by the following formula:

$$f_i = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}\left(\tan\beta_j\right)^x} \quad \text{for} \quad \tan\beta > 0 \tag{3}$$

with i, j = flow direction (1...8), f_i = flow proportion (1...0) in direction i, $tan\beta_i$ = slope gradient between the central cell and cell in direction i and x = variable exponent. For $x = 1$ the formula turns into the basic multiple flow direction method by Quinn et al. (1991) exhibiting a very wide spreading, while for higher x values the flow converges more and more and becomes a single direction flow for $x \longrightarrow \infty$ (O'Callaghan and Mark, 1984). In addition to the influence of the slope on the flow direction, the effect of any directional change is considered, in other words the inertia of the flow. In the modeling context this parameter is called *persistence* which is a weight defined as a function of the change in angle from the last flow direction. Thus the final probabilities are the combination of the spreading and the persistence (Horton et al., 2008).

The distance reached by the flow is computed with simple energy-based calculations not considering source masses since they are mostly unknown in first medium-scale analyses. The kinetic energy E_{kin} at the time step i is obtained by the following formula:

$$E^i_{\text{kin}} = E^{i-1}_{\text{kin}} + \Delta E^i_{\text{pot}} - E^i_{\text{loss}} \tag{4}$$

with ΔE^i_{pot} = the change in potential energy and E^i_{loss} = the constant loss. For the estimation of the energy loss, a constant friction loss angle referring to the *angle of reach* (*Fahrböschung*) concept (Heim, 1932; Corominas, 1996) is added. The angle of reach is defined as the angle between the horizontal and an imaginary line connecting source area and the end point of the flow along the flow path. This angle of reach is applied as a constant friction loss during the propagation from pixel to pixel. The flow stops as soon as the kinetic energy drops below zero. The procedure of runout calculation is performed for each source pixel and results in two products (output grids), the kinetic energy and the spatial probability. Where the flows originating from different sources overlap, either the maximum value or the sum of the spatial probabilities is computed. For the kinetic energy always the maximum value of overlapping flows is calculated.

Summarizing, this methodology enables a first assessment of the overall area possibly giving rise to debris-flows (source identification) and the area potentially affected by the debris-flow runout. Not single events but the sum of all possible incidences is estimated. This modelling approach was implemented in the Flow-R model which has been developed at the University of Lausanne (Horton et al., 2008) and is available on request at www.flow-r.ch.

3.2 Data acquisition

3.2.1 Distributed data

A digital elevation model (DEM) with a resolution of 10 m was calculated on basis of the digitised contour lines and breaklines of channels of the 1:10 000 topographic maps from IGN (Institut Géographique National). Scanning and georeferencing of the maps have been carried out by Thiery et al. (2007) and the interpolation was realised with the software program SURFER using a kriging method and the semivariogram elaborated by Thiery (2006). The resulting DEM was smoothened by 9-nodes averaging, the sinks were filled and flow accumulations as well as planar curvature were derived. On basis of the aerial photographs of 2004 the land use was digitised and classified into dense coniferous forest, coniferous forest of average to low density, deciduous forest, natural grassland, arable land/permanent crops, pastures, bare rock, bare soil, urban areas, mining sites, water courses and marshes and water bodies (Bordonné, 2008). The information on the lithology was digitised from the geological map (1:50 000) and converted into a raster file with 10-m resolution as the DEM, constituting the following ten classes: marls, torrential alluvium, limestone, boulder fields, talus slopes, flysch, gypsum, lacustrine deposits, calcareous marls and moraines (Bordonné, 2008).

Although the resolution of the geological map is rather low, this information was included due to the importance within the modelling procedure. A possible option to cope with small-scale input is according to Bell and Glade (2004) the display of the final result in accordance to the scale of the least detailed input. We complied with this principle by preparing the resulting maps at a scale lower than 1:50 000.

3.2.2 Inventory data

A first inventory comprises the envelopes (polygons) of the deposition of the debris-flow events observed in 1996, 2002 and 2003 at the Faucon, Sanières and Bourget torrents based on post-event field observations (Remaître, 2006). The inventory is later on included in Fig. 6. A second debris-flow inventory using aerial photograph interpretation was compiled by Stummer (2009). By means of comparison of each two consecutive aerial photographs of the years 1956, 1974, 1982, 1995, 2000 and 2004, debris flows which had happened in each of the periods were visually identified and digitised. This collection comprises mostly small events on steep slopes while bigger events flowing principally in the torrents are in most cases not identifiable. Furthermore, neither the source nor the deposition area could be identified for all events, thus we extracted only the digitized linear flow paths (lines) to be used in this study. The inventory covers only a part of the study area, and the Abriès catchment, for example, was not mapped. A drawback of this method is that very active torrents producing debris flows in each time step can not be identified since no differences are visible between the consecutive photographs (the inventory is later on included in Fig. 4). A third inventory contains the number of events per torrent/catchment between 1850 and 2004, compiled from archive investigation by Sivan (2000) and Remaître (2006). Geographically this information can only be linked to the respective torrent/whole catchment since no detailed information about source, runout and deposition is available. The three inventories were not merged into one overall inventory since they comprise very differing information (regarding type of information, resolution, shape etc.) but retained separately and used for distinct purposes as detailed in the following sections.

3.3 Model parameter determination

3.3.1 Source identification

For the first modelling step, the source identification, the three topographic parameters slope, flow accumulation and planar curvature were complemented by lithology and land use. Each parameter was implemented as 10-m raster into the model and the following criteria were applied for the classification of the single grid layers: the threshold for the size of the upslope area was considered in relation with the slope angle as explained in the model description and the extreme fitting (Fig. 2) was chosen since it allows, in contrast to the rare fitting, the identification of small and less steep sources, too, and matches the objective of worst-case scenario modelling well. The threshold for planar curvature was set to –2/100 m^{-1} according to the experience of Horton et al. (2008) in the Canton de Vaud, Switzerland.

All geological units but the limestone were included as potential source areas. This includes torrential deposits, moraines, boulder fields, marls and calcareous marls, talus slopes, lacustrine deposits, gypsum and flysch. Concerning land use, dense coniferous forest, deciduous forest, natural grassland, arable land/permanent crops, pastures, urban areas and mining sites were excluded and coniferous forest (average to low density), marshes and water bodies, bare rock and bare soil were included.

Finally, all pixels being at least once included and never excluded as possible source were designated as susceptible to debris flow initiation.

3.3.2 Runout

Worst-case scenario

To define the runout distance for the worst-case scenario the literature was revised for minimum values of angles of reach in debris-flow inventories and already existing estimates of worst-case angles: Huggel et al. (2002) established a worst-case angle of reach for debris flows resulting from glacier lake outbursts. Reviewing a number of cases in the European Alps and in Canada, they fitted a curve to the angle of reach as function of the maximum discharge and assessed a threshold angle of 11°. Zimmermann et al. (1997) studied a set of debris flows especially in the Swiss Alps and found a minimum angle of reach of $\sim 11°$ (20%) for coarse- and medium-grained and $\sim 7°$ (12%) for fine-grained debris flows. Prochaska et al. (2008) identified, reviewing a large quantity of investigations, a minimum angle of reach of 6.5°. Bathurst et al. (1997) mention a rule of thumb applied in Japan using an angle of about 11° (20%) according to T. Takahashi, personal communication, 1994. Rickenmann and Zimmermann (1993) mapped about 800 debris-flow events, triggered in the Swiss Alps during intense rainstorms in the summer of 1987 and identified a minimum angle of reach of nearly 11°. We chose the lowest angle found in the literature: $\sim 7°$ and added the angle of 11° since it was mentioned several times, including as result of a statistical analysis for the worst-case runout angle calculation (Huggel et al., 2002).

For the spreading of debris flows Holmgren (1994) proposes a range of x between 4 and 6 in the Eq. (3) and Claessens et al. (2005) and Horton et al. (2008) chose $x = 4$ for their debris-flow modelling (the lower the exponent the wider the spreading). However, since the objective is not to model a certain event realistically but to compute a worst-case scenario the widest spreading possible was applied choosing $x = 1$. Thus, the spreading is not representing a single event but covers the extent of all possible events.

Qualitative susceptibility scenarios

Apart from worst-case-runout-modelling the capability of the methodology to assess certain hazard scenarios was investigated, based on the following assumptions: according to Corominas (1996, p. 270 and 260) “the relative mobility increases with the volume of the landslide” and “[t]he angle of reach is found to be a proper indicator of the relative mobility of landslides” (the term *landslide* is used by Corominas (1996) for a range of processes and among them the debris flows). Corominas and Moya (2008, p. 198) link the different magnitudes with frequency: “it has been observed that large landslides are able to travel for longer distances than smaller ones. Should small and large landslides be produced in the source area, most of them would reach points located close to the source but only a small percentage – the largest landslides – would reach points located far away. Consequently, the observed temporal frequency of the landslide events will decrease with the distance from the landslide source. Frequency is, therefore, a spatially distributed parameter”. Thus it should be possible to define several magnitude- and frequency-scenarios, respectively, and to model them by means of

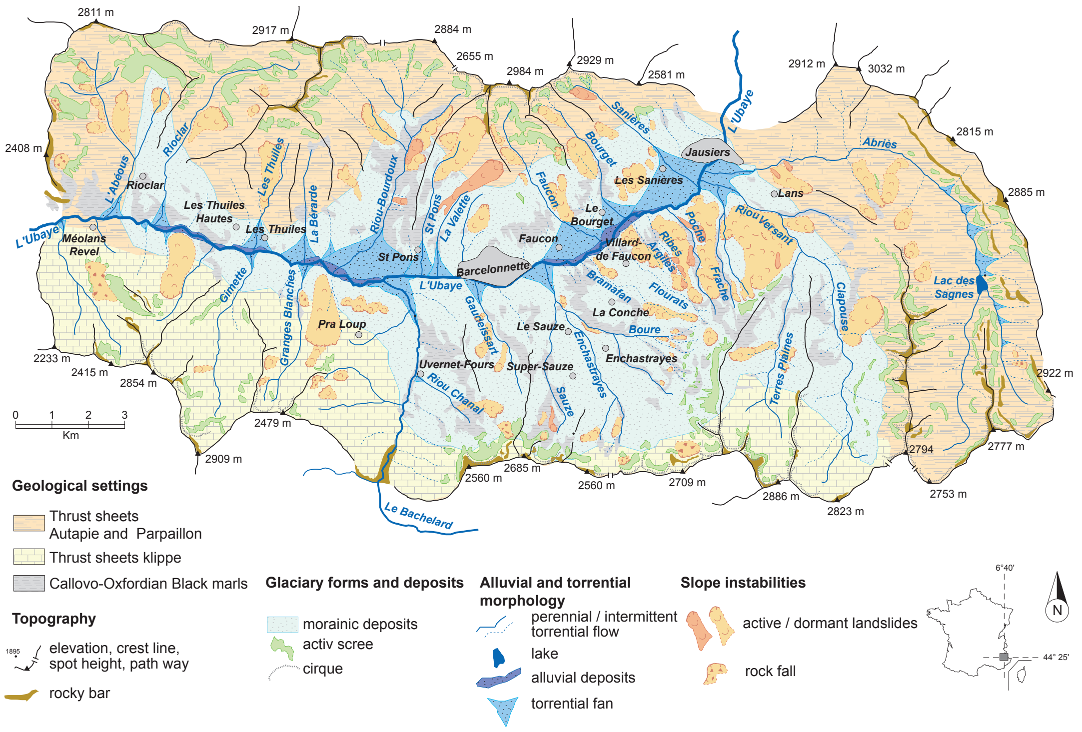

Fig. 3. Geomorphological map of the Barcelonnette Basin depicting the extent of the torrential fans, after Remaître (2006).

different angles of reach. Smallwood et al. (1997) cite a classification of Morgan et al. (1991) into small ($<50\,\mathrm{m}^3$), medium (50–$500\,\mathrm{m}^3$), large (500–$5000\,\mathrm{m}^3$) and very large ($>5000\,\mathrm{m}^3$) debris flows with angles of reach of 13.5°, 13.5°, 11° and 8°.

Since in the Barcelonnette Basin information on the volume and the corresponding angle of reach is available only for one event no analyses on volume – angle of reach relationships and no computation of magnitude-frequency scenarios could be carried out. However, a high potential was seen in the two spatial inventories available: in the aerial photograph interpretation (Stummer, 2009) a number of small debris flows has been identified and the number per time interval between two photographs indicates a relatively high frequency of several events per year in the study area, forming the basis for the high frequency scenario. The second spatial inventory, compiled by Remaître (2006), which consists of the debris-flow footprints of 1996, 2002 and 2003 on the fans of Sanières, Faucon or Bourget, indicates events of medium frequency which occur every few years and show a higher magnitude than the previous ones. These two constellations of high-frequency low-magnitude and medium-frequency medium-magnitude events were complemented by a third one for low-frequency high-magnitude on basis of the following assumption: the torrential fans (Fig. 3) are predominantly the result of debris-flow events, this means they were affected in the past and will possibly be affected in the future. Thus, the runout angle was iteratively adjusted and set as low as necessary to cover the length of the torrential fans (especially of those torrents described in the literature as very dangerous as e.g. the Riou Bourdoux) as far as the confluence with the Ubaye River.

Following the suggestion of Horton et al. (2008) to set the exponent in the spreading algorithm of Holmgren between 4 and 6 for debris flows, a value of 5 was chosen for all three scenarios. This is a less wide spreading than in the worst-case model (with an exponent of 1) for which an especially wide spreading was chosen. The fitting was done by modelling with several angles of reach and adjusting recalculations to adapt the model to the runout distance of the recorded events.

3.4 Assessment of the model performance

Beguería (2006) presents two main approaches for the validation of predictive models: confusion matrices for classified results and receiver-operating characteristics (ROC) for continuous results. With confusion matrices the modelling result is opposed to the recorded events resulting in four groups (Carranza and Castro, 2006): true positives (event observed and model identified the threat), true negatives (no event observed, no threat modelled), false positives (no event observed but model identified threat) and false negatives (event observed but no threat was modelled). The ROC curves oppose the false positive to the true positive rates by continuously changing the threshold used for the classification (Carrara et al., 2008). Due to the low availability of spatial information on past events only two measures were implemented: the sensitivity which is “the proportion of positive cases correctly predicted” and its opposite, the false negative rate which is “the proportion of false negatives in the total of positive observations” (Beguería, 2006, p. 321). The modelling results were furthermore evaluated in a qualitative way.

3.4.1 Source identification

The identified sources were visually compared with the aerial photograph inventory (Stummer, 2009) and the record of the debris flow of the Faucon catchment of 2003 (Remaître, 2006), where the source area had been mapped in the field. Furthermore, the percentage of source pixels per catchment was compared with the percentage of events which had happened between 1850 and 2004 in several catchments. Based on the assumption that catchments exhibiting a higher extension of unstable area produce more debris flows over time, the percentage of modelled source area was compared to the percentage of recorded events per catchment. An attempt was made to use the assumed relation for the validation of the modelling results.

3.4.2 Runout

The runout model performance was assessed by means of a comparison of the potentially affected areas with the footprints of the past events. Since the modelling of the runout is based on two types of functions, the flow direction (or spreading) and runout distance algorithms, consequently the validation is also split into these two categories. This means that the longitudinal profile and the lateral characteristics of the flows are revised. For the worst-case scenario an enclosure of all past events into the modelled area is assumed and checked by an overlay of the area susceptible according to the model and the footprints of recorded debris flows.

The fitting of the susceptibility scenarios (high, middle and low frequency) was also assessed in a qualitative way comparing the modelling results with the spatial inventories of Stummer (2009); Remaître (2006) and the longitudinal coverage of the torrential fan of the Riou-Bourdoux. For the event in the Faucon catchment in 2003 it was possible to calculate the angle of reach since in this case the full debris-flow path from the source to the endpoint is available. It was compared to the angle of reach adjusted for the medium frequency scenario.

4 Resulting susceptibility assessment

4.1 Source area identification

The model identified approximately 0.96 km^2 of potentially unstable area from a whole of 199.66 km^2. About 65% are located on the north-facing slopes including the Abriés catchment and 35% on the south-facing slopes (Fig. 4a). However, the highest percentage of potential sources (of over 45%) was identified in the Abriés catchment. Leaving this catchment out of the calculation, 71% of the sources are located on the south-facing and only 29% on the north-facing slopes.

The ranking of the catchments according to the percentage of recorded events shows especially for the four most active torrents Riou-Bourdoux, Sanières, Faucon and Bourget a very good relation with the ranking on basis of the percentage of the area of modelled sources per catchment (diagram in Fig. 5). For the four other south-facing catchments possessing much lower percentages of recorded events as well as modelled sources no clear trend is visible. However, the order of magnitude of modelled and recorded percentages is similar. The south-facing catchments show in general very low numbers of recorded events and also the percentages of modelled sources are very low, except for the Riou-Versant and especially the Abriès catchment. No clear trends are observable and the orders of magnitude differ as well, especially for the Riou-Versant and the Abriès catchment which exhibit much higher percentages of modelled sources than recorded events although both catchments could not be included completely into the analyses. For several catchments such as Enchastrayes, Boure, Sauze or La Tour no events were recorded but the model identified potential sources. In only one case, the Claveaux catchment, events were recorded but no susceptible areas were computed.

The threat posed by possible debris-flow formation on the mudslides could be identified as well. Three possible source pixels were identified on the lower part of the Poche mudslide, 21 especially in the upper part of the La Valette mudslide and 27 relatively equally distributed on the Super Sauze mudslide.

The comparison with the 2003 debris flow in the Faucon catchment shows a clear identification of the source area (Fig. 4b). The comparison with the starting points of the events mapped on the aerial photographs by Stummer (2009) showed almost no exact matches, however many slope segments, gullies and channels obviously prone to debris flows could be identified by the source modelling (Fig. 4a).

4.2 Runout area modelling

4.2.1 Worst-case scenario

The results of the two models with angles of reach of 7° and 11°, respectively, are matching nearly completely for the slopes and the torrential fans. Minor differences are

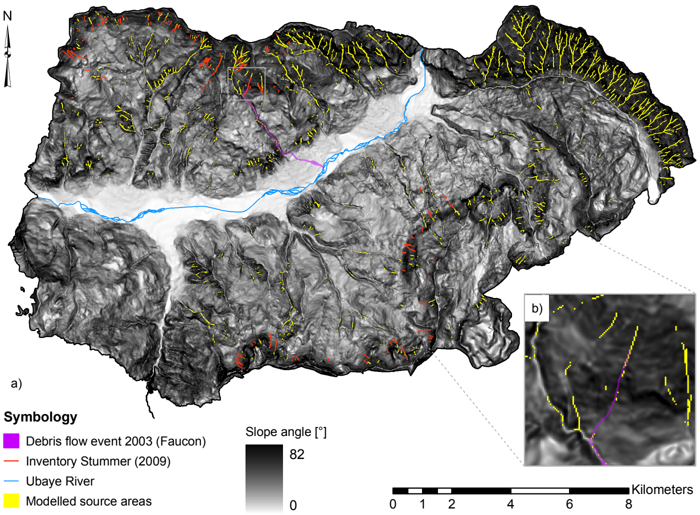

Fig. 4. Potential source areas identified by the model in comparison with the inventory by Stummer (2009) and the 2003 event observed in the Faucon catchment (Remaître, 2006) **(a)** and an amplification of the upslope region of the Faucon catchment where the 2003 event had been triggered **(b)**.

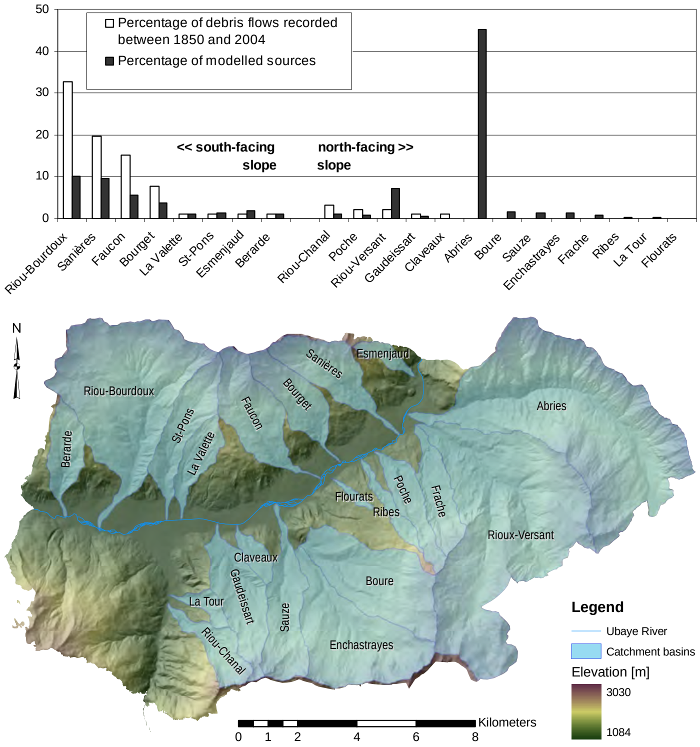

Fig. 5. Comparison of the source modelling result with the recorded events per catchment (diagram). The catchment locations are indicated in the map below the diagram.

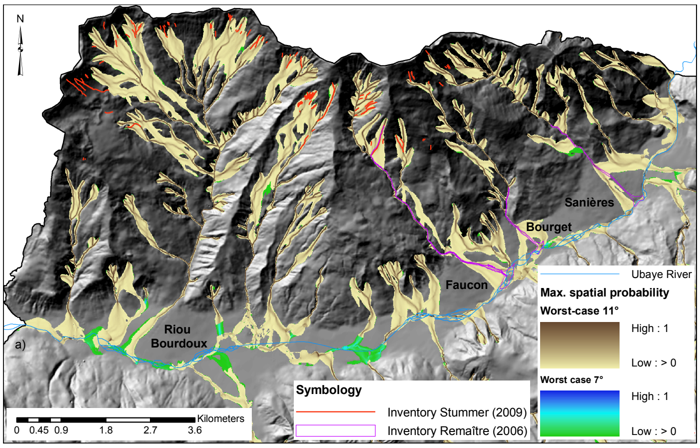

Fig. 6. Worst-case debris-flow scenarios showing the south-facing slope of the Barcelonnette Basin, with angles of reach of 7° and 11° (the 7° scenario is underlying the 11° scenario and identical with it for the area where it is invisible) in comparison with the debris-flow inventory according to Stummer (2009) and the inventory of Remaître (2006) which consists of the envelopes of the observed events in 1996, 2002 and 2003.

observable only for the further runout in the flood plain of the Ubaye (Fig. 6). Longitudinally, the runouts are covering most of the torrential fans (Fig. 3), especially of the most active torrents Riou-Bourdoux, Faucon, Sanières and Bourget, and reach the confluence with the Ubaye.

The comparison of the modelling result with the footprints of the events of 1996, 2002 and 2003 shows a sensitivity of 77% which expresses the coincidence of the affected and modelled area. On the contrary the false negative rate amounts to 33% which refers to the area of recorded events but the modelling result does not indicate a threat. A closer look reveals, that the areas affected on the Faucon and Bourget torrential fan were modelled with only minor differences and the main course of the flow was identified (Fig. 8). In the case of the event in 2002 on the torrential fan of the Sanières torrent the model identified a strongly differing pathway, splitting shortly after having passed the apex of the fan into two flows while the event in 2002 had propagated straight ahead.

The comparison with the debris-flow courses mapped on the aerial photographs (Stummer, 2009) exhibits a 60% coverage by the model. A high number of the mapped events is not or only partly covered since the respective source areas had not been identified but where the source areas were detected, the debris-flow courses identified on the photographs lie completely within the modelled susceptible area (see e.g. the Riou-Bourdoux catchment in Fig. 6).

4.2.2 Qualitative susceptibility scenarios

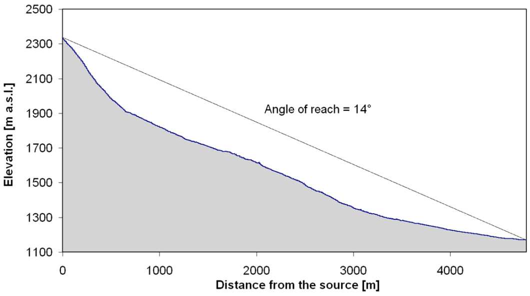

Fig. 7. Profile of the 2003 debris-flow in the Faucon torrent. A line for the identification of the angle of reach was positioned between the source area and the furthest point of the runout.

The adaptation of the model to the spatial inventories and using an assumption on extreme runout for the development of high (low), medium (medium) and low (high) frequency (magnitude) scenarios resulted in the following angles of reach: the adjustment to the inventory according to Stummer (2009) gave an angle of 30° (Fig. 9). The modelling result represents events of low magnitude with a high frequency of several events per year distributed over the investigated area. The short flows are in most cases only flowing down the steep slopes and ending as soon as they get to the torrential channels. The torrential fans in the valley are not reached.

With an angle of reach of 14° the maximum runout distance exhibited by the events in 1996, 2002 and 2003 of the torrents Faucon, Sanières and Bourget can be represented well. An investigation of the angle of reach of the debris-flow event in the Faucon torrent in 2003 also reveals an angle of reach of 14° (Fig. 7), matching exactly the empirically (by model iteration) adjusted angle of reach for medium

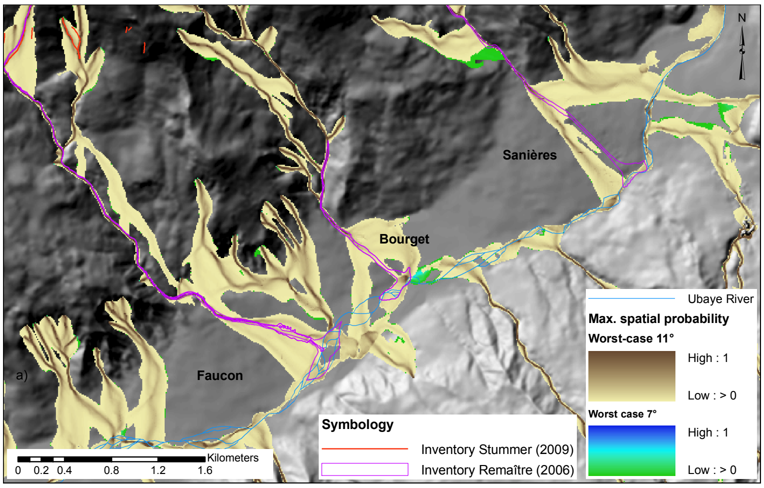

Fig. 8. Amplification of the three torrential fans showing the worst-case scenarios and the footprints of several observed events of the inventory of Remaître (2006).

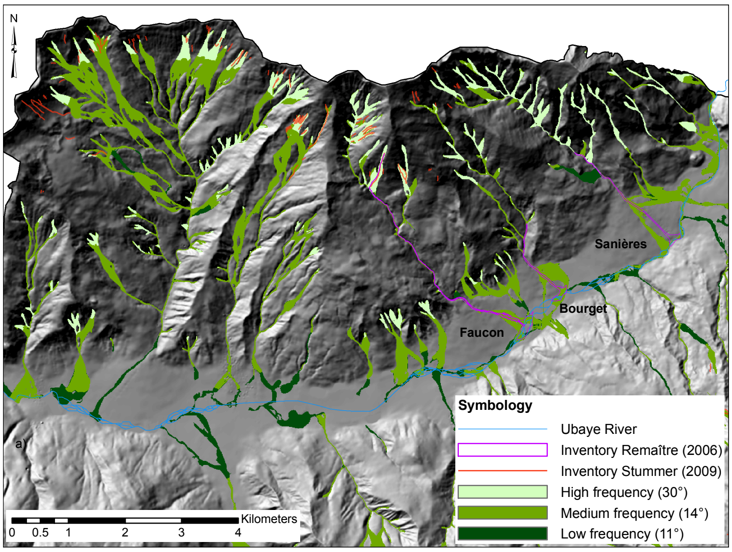

Fig. 9. Modelling results for the qualitative scenarios of high, medium and low frequency in comparison with the inventory after Stummer (2009) and the envelopes of events in 1996, 2002 and 2003 (Remaître, 2006), showing the south-facing slopes.

frequency events. The comparison of the modelled spreading of the flow and the recorded events on the Faucon, Bourget and Sanières torrential fans exhibits a very similar result to the worst-case models. It shows the same pattern of a good identification of the flow pathways on the Faucon and Bourget fans but a strong deviation on the Sanières fan. The higher value of the exponent in the spreading algorithm resulted in only marginally narrower spreading.

In contrast to the worst-case scenarios for the medium frequency scenario several other torrential fans are not reached by the modelled flows such as the Riou-Bourdoux and several north-facing torrents.

The angle of reach identified to cover longitudinally the torrential fans of the valley is consistent with the 11° worst-case scenario. As main indicator of the success of the modelling result on the torrential fan of the Riou-Bourdoux was observed, since this torrent was described in Sivan (2000) as one of the most active ones in the Barcelonnette Basin. Any higher angle than 11° would not cover the whole length of the Riou-Bourdoux torrential fan till the Ubaye. For the other fans this angle exhibits good results as well and, as observed by the comparison of the 11° with the 7° worst-case model, virtually no differences could be identified for the runout on the slopes, in the channels and on the torrential fans.

5 Discussion

The source area identification could only be validated on the basis of a small number of evidences: the event of 2003, the aerial photograph interpretation inventory (Stummer, 2009) and a comparison of the percentage of recorded events with the percentage of modelled sources per catchment. A clear identification of the source of the 2003 event contrasts with a very low identification rate of the sources of smaller events of the aerial photograph interpretation inventory. However, the reasons for the difficulties in the identification are numerous, starting with the inventory itself which includes the source areas only in a few cases while for most events only segments of debris-flow tracks could be determined and mapped. Furthermore most of the events were obviously very small, having occurred in small gullies and concavities which are very difficult to identify with a 10-m resolution DEM. The DEM creation on the basis of a topographic map with limited detail as well as the interpolation and smoothing led probably to further generalisation and loss of small scale forms. And finally, the high altitudinal differences in the area posed a challenge for the orthorectification of the aerial photographs resulting in small mismatches between the photographs and further spatial information. However, the very small sources are presumably not the ones releasing the very dangerous events and the larger channels and torrents to which they contribute are indentified in any case. Thus, the non-recognition of these sources is most probably of minor effect on the runout on the torrential fans.

The assumption of a relation between the percentage of modelled source area and the percentage of recorded events seems at first sight viable and offers a possibility for qualitative validation. The two percentages indicate a good identification of the most important torrents on the south-facing slope Riou-Bourdoux, Faucon, Bourget and Sanières as well as a the same ranking of the four torrents (Fig. 5). Though the ranking is matching well the values are not directly comparable This fact is attributed to the high percentage of more than 45° slopes of the modelled sources identified in the Abriès catchment while very few events were recorded. This leads to a distortion of the percentages of modelled sources for other catchments and especially in comparison with the percentages of recorded events. The explanation for the wide difference in the percentages of the Abriès catchment lies in its specific setting: the Abriès itself cannot be considered a torrent since it exhibits an only moderate slope of about 6.5° (Remaître, 2006). However, a large number of small very steep torrents and gullies, tributaries to the main flow, were identified as very active by the model. Nevertheless, they are most probably not producing effects which would reach the confluence with the Ubaye and since the catchment is nearly unpopulated and no road is passing under the most active slopes, these comparatively small events were not recorded. A field check confirmed, that these small torrents are indeed very active, not only concerning debris flows but also rockfalls. For a number of catchments such as the Boure, Sauze or Riou de Ribes, only possibly unstable areas, but no events were recorded. Considering the minor morainic cover of the north-facing slopes already mentioned, the non-recording of events is not necessarily a non-existence of past or future events but might indicate a lower frequency due to lower material availability. In conclusion the dependence of the comparability of the two percentages on the recording activity becomes obvious. However, taking this aspect into account the comparison served for discussion and validation purposes very well.

Between the two worst-case scenario models with angles of reach of 7° and 11° only minor differences were observed for the runout in the river bed of the Ubaye. This indicates, that an assumed worst-case angle of reach of 11° would be sufficient to identify the areas threatened by debris flows in the Barcelonnette Basin. The possible further runout in the wide river bed is of less interest since the area is not used and a possible damming of the Ubaye River does not have to be expected due to the width of the bed. In general, the runout distance of former debris flows was captured very well in the worst-case scenario. However, despite its designation as *worst-case scenario*, it does not completely contain the area affected by the recorded past events. Especially on the torrential fan of the Sanières torrent the differences are very high since the model identified a diverging course of the flow and did not cover the actual event of 2002. The reason lies most probably in the quality of the DEM. Especially in relatively flat areas the spreading of the flow reacts very sensitively to elevation differences and thus to errors in the digital elevation model. DEMs built on digitised elevation lines which exhibit further runout distances for flatter areas are rather prone to generalisations of the actual topography as well as to errors. In contrast to the strong reaction of the spreading to errors, the runout distance seems to be much less sensitive. However to prove these hypotheses further investigation has to be carried out. The resulting errors are especially problematic for the worst-case modelling. Understanding this term literally would assure the safety of the complete area outside the identified regions. However, the interpretation of such modelling results can only be done being aware of the assumptions inherent in the model, its strong dependence on the quality of the DEM and the accuracy and scale of the input data.

The qualitative scenarios computed on basis of the empirically determined angles of reach match rather well with the inventories and the assumption of full longitudinal coverage of the largest torrential fans. Especially the fact that the angle of reach calculated for the 2003 event in the Faucon catchment matches exactly with the empirically adjusted angle. The match of the angle of reach of high magnitude events and the worst-case calibration indicate a good adjustment of the scenarios. However, the data basis on which the scenarios are defined and modelled is very small and the estimation of the frequencies and magnitudes of the three classes would have to be confirmed. The results have to be interpreted being aware of these facts. Against this background, the results indicate a ranking of susceptibility. Priorities for more detailed studies can be determined by this approach.

6 Conclusions

The aim of a medium-scale debris-flow susceptibility analysis as a first overview for the Barcelonnette Basin with limited spatial information on past events was fulfilled. The source areas as well as the worst-case runout modelling resulted in reasonable outcomes without site-specific information linked to past events but by adoption of empirical relations and parametrisation developed in other regions. The comparison of the percentage of modelled sources with the percentage of recorded events per catchment proved very helpful, not only for the validation of the source modelling results but also for shedding light on the model, inventory and catchment characteristics. The development of scenarios needs more input and particularly estimations of the return periods of the events. However, detailed inventories containing information on angles of reach and volumes are not necessarily needed. With the model used in this study, a direct calibration of the scenarios on the basis of mapped deposition areas and frequency estimates is possible. The quality of the DEM was identified as a critical factor in the modelling process. Especially DEMs interpolated on the basis of contour lines exhibit a variety of errors and generalisations which have an important impact on the reliability of the modelled susceptibility. However, the application of the results lies in the identification of the most threatened areas and not in the determination of threatened areas for final decision making. E.g. effects such as volume-specific friction, scouring and increase of the volume during the movement cannot be taken into account but play an important role. The angle identified as angle of reach subsumes but does not describe the individual effects. Due to these strong generalisations, not even for the worst-case scenario can a guarantee be given that future events will lie entirely within the identified limits. The interpretation of the resulting maps is only possible with the knowledge of the model assumptions and the accuracy and scale of the input data. For future better adjustment of the model to unknown areas with low data availability it would be of great interest to fit the model to various settings and compare the parameterisation in relation to the environmental conditions. Information on the parameter ranges and the resulting differences, especially in regions with detailed information on angles of reach and volumes of past events, would provide support for the calibration of the model to unknown zones.

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References

Aleotti, P. and Chowdhury, R.: Landslide hazard assessment: summary review and new perspectives, B. Eng. Geol. Environ., 85, 21–44, 1999.

Ancey, C.: Geomorphological fluid mechanics, chap. Debris flow related phenomena, Springer Verlag, Berlin, Germany, 528–547, 2001.

Bathurst, J., Burton, A., and Ward, T.: Debris flow run-out and landslide sediment delivery model tests, J. Hydraul. Eng.-ASCE, 123, 410–419, 1997.

Beguería, S.: Validation and evaluation of predictive models in hazard assessment and risk management, Nat. Hazards, 37, 315–329, 2006.

Bell, R. and Glade, T.: Quantitative risk analysis for landslides – Examples from Bíldudalur, NW-Iceland, Nat. Hazards Earth Syst. Sci., 4, 117–131, doi:10.5194/nhess-4-117-2004, 2004.

Benda, L. and Cundy, T.: Predicting deposition of debris flows in mountain channels, Can. Geotech. J., 27, 409–417, 1990.

Blahut, J., van Westen, C., and Sterlacchini, S.: Analysis of landslide inventories for accurate prediction of debris-flow source areas, Geomorphology, Geomorphology, 119(1–2), 36–51, doi:10.1016/j.geomorph.2010.02.017, 2010.

Bordonné, M.: Cartographie de laves torrentielles dans le bassin de Barcelonnette, Master's thesis, Université Louis Pasteur, Strasbourg, 2008 (in French).

Carranza, E. and Castro, O.: Predicting lahar-inundation zones: case study in West Mount Pinatubo, Philippines, Nat. Hazards, 37, 331–372, 2006.

Carrara, A., Crosta, G., and Frattini, P.: Comparing models of debris-flow susceptibility in the alpine environment, Geomorphology, 94, 353–378, 2008.

Chau, K. T. and Lo, K. H.: Hazard assessment of debris flows for Leung King Estate of Hong Kong by incorporating GIS with numericalsimulations, Nat. Hazards Earth Syst. Sci., 4, 103–116, doi:10.5194/nhess-4-103-2004, 2004.

Claessens, L., Heuvelink, G., Schoorl, J., and Veldkamp, A.: DEM resolution effects on shallow landslide hazard and soil redistribution modelling, Earth Surf. Proc. Land., 30, 461–477, 2005.

Corominas, J.: The angle of reach as a mobility index for small and large landslides, Can. Geotech. J., 33, 260–271, 1996.

Corominas, J. and Moya, J.: A review of assessing landslide frequency for hazard zoning purposes, Eng. Geol., 102, 193–213, 2008.

Delmonaco, G., Leoni, G., Margottini, C., Puglisi, C., and Spizzichino, D.: Large scale debris-flow hazard assessment: a geotechnical approach and GIS modelling, Nat. Hazards Earth Syst. Sci., 3, 443–455, doi:10.5194/nhess-3-443-2003, 2003.

Flageollet, J.-C., Maquaire, O., Martin, B., and Weber, D.: Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France), Geomorphology, 30, 65–78, 1999.

Glade, T.: Linking debris-flow hazard assessment with geomorphology, Geomorphology, 66, 189–213, 2005.

Guinau, M., Vilajosana, I., and Vilaplana, J. M.: GIS-based debris flow source and runout susceptibility assessment from DEM data - a case study in NW Nicaragua, Nat. Hazards Earth Syst. Sci., 7, 703–716, doi:10.5194/nhess-7-703-2007, 2007.

Heim, A.: Bergsturz und Menschenleben, Beiblatt zur Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich, 1932.

Heinimann, H., Hollenstein, K., Kienholz, H., Krummenacher, B., and Mani, P.: Methoden zur Analyse und Bewertung von Naturgefahren, Umwelt-Materialien Nr. 85, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland, 1998 (in German).

Hofmeister, R. and Miller, D.: Debris-flow hazards mitigation: mechanics, prediction, and assessment, chap. GIS-based modeling of debris-flow initiation, transport and deposition zones for regional hazard assessments in western Oregon, USA, Millpress, Rotterdam, Netherlands, 1141–1149, 2003.

Hofmeister, R., Miller, D., Mills, K., Hinkle, J., and Beier, A.: Hazard map of potential rapidly moving landslides in Western Oregon, Interpretive Map Series IMS-22, Oregon Department of Geology and Mineral Industries, 2002.

Holmgren, P.: Multiple flow direction algorithms for runoff modelling in grid based elevation models: an empirical evaluation, Hydrol. Process., 8, 327–334, 1994.

Horton, P., Jaboyedoff, M., and Bardou, E.: Debris flow susceptibility mapping at a regional scale, in: 4th Canadian Conference on Geohazards, Université Laval, Québec, Canada, 2008.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., and Paul, F.: Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps, Can. Geotech. J., 39, 316–330, 2002.

Hürlimann, M., Rickenmann, D., Medina, V., and Bateman, A.: Evaluation of approaches to calculate debris-flow parameters for hazard assessment, Eng. Geol., 102, 152–163, 2008.

Iverson, R. and Denlinger, R.: Mechanics of debris flows and debris-laden flash floods, in: Proceedings of the Seventh Federal Interagency Sedimentation Conference, 2001.

Iverson, R., Schilling, S., and Vallance, J.: Objective deliniation of lahar-inundation hazard zones, GSA Bulletin, 8, 972–984, 1998.

Malet, J.-P., Maquaire, O., Locat, J., and Remaître, A.: Assessing debris flow hazard associated with slow moving landslides: methodology and numerical analyses, Landslides, 1, 83–90, 2004.

Maquaire, O., Malet, J.-P., Ramaître, A., Locat, J., Klotz, S., and Guillon, J.: Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Basin, South East France, Eng. Geol., 70, 109–130, 2003.

Melelli, L. and Taramelli, A.: An example of debris-flows hazard modeling using GIS, Nat. Hazards Earth Syst. Sci., 4, 347–358, doi:10.5194/nhess-4-347-2004, 2004.

O'Callaghan, J. and Mark, D.: The extraction of drainage networks from digital elevation data, Comput. Vision Graph., 28, 328–344, 1984.

Prochaska, A., Santi, P., Higgins, J., and Cannon, S.: Debris-flow runout predictions based on the average channel slope (ACS), Eng. Geol., 98, 29–40, 2008.

Quinn, P., Beven, K., Chevallier, P., and Planchon, O.: The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models, Hydrol. Process., 5, 95–79, 1991.

Remaître, A.: Morphologie et dynamique des laves torrentielles: applications aux torrents des Terres Noires du bassin de Barcelonnette (Alpes du Sud), Ph.D. thesis, Université de Caen/Basse-Normandie, 2006 (in French).

Remaître, A. and Malet, J.-P.: The effectiveness of torrent check dams to control channel instability: example of debris flow events in clay shale, in: Check Dams, Morphological Adjustments and Erosion Control in Torrential Streams, edited by: Garcia, C. C. and Lenzi, M. A., Nova Science Publishers, 211–237, 2010.

Remaître, A., Malet, J.-P., Maquaire, O., C., A., and Locat, J.: Mobility of debris-flows in clays-shale basins. Part II: Flow behaviour, runout modelling and torrential hazard assessment, Earth Surf. Proc. Land., 30, 479–488, 2005.

Remaître, A., van Asch, Th. W. J., Malet, J.-P., and Maquaire, O.: Influence of check dams on debris-flow run-out intensity, Nat. Hazards Earth Syst. Sci., 8, 1403–1416, doi:10.5194/nhess-8-1403-2008, 2008.

Rickenmann, D.: Empirical relationships for debris flows, Nat. Hazards, 19, 47–77, 1999.

Rickenmann, D. and Zimmermann, M.: The 1987 debris flow in Switzerland: documentation and analysis, Geomorphology, 8, 175–189, 1993.

Scheidl, C. and Rickenmann, D.: Empirical prediction of debris-flow mobility and deposition on fans, Earth Surf. Proc. Land., 35, 157–173, 2010.

Sivan, O.: Torrents de l'Ubaye, Sabenca, Association de la Valeia, Barcelonnette, France, 2000 (in French).

Smallwood, A., Morley, R., Hardingham, A., Ditchfield, C., and Castleman, J.: Engineering Geology and the Environment, chap. Quantitative risk assessment of landslides: case histories from Hong Kong, Balkema, Rotterdam, Netherlands, 1055–1060, 1997.

Stummer, R.: Räumliche und zeitliche Variabilität von Murereignissen, Master's thesis, University of Vienna, Austria, 2009 (in German).

Takahashi, T.: Estimation of potential debris flows and their hazardous zones; soft countermeasures for a disaster, Journal of Natural of Disaster Science, 3, 57–89, 1981.

Tarboton, D. G.: A new method for fhe determination of flow directions and upslope areas in grid digital elevation models, Water Resour. Res., 33, 309–319, 1997.

Thiery, Y.: Susceptibilité du bassin de Barcelonnette (Alpes du sud, France) aux "mouvements de versant": cartographie morphodynamique, analyse spatiale et modélisation probabiliste, Ph.D. thesis, Université de Caen/Basse-Normandie, 2006 (in French).

Thiery, Y., Malet, J.-P., Sterlacchini, S., Puissant, A., and Maquaire, O.: Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment, Geomorphology, 92, 38–59, 2007.

van Westen, C., van Asch, T., and Soeters, R.: Landslide hazard and risk zonation – why is it still so difficult, B. Eng. Geol. Environ., 65, 167–184, 2006.

Zimmermann, M., Mani, P., and Gamma, P.: Murganggefahr und Klimaänderung – ein GIS-basierter Ansatz, vdf Hochschulverlag AG, ETH Zürich, 1997 (in German).

A.4. A Multi-Hazard Risk Analysis Tool: the MultiRISK Platform

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The conceptual development of MultiRISK and the case study were carried out by Melanie S. Kappes as well as the initation and the writing of the article. Klemens Gruber programmed the MultiRISK Modelling Tool and Simone Frigerio the Visualisation Tool according to the conceptual approach of and in close cooperation with Melanie S. Kappes. Margreth Keiler, Rainer Bell and Thomas Glade contributed with scientific exchange, discussions and feedback on the manuscript.

The MultiRISK Platform: The technical concept and application of a regional-scale multi-hazard exposure analysis tool

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Abstract

World-wide many regions are threatened by multiple natural hazards with the potential to cause high damages and losses. However, their joint analysis is still in the early stages of development since a range of serious challenges emerges in the multi-hazard context such as differing modeling approaches in use for contrasting hazards, the time- and data-demanding conduct of each single preparative, intermediate and analysis step, and the clear visualization of the modeling outcome. Under consideration of these difficulties a regional multi-hazard exposure analysis concept is developed for the five natural hazards debris flows, rock falls, shallow landslides, avalanches and river floods, complemented by a visualization scheme to present the modeling outcome. An automation of the two schemes resulted in the MultiRISK Modelling and the MultiRISK Visualization Tool forming together the MultiRISK Platform. To test MultiRISK a case study is performed in the Barcelonnette basin in France with a worst-case parameterization of the models on basis of extensive literature reviews. Although this analysis apparently leads to an overestimation of the susceptible areas and the number of exposed elements, it offers the determination of general hazard distributions, overlaps and areas of potential risk without data-demanding calibration. Thus, the proposed parameter set may also serve for the performance of an approximation in other, completely unknown, areas for a first identification of general hazard and risk patterns. Furthermore, the case study offered many insights into the multi-hazard topic and even more questions e.g. with respect to coherent multi-hazard model parameterization or the comparability and interpretation, respectively, of single-hazard modeling results. Although analysis schemes can be proposed and software tools can be provided to facilitate many steps, a well-conceived and reflective approach to multi-hazard settings is essential.

Keywords: Multi-hazard risk, modeling software, web-mapping

1. Introduction

Many areas of this world as for example coastal zones, mountainous regions or volcano vicinities are threatened by multiple natural hazards. However, natural hazards are usually still examined and managed separately. Only in few studies multiple threats are analyzed jointly and the overall risk is assessed, e.g. by van Westen et al. (2002), Bausch (2003), Bell and Glade (2004), Glade and van Elverfeldt (2005), Reese et al. (2007), Bründl et al. (2009) or Marzocchi et al. (2009). With the joint analysis of hazards, numerous challenges and difficulties arise (Kappes et al., subm.): (a) hazards are not directly comparable since their characteristics and their describing metrics differ, for instance inundation depth of floods versus impact pressure of rock falls. Furthermore, also the analysis methods and models diverge widely. These differences complicate the comparability of analysis results. (b) Hazards are related, interact and influence each other with the result of unexpected incidences and hazard chains (Kappes et al., 2010). (c) The estimation of the vulnerability of threatened elements is difficult since the vulnerability approaches vary between hazards (Papathoma-Köhle et al., 2011). (d) Risks are expressed in hazard-independent units as e.g. annual losses, lives lost etc. and hence easier to compare than hazards. However, a variety of risk measures exists (annual losses or losses for a specific scenario as a 100-year event, loss of lives, injuries or damage to buildings etc.). Therefore, at least a common metric at a predefined scale has to be specified to enable the comparison of single risk results (Marzocchi et al., subm.).

Apart from the challenges concerning the comparability of hazards and risks, respectively, another major difficulty is the performance of such an analysis. Knowledge and experience from many different disciplines is required and the data acquisition, preparation and the hazard, vulnerability and risk modeling for single hazard procedures consist of a large number of different analysis steps which are complicated and thus time-consuming and error prone. However, it would be desirable to be able to re-run the analysis repeatedly to evaluate e.g. the effect of management options or to consider changes in land use, in the climate, the general environmental setting or alterations of the elements at risk (Dai et al., 2002; Fuchs and Keiler, 2006; Slaymaker and Embleton-Hamann, 2009).

A possible solution is the automation of the single steps in a software tool offering the analysis of a set of hazards according to a coherent analysis scheme which results in comparable single-hazard (risk) results. Some developed approaches include HAZUS in the USA (Schneider and Schauer, 2006; FEMA, 2008) which offers hurricane, earthquake and flood hazard and risk modeling. RiskScape in New Zealand (Reese et al., 2007) facilitates currently volcanic ashfalls, floods, tsunamis, landslides, storms and earthquakes. CAPRA in Central America provides the analysis of hurricanes, heavy rainfall, landslides, floods, earthquakes, tsunamis and volcanic hazards (CEPREDENAC et al.). Such tools do not only provide user-friendly and straightforward performance of multi-hazard analyses and comparability between single hazards but their wide-spread and repeated use also guarantees comparability between e.g. municipalities or departments and between analyses over time.

A final difficulty in the multi-hazard context is the huge data requirement. Extensive and qualitatively high standard inventories of past events including detailed spatio-temporal patterns, and particularly with equivalent standard for multiple hazards, are rare. In most regions huge differences in quality and dimension exist between the single-hazard inventories - if records of past events are available at all. Furthermore, the more detailed the models, the more detailed data on topography, geology, soils, land use, precipitation distribution etc. is required. A possibility to partly overcome this constraint is a top-down approach. A simple and fast analysis at small scale provides an approximation. In a next step, more detailed and sophisticated, and thus also more data requiring methods at a larger scale, is applied. By using the small-scale modeling results to define those areas for which detailed studies have to be carried out, resources can be utilized very effectively.

Under consideration of the previously mentioned challenges, the MultiRISK platform has been developed. This software consists of a multi-hazard risk analysis, projected according to a top-down approach, and a visualization tool to display the results. In the current version, the GIS-based regional to medium-scale overview analysis is completed (1:10.000-1:25.000) including the typical mountain hazards avalanches, debris flows, rock falls, shallow landslides and river floods. In this article the development of MultiRISK and the product will be presented together with the performance of a multi-hazard exposure analysis in the test site of Barcelonnette in France. The analysis scheme for hazard modeling based on well-available input data, hazard model validation and exposure analyses is presented in section 2. A visualization scheme to display and communicate the results in a well-structured way is outlined in section 2.4. The analysis scheme is automated in a user-friendly software (section 3.1). The visualization outline is implemented into a visualization tool to present the results automatically in a web browser interface (section 3.2). In order to test the developed MultiRISK modeling and visualization tool, it is applied in the Barcelonnette basin (section 4). On basis of the findings of the analysis scheme development, the MultiRISK development and implementation in the case study, the challenges and specifics in a multi-hazard setting are discussed in section 5.

The definition of key terms differs between scientists as well as between disciplines and processes. This has become evident when working in the field of multi-hazards and risks. Thus a short explanation is added in Table 1 to clarify the terminology used in this contribution.

Table 1 Key terminology used in this contribution

Hazard	describes “[a] dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage” (UN-ISDR, 2009b; p. 7). However, in a technical context hazard refers usually to quantitative information on the “likely frequency of occurrence of different intensities for different areas, as determined from historical data or scientific analysis” (UN-ISDR, 2009b; p. 7). In relation to multi-hazard both definitions of hazard are needed: hazard according to a wider definition is used when generally referring to one or several processes and hazard according to the technical definition is required to describe the level of information available for a certain process (in contrast to susceptibility). To be able to distinguish between the two meanings the second (technical) definition will relate in this article to ***Full-Hazard***.
Susceptibility	offers in particular spatial information, i.e. “the probability that any given region will be affected” (Guzzetti et al., 2005; p. 277). In contrast to full-hazard, susceptibility lacks information on the hazard intensity including frequency and magnitude.
Risk	refers to the “[e]xpected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period” (WMO, 1999; p. 2). The social dimension of risk (e.g. Wisner et al., 2004) is not addressed in this contribution.

Exposure	is defined as "[p]eople, property, systems, or other elements present in hazard zones that are thereby subject to potential losses" (UN-ISDR, 2009b; p. 6). In this article the definition includes hazard (i.e. full-hazard) zones as well as susceptibility zones.

Note: Additional terms such as coping capacity, adaptation and resilience, to name a few only, are not addressed in this contribution and are therefore not included in this table.

2. Development of a regional-scale analysis and visualization scheme of multi-hazard exposure

The multi-hazard risk analysis scheme proposed in the present follows a top-down approach in which a regional exposure analysis provides the identification of hazard distributions, hazard overlaps and zones potential risk. Subsequently, detailed, local risk analyses on basis of more sophisticate models are to be carried out at the previously defined points. In the present study, however, only the regional scale exposure analysis scheme is outlined and its implementation into a software tool is presented, while the local level analysis will be elaborated in future works and by now only its function is defined.

The regional exposure analysis is composed of three components, the hazard modeling, the validation of the modeling results and the exposure analysis. These will be explored in the following.

2.1. *Hazard modeling*

The first step in a multi-hazard top-down approach shall offer a regional approximation by means of fast and simple methods. As explained before, the data need for multi-hazard risk analyses is in general a limiting factor. Consequently, the availability of input data is a major criterion for the model choice and determines significantly the tool's applicability. For GIS-based models "input" refers to two types of information: (1) area-wide information, i.e. information layers (e.g. elevation, land use or geology) and (2) information to calibrate or parameterize the model as e.g. inventory data, soil properties and precipitation or discharge time series. (1) Topographic characteristics, derived from digital elevation models (DEM), are for GIS-based modeling of natural hazards usually the most important area-wide input data. This information is already available in many regions in the world or can be produced with acceptable effort from topographic maps, satellite imagery and laser scanning. From the DEM, a variety of derivatives such as slope angle, curvature, aspect or distance to ridge/drainage line can be deduced. Especially the mountain hazards are strongly coupled with topographic characteristics and therefore, this data is highly valuable for any model. Consequently, the regional analysis is primarily based on the DEM including its derivatives and the required models to be chosen have to be operable with this topographic input.

To optionally extent the topographic information additional data such as land use/cover was implemented. This data is rather easy to create, for example from remote sensing data or, in coarse resolution, as free image sharing from GoogleEarth. Furthermore, lithological information is included into the modeling approach since geological maps exist in many countries and regions and the lithology and tectonic lineaments influence and even determine many natural hazards significantly. In both additions, however, the spatial resolution is of crucial importance and needs to be assessed carefully. (2) The second criterion for the model choice is the straightforwardness of the model calibration/parameterization. Models with indispensible need of data from field or laboratory analyses, time series or extensive inventories do not fit the objective of a simple and fast first approximation of an area. The models have to be straightforward and comprehensive to enable a flexible calibration on the basis of detailed information, if available. However, in cases of low data availability it has to be possible to complement with expert knowledge or even parameterize exclusively with expert experience or studies carried out in comparable settings.

Furthermore, only models developed for a regional scale (1:10.000-1:50.000) were selected to ensure, as far as possible in a multi-hazard environment, the comparability of the results. Apart from these criteria, the model choice is open and the models selected here can be easily exchanged by other suitable ones (concerning scale, data input needs etc.). In the current version of MulitRISK, the processes snow avalanches, shallow landslides, debris flows, rock falls and river floods are considered. The different selected models and the methodology of their implementation is presented in the following paragraphs.

Debris flows

The source identification is carried out with Flow-R model (Horton et al., 2008; Horton et al., in prep.). Only those parameters and algorithms of Flow-R are presented which are included in the analysis scheme and later in MultiRISK. For more detail on Flow-R refer to Horton et al. (2008), Blahut et al. (2010), Kappes et al. (2011), and Horton et al. (in prep.). This model is based on the three topographic parameters slope angle, upslope area and planar curvature. They represent in directly (slope) or indirectly (upslope area and planar curvature) three major factors for debris flow disposition (Takahashi, 1981; Rickenmann and Zimmermann, 1993), slope gradient, sediment availability and water input. Flow accumulation and planar curvature serve as indicators for the convergence of sufficient water and material in gully structures. Flow accumulation is considered in combination with slope angle since in smaller catchments less material is accumulated and more water from steeper slopes is needed to enable the debris flow initiation. In contrast, larger catchments are supposed to accumulate higher volumes of sediment and water which starts moving at lower angles (Figure 1).

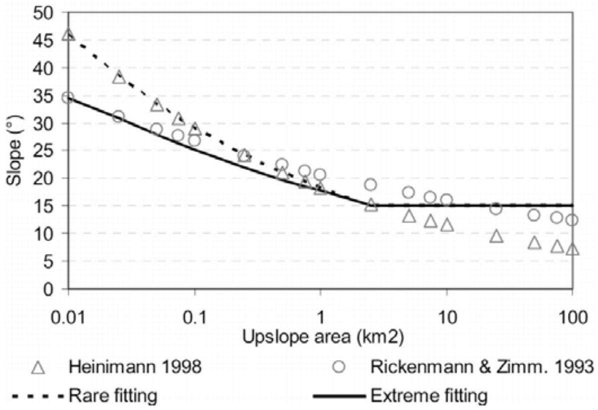

Figure 1 Coupled consideration of slope angle and upslope area (Horton et al. 2008). Below an upslope area of 2.5km^2 the slope angle to start the movement is rising with decreasing area while above 2.5km^2 it is assumed to be constant at 15°.

Additionally, certain land use/cover types and lithological units can optionally be excluded. For example dense forest influences surface runoff and buildup areas or outcropping rocks determine material availability.

In a second step, Flow-R offers a 2D run out modeling option. The spreading of the flow is computed with the multiple flow direction algorithm according to Holmgren (1994), an expansion of the basic multiple flow direction algorithm developed by Quinn et al. (1991):

$$f_i = \frac{(\tan \beta_i)^x}{\sum_{j=1}^{8} (\tan \beta_j)^x} \qquad \textit{for all } \tan \beta > 0 \qquad \text{Equation 1}$$

where *i,j* = flow direction (1..8) [-], f_i = flow proportion (1..0) [%] in direction *I* [-], *tan* β_i [-] = slope gradient between the central cell and cell in direction *I* and *x* an exponent introduced by Holmgren (1994). For $x = 1$ the algorithm converts into the basic multiple flow direction after Quinn et al. (1991) and for $x \rightarrow \infty$ into a single flow. The spreading is complemented by a persistence function. This function accounts for the inertia of the flow by a weighting of the change of angle from the last flow direction. For 0° a weight of 1 is assigned, for 45° 0.8, for 90° 0.4, for 135° and for 180° 0). The distance of the run out is computed with a constant friction loss angle, thus not considering the surface roughness. This angle corresponds to the *Fahrböschung* of Heim (1932), translated as *angle of reach* by Corominas (1996), which refers to the angle between a line from the highest point of the source area to the maximum run out and the horizontal. In Flow-R the angle is applied as constant loss variable in an energetic computation while the flow propagates from pixel to pixel (Horton et al., 2008):

$$E_{kin}^{i} = E_{kin}^{i-1} + \Delta E_{pot}^{i} - E_{loss}^{i} \qquad \text{Equation 2}$$

with the time step i, the kinetic energy E_{kin}, the change in potential energy ΔE_{pot} and the constant loss E_{loss}. The flow stops as soon as the kinetic energy drops below zero. At the overlap of the flows from different sources the maximum value of the spatial probability that this pixel might be hit and the maximum kinetic energy of all overlapping flows are calculated.

Two run out calculation modes are offered: quick and complete. In the complete mode, each single source pixel is propagated. In the quick models first the superior sources are propagated. If lower ones follow the same path with a similar or lower kinetic energy they are neglected. This reduction of single calculations enables significant time saving.

Rock falls

A commonly used method for automatic rock fall source identification is the classification of the slope gradient map. Hereby, a threshold angle is defined above which the area is identified as potentially rock fall producing rock face (Wichmann and Becht, 2006; Guzzetti et al., 2003; Ayala-Carcedo et al., 2003; Jaboyedoff and Labiouse, 2003; Frattini et al., 2008). As already described for the debris flow source modeling, specific land use/cover and lithological units as e.g. outcropping marls can also be excluded as potential rock fall source areas. As for debris flows, the run out is modeled by means of the Flow-R model according to Horton et al. (2008).

Shallow landslides

In comparison to the processes treated until now, areas susceptible to shallow landslides are rather analyzed with statistical and physically-based methods than with empirical models. However, statistical models are commonly not easy to transfer and physically-based models require a high quantity of geotechnical input data and are thus also not suitable for a regional approach. Nevertheless, a variety of physical models was adjusted to the input of information derived from DEMs. Since topographic characteristics control water confluence, downslope forces etc. this effort proved to be successful as multiple models indicate, e.g. SLIDISP of Liener and Kienholz (2000), SHALSTAB of Montgomery and Dietrich (1994) and Dietrich and Montgomery (1998) or SMORPH of Shaw and Johnson (1995). Among these methods SHALSTAB (SHAllow Landsliding STABility; Montgomery and Greenberg, 2009) was selected because it offers the option to compute a first approximation of an area without the need of detailed calibration. The Slope Stability Package after Montgomery and Greenberg (2009) which refers to SHALSTAB was chosen since it can directly be included as toolbox in ArcGIS 9.x, while the original version of Dietrich and Montgomery (1998) is an ArcView 3.x application. SHALSTAB couples a "hydrological model to a limit-equilibrium slope stability model to calculate the critical steady-state rainfall (Q_c) necessary to trigger slope instability at any point in a landscape" (Montgomery et al., 1998; p. 944). Under negligence of the soil cohesion the following equation emerges (Montgomery and Dietrich, 1994; Montgomery et al., 1998):

$$Q_c = \frac{T \sin\theta}{a/b}\left[\frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\right] \qquad \text{Equation 3}$$

with the soil transmissivity T [m^2/day], the hillslope angle θ [°], the drainage area [m^2] a, the outflow boundary length b [m], the soil bulk density ρ_s [kg/m^3], the water bulk density ρ_w [kg/m^3], and the angle of internal friction ϕ [°]. By using a "single set of parameter values" (ρ_s and ϕ, ρ_w are a constants) plus the area-wide DEM derivatives (a, b and θ) the "regional influence of topographic controls on shallow landsliding" can be assessed without any specific calibration (Montgomery et al., 1998; p. 943). Dietrich and Montgomery (1998) explain that SHALSTAB is not performing well in areas dominated by rocky outcrops or cliffs. Hence, an option is included to optionally exclude e.g. limestone outcrops and other lithological units as potential sources.

Although much less used, the angle of reach principle can also be applied for the run out calculation of shallow landslides (e.g. Corominas et al., 2003) and thus the Flow-R model was applied in this case as well.

Avalanches

Maggioni and Gruber (2003) developed a methodology for the determination of potential release areas primarily based on topographic parameters which was simplified by Barbolini et al. (2011). For avalanche initiation a certain minimum slope angle is necessary to enable the movement, however, very steep slopes will not accumulate enough snow for avalanche formation. Thus, avalanches can be expected at slopes between a lower and an upper threshold angle. Specific land use types as especially dense forest that will stabilize the snow in the release area can be excluded as potential sources as well as ridges where too little snow accumulation can be assumed (identified by a curvature >1/100m and a change of aspect > 40°; see Maggioni (2004) for further detail).

For the computation of the avalanche run out apart from the angle α which corresponds to the angle of reach further ones are in use. β is the angle of the avalanche track between source and the point of the slope with 10° (β point) and δ is the average angle of the run out zone between the β point and the stopping point of the avalanche (Bakkehøi et al., 1983; Keylock, 2005). To keep the methodology simple the angle of reach and the α approach, respectively, was chosen and run out calculation is performed by means of Flow-R as well.

Floods

The simplest method to estimate floodplain inundations is the linear interpolation of a gauge water level in intersection with a DEM (Apel et al., 2009). Models representing hydrodynamic characteristics such as HEC-RAS, Sobek and others need more detailed information on channel geometry and roughness, hydrograph information etc. The ArcGIS extension FloodArea of Geomer (2008) offers both methods, the modeling on basis of a certain inundation depth or by means of a hydrograph and several more options. However, in the modeling scheme and the MultiRISK software only these two approaches were included and offer a choice based on data availability to calibrate/parameterize them.

The combination of the previously described single-hazard models to one overall analysis scheme is challenging. However, it is evident that different natural hazard models require similar data, and therefore it is of major advantage to combine these models in a multi-hazard analysis in order to gain synergies and consequently time-saving in a joint study. The flow chart of the resulting model set-up is presented in Figure 2.

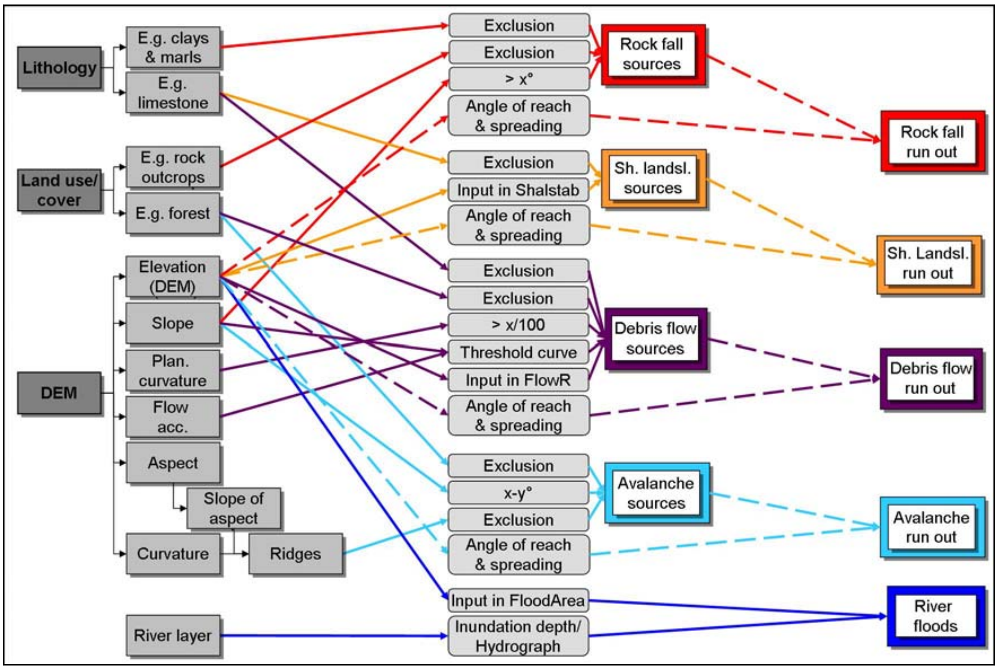

Figure 2 Flow chart of the analysis scheme for rock fall, shallow landslides, debris flows, avalanches and floods. On basis of the DEM and optionally land use and lithology (in dark grey boxes on the left side) a multitude of derivatives such as slope, planar curvature or flow accumulation (medium grey boxes) are computed. They form the input for the models (light grey boxes with rounded edges) by means of which first the source areas are identified and second the run out is modeled (dashed lines).

2.2. Validation

Since comprehensive event inventories at a comparable quality and extent for a multitude of hazards are scarce, not only the calibration/parameterization of the models but also the validation has to be flexible concerning the input of information on past. Due to their simplicity, confusion matrices as described by Beguería (2006) and Carranza and Castro (2006) meet exactly this need. They are based on an overlay of the binary (yes/no) layer containing the modeling result with the layer of the recorded events. The models described in the previous section produce directly binary source maps while the run out computations yield spatial probability and kinetic energy, respectively, and the flood modeling outputs the inundation depth. Reclassifying the continuous results, binary maps were produced. Two options of validation of the modeled source and of validation of the complete area as a composite of the modeled sources and run out are given. However, especially in the case of shallow landslides, a clear differentiation between source area and run out is often very not possible. Therefore, a division in sources and complete area seems to be much more practical than to differentiate between sources and run out. Furthermore, river flooding cannot be subdivided into source and run out zone, however, the area susceptible to floods can be perfectly assigned to the *complete* category.

From the overlay of the modeling results and the recorded events four classes emerge. In these classes, the totality of pixels is classified and the numbers are depicted in a confusion matrix (Table 2).

Table 2 Confusion matrix according to Beguería (2006). Either the area [m^2] or the area proportion [%] can be depicted in the cells.

		Observed	
		Yes	No
Predicted	Yes	True positive (a)	False positive (b)
	No	False negative (c)	True negative (d)

The true positives refer to the recorded events which were correctly modeled as threatened while the false negatives draw attention to those zones which were missed by the model. The false positives, are de facto not errors but "cases highly propense to develop the dangerous characteristic in the future" (Beguería, 2006; p.322). The identification of these areas in which still no events took place but a high risk of future incidences exists, is the objective of hazard modeling. However, a too conservative modeling approach could lead to a strong overestimation of the actual threat, thus the proportion of false negatives should be compared to the proportion of true positives to better appraise the quality of the prediction. The true negatives are even more difficult to evaluate because in general inventories indicate only the recorded zones but not *unsusceptible* ones. Thus, the remaining area adjacent to the recorded events is not *surely safe* but events might simply not have been recorded or happened yet. However, this does not indicate a sure exclusion of the possibility that it could happen and consequently no *true negatives* exist in the strict sense of the term.

On basis of the four classes of the confusion matrix (Table 2) Beguería (2006) proposes several quality indicators. Two of them were chosen for the multi-hazard context:

Sensitivity: $a/(a+c)$ Equation 4
Positive Prediction Power: $a/(a+b)$ Equation 5

While the sensitivity indicates, which proportion of the recorded events has been modeled correctly and which proportion not, respectively, the positive prediction power (PPP) serves as measure of the effectiveness of the susceptibility estimation. For instance a very high sensitivity might suggest a very good modeling result, however a coincident low PPP indicates an overestimation of the susceptible area.

2.3. Exposure analysis

The exposure is analyzed by overlaying the susceptibility footprints with the elements at risk and those elements situated within the susceptibility zones are marked. As for the validation two options are offered: the area susceptible to source instabilities and the complete susceptible area. Especially for the comparison with the elements exposed to river flooding the *complete* options is very important, however, for shallow landsliding a significant difference exists between those houses situated on the slide and those possibly being hit by a slide. By offering both options (sources & complete) the specifics of landslides and floods are accounted for, as well as for the comparability between them.

In accordance to overlay options and the feature classes available in ArcGIS three different exposure analyses are possible:

1. Punctual, lineal or areal elements (points, lines or polygons) are uploaded and are treated as entire units: The element is identified as exposed if it intersects at least partly with the hazard area and the number of affected elements is counted. This is suitable for buildings uploaded as point or polygons, pylons etc.
2. Linear elements (lines): The length of the line intersecting with the susceptible area is identified, marked and measured. This option is offered for the examination the exposure of lineal elements such as roads or water supply lines.
3. Areal elements (polygons): The area intersecting with the hazard area is identified, marked measured. This option especially suits the analysis of built-up areas and land use units.

2.4. Visualization scheme for the display of multi-hazard risk analysis results

As identified in the review of Kappes et al. (subm.), the visualization of the multi-dimensional result of a multi-hazard risk analyses poses an exceptional challenge. Several options to depict the different facets of the output have been identified in this contribution (refer to Kappes et al. (subm.) for details):

- Visualization of susceptibility, full-hazard, exposure or risk of each single hazard separately and in detail (e.g. Dilley et al., 2005; Bell, 2002; Odeh Engineers, Inc, 2001). This option allows discovering and recognizing single-hazard patterns without confusing the map reader with too much information.
- Visualization of the overlay of several hazards (e.g. Bell, 2002; UN-ISDR, 2009a). This form of display has the special potential to indicate the areas where hazards overlap. However, the number of hazards which can be included is limited since an overloading with too much information may lead to confusion.
- Visualization of the number of overlapping hazards (e.g. Odeh Engineers, Inc, 2001). This visualization form offers a clear focus on the identification of zones susceptible to several processes mentioning just the number of overlapping hazards without running the risk to get chaotic or unclear.

The previously mentioned options were adopted and used as the core of a visualization scheme which communicates step by step the different aspects and results of the multi-hazard exposure analysis:

1. **General setting**: Display of basic information on the area as the input data of the hazard models (e.g. slope, curvature, lithology, land use/cover etc.) and others. The user gets the possibility to become acquainted with the area and its characteristics.
2. **Single hazards**: Single-hazard susceptibility outputs are visualized separately (refer to explanation above).
3. **Overlapping hazards**: Overlay of up to three hazards. No details are given on the single hazards, only the footprints are shown to not confuse the map reader.

4. **Number of hazards:** To give the full overlay information but not confuse the reader the number of overlapping hazards is shown without depicting the type of hazards summing up to this number.
5. **Past events:** Visualization of the uploaded records of past events which were used for the validation. The user gets the opportunity to observe the distribution, coverage and patterns of recorded past events.
6. **Validation:** Visualization of the overlay of records and modeling result for each single hazard separately. The distribution of true positives and false negatives may indicate situations the model can account for very well and others it cannot. Furthermore, the pattern of those zones which have not been affected until now (or at least no events have been recorded) but might in the future be hit, the false positive, manifests.
7. **Exposed elements**: Depiction of the elements exposed to each of the single process separately, plotted together with the susceptibility information of the respective hazard.

3. The MultiRISK Platform

3.1. MultiRisk Modeling Tool

Due to the large number of single steps (Figure 2) and the, therefore, time-consuming and error-prone performance of a multi-hazard analysis, the whole procedure was automated in the software called MultiRISK Modeling Tool. MultiRISK is programmed in Python accessing ArcGIS 9.x toolboxes and offers a graphical user interface for the straightforward operation. The single models are implemented either by activation of external software as in case of the Matlab-programmed stand-alone software Flow-R, direct inclusion as in case of the ArcGIS toolbox FloodArea or programming in Python on basis of ArcGIS tools of the ArcToolbox as in case of e.g. the source identification method after Maggioni (2004). The user is guided through the single steps of the three main components of the Modeling Tool, the hazard modeling (first column in Figure 3. For an overview over the parameters to be chosen refer to Table 3), the hazard model validation and the exposure analysis. If already a hazard analysis has been carried out, the tool offers the upload of this project and the subsequent performance of any of the three further steps (see bended arrows in Figure 3). After having finished the multi-hazard exposure analysis the preparation of the MultiRISK Visualization can directly be launched to view the results thereafter.

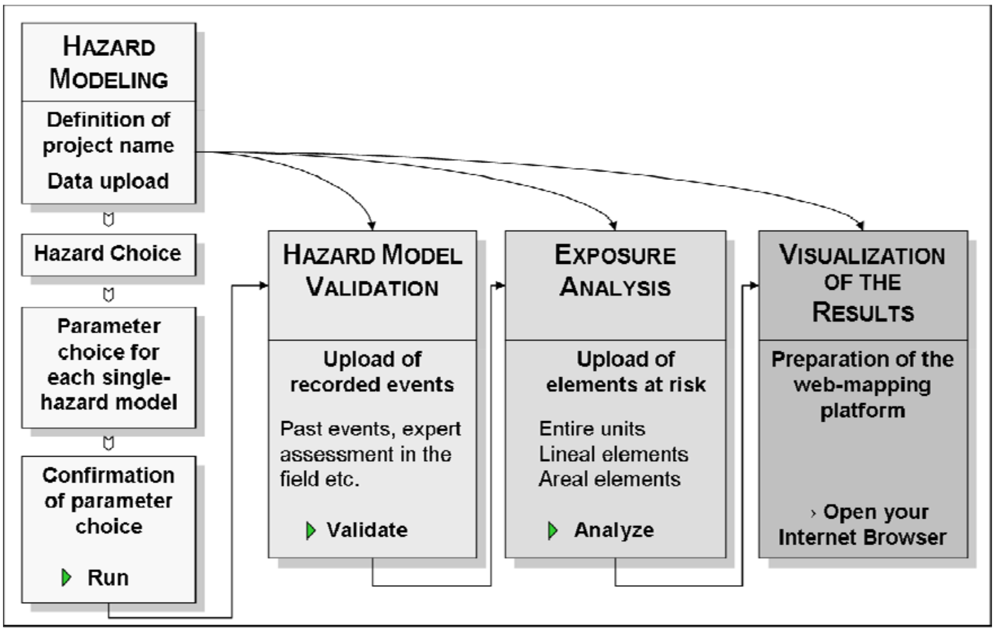

Figure 3 Flow chart of the MultiRISK Modeling Tool.

The preparation primarily implies the copying of all result files in a previously defined folder from which the Visualization Tool obtains the information for display. The following files can be produced during the analysis procedure:

- Hazard modeling: Source and run out files are written for avalanches, rock falls, debris flows, and shallow landslides while only one file for the complete area susceptible to floods is saved (rasters - max. 9 files).
- Validation: The sources and/or the complete area (sources + run out) can be validated. Thus, for all hazards except flood two files can be produced (shape files - max. 9 files).
- Exposure: Exposure to source instability or to the complete process area can be computed, for floods only the *complete* option applies (shape files - max. 9 files).
- Overlapping hazards, result of the intersection of all five *complete* hazard footprints (polygon shape file - one file).
- Number of hazards resulting from the overlay of all five *complete* hazard footprints (raster - one files).

In order to not burden the user with the naming of the many output files the names are generated automatically according to a modular terminology. Appended to the user-defined project name (max. 7 letters), extensions referring to the process (_av for avalanches or _rf for rock fall), to the area (_s for sources, _r for run out and _c for complete) and to the analyses carried out (_val for validation) are added. Consequently, the **VAL**idation result of the **C**omplete area susceptible to **AV**alanches for a project called Barcelo would be named Barcelo_av_val_c (for more detail refer to Kappes, 2011). All files are saved in the project folder defined by the user in the very beginning of the analysis.

3.2. MultiRISK Visualization Tool

The visualization has been automated to prevent the user from having to open each of the max. 29 result files in ArcGIS and define colors, patterns and symbols. Additionally, the contemplation of the outcome in such an application does not require GIS and cartography experience and enables in this way the presentation of the results to a broader audience. The Visualization Tool is designed with the comprehensive and free Web-GIS framework CartoWeb and is embedded in a MapServer engine. The final tool is accessible by the user with a standard internet browser. Currently it is applied in a local host environment but can be modified in the future to be published in the internet, potentially also considering different user groups and respective access to the various data sets. It is structured in different switches, i.e. interactive maps, according to the visualization scheme previously presented (Figure 4):

1. General settings: land use/cover information, lithology, slope and planar curvature are presented and can be examined since they form the basis for the modeling. According to user needs further information of interest could be additionally included in the future.
2. Single hazards: Only one hazard is shown at the time, but in detail, i.e. the source susceptibility (binary, yes/no) and the run out susceptibility (spatial probability with values between 0 and 1) of debris flows, rock fall, shallow landslides or avalanches or the susceptibility to river floods expressed as inundation depth. The color scheme is adopted from the Swiss “Symbolbaukasten” of Kienholz and Krummenacher (1995).
3. Overlapping hazards: A maximum of three hazards can be shown simultaneously. The overlapping areas are displayed as combinations of the colors and patterns of the respective hazards.
4. Number of hazards: The number of hazards is displayed with the option to enquire by means of a spatial query which hazards combine to the respective number.
5. Past events: The records on past events which were uploaded for the validation are presented.
6. Validation: The true positives, areas which were correctly identified as threatened; the false negatives, areas for which events were recorded but which could not be modeled as hazardous; and the false positive, zones which were modeled as potentially hazardous and might in the future be affected by events are visualized. By clicking on a hyperlink an additional tab opens showing the confusion matrix as table indicating the area in m^2.
7. Exposure: For one hazard at a time the susceptibility zones, either source or complete area, are depicted together with the highlighted exposed elements. By clicking on a hyperlink an additional tab opens with the number of e.g. buildings (entire elements), length of e.g. infrastructure and/or e.g. built-up area (proportion of polygons) exposed.

Basic information is offered for display in each tab and includes hillshade, buildings, infrastructure, build up areas and water courses.

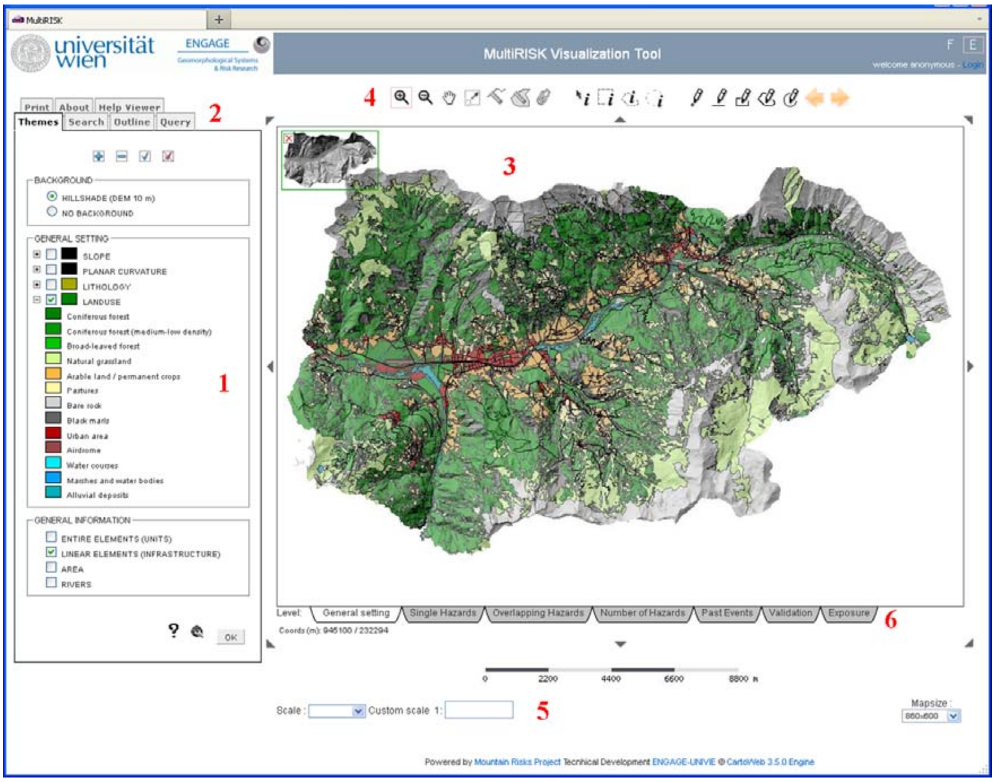

Figure 4 Screenshot of the Visualization Tool. The following descriptions refer to the red numbers in the graphic: 1) Layers tree, managed by the user. According to predefined options layers can be switched on, off, overlain etc. 2) Tabs for query, printing and online guide. 3) Map area and key map visualization. 4) Tools for cartographic interaction as zoom in/out, spatial query etc. 5) Scale and map size customization. 6) Tabs to access the different interactive maps.

4. Case study: An Exposure Analysis in Barcelonnette, France, considering multi-hazards

To test the practicalness and user-friendliness of the MultiRISK Platform a case study has been performed in the Barcelonnette basin. Moreover, the ability of the multi-hazard exposure analysis scheme to account for challenges arising in the multi-hazard context is examined.

4.1. The Barcelonnette Basin

The Barcelonnette basin is located in the southern French Alps in the Département Alpes des Haute Provence. It covers the major part of the community of Communes “Vallé de l’Ubaye”, an alliance of eight communities with a population of approximately 6500 inhabitants. The valley varies between an altitude of 1,100 and 3,100 m and is drained by the Ubaye river. A large number of torrents flow in this river (see Figure 5). It exhibits (1) a mountain climate with pronounced inter-annual rainfall variability (735 ± 400 mm) and 130 freezing days per year, (2) continental influence with large intra-day thermal amplitudes (>20°) and multitudinous freeze-thaw cycles and (3) Mediterranean influence with summer rainstorms providing occasionally more than 50mm/h (Flageollet et al., 1999; Maquaire et al., 2003; Kappes et al., 2011). Apart from summer rainstorms, heavy precipitation onto melting snow accumulations in spring result in high discharge (Flageollet et al., 1999). Meso-climatic differences emerge due to the East-West orientation of the valley, especially between the north- and south-facing slopes. Geologically, the valley presents a structural window with autochtonous Callovo-Oxfordian black marls (the 'Terres Noires') below allochtonous Autapie and Parpaillon flysch (Évin, 1997; Maquaire et al., 2003).

The geological setting is reflected in the specific morphology. The upper slopes between 1,900 and 3,000 m a.s.l. are composed by thrust sheets of cataclastic calcareous sandstones and exhibit slope angles steeper than 45°. These slopes are partly covered by layers of non-consolidated debris with thickness ranging between 0.5 and 5 m. The lower slopes from 1,100 to 1,900 m a.s.l. consist of Callovo-Oxfordian black marls, fragile plates and flakes in a clayey matrix are much gentler with slope angles between 10 and 30°. These slopes are mostly covered by quaternary deposits as poorly sorted debris at taluses, moraine deposits or landslide material (Kappes et al., 2011).

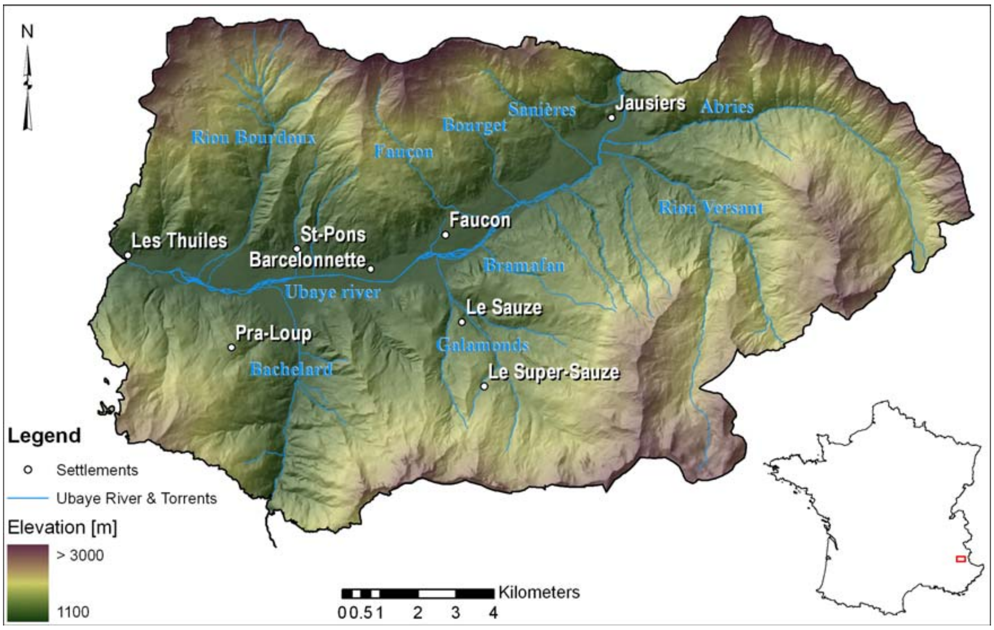

Figure 5 Presentation of the study area indicating the principal settlements and catchments (in blue letters).

The situation and the specific characteristics of the basin give rise to the occurrence of several natural hazards. A large number of river floods produced by the Ubaye are recorded with major events in 1856 and 1957 (Le Carpentier, 1963; Sivan, 2000). Likewise the torrents are very active, Remaître (2006) collected information of approximately 100 debris flows and 461 flash floods in the period between 1850 and

2004. Three large earthflows (Super Sauze, La Vallette and Poche) pose a threat of possible unexpected mobilization and release of debris flows (Malet et al., 2004). In the year 2000 about 250 active rotational and translational landslides were mapped by Thiery et al. (2004). Although rock falls occur predominantly in the higher parts of the valley, also several low-lying regions, as for example in the municipality of Jausiers, are threatened (RTM, 2000). The avalanche inventories of the "Enquête Permanente sur les Avalanches" (EPA) and "Les Donnees de la Carte de Localisation des Phéonoènes d'Avalanche" (CLPA, MEDD) indicate a rather high avalanche activity. As in the case of rock falls,, however, their concentrated is in the upper zone of e.g. the Riou Bourdoux and the Sanières catchment or in uninhabited catchments as the Abries.

In France the prefect of each "Département" is instructed to demand the elaboration of risk prevention plan (formerly a Plan d'Exposition aux Risques Naturels - PER, now a Plan de Prevention des Risques Previsibles - PPR) from all municipalities at risk from natural hazards. Due to the hazard situation in the Barcelonnette basin, all municipalities have to elaborate such a plan and the zoning is incorporated in the spatial planning. The plans indicate areas of high and medium risk in which no or only under the consideration of specific requirements new constructions can be built. The determination of the zones is the result of a combination of modeling, records of past events and expert judgement and covers only the settled areas.

4.2. Input data

A digital elevation model (DEM) with a resolution of 10 m was interpolated from the digitized contour lines and breaklines of channels of the 1:10.000 topographic maps from IGN (Institut Géographique National). Scanning and georeferencing of the maps have been carried out by Thiery et al. (2007). The interpolation was realized with the software program SURFER using a kriging method on the basis of the semivariogram elaborated by Thiery (2007). The resulting DEM was smoothened by 9-nodes averaging and sinks were filled. Furthermore, a second DEM, or to be more precise a digital terrain model (DTM), on basis of airborne interferometric synthetic aperture radar (IFSAR) with a resolution of 5 m derived form an initial digital surface model (DSM) is available. On the slopes the quality of the DGM is clearly better because the DTM was produced by filtering out the forest, a procedure that leads to strong smoothing of the respective areas. In the flood plain and especially in the river channel, itself the quality of the DTM is much higher since on the one hand the distance of the elevation lines which formed the basis of the DEM are very sparse while on the other hand no forest cover interfers the radar image. Thus, the DEM was used for the processes primarily happening on the slopes (debris flows, rock falls, shallow landslides and avalanches) while for the flood modeling the DTM was employed.

On basis of the aerial photographs of the year 2000, the land use was digitized and classified into dense coniferous forest, coniferous forest of average to low density, deciduous forest, natural grassland, arable land/permanent crops, pastures, bare rock, bare soil, urban areas, mining sites, water courses and marshes and water bodies by Bordonné (2008). The information on the lithology was digitized from the geological map (1:50,000) constituting the following ten classes (Bordonné, 2008): marls, torrential alluvium, limestone, boulder fields, talus slopes, flysch, gypsum, lacustrine deposits, calcareous marls and moraines.

With respect to elements at risk, databases with the footprints of all buildings, outline of the settled areas and infrastructure (roads and paths) was at disposal from the LIVE institute (Laboratoire Image, Ville, Environment) of CNRS, University of Strasbourg.
With respect to past events the following information is available:

- Debris flows: Envelopes (polygons) of the deposition of the debris-flow events observed in 1996, 2002 and 2003 at the Faucon, Sanières and Bourget torrents based on post-event field observations (Remaître, 2006). For the 2003 event in the Faucon catchment the full process area is available (source, transport and deposition).
- Shallow landslides: Out of the landslide inventory of Thiery (2007) and Thiery et al. (2007), compiled at a scale of 1:10,000 on basis of literature analyses, aerial photo interpretation and field surveys those records referring to translational (debris) slides were extracted. A limitation of this inventory is its restriction to the eastern part of the study area, from Faucon and Galamonds to the east.
- Rock fall: As for shallow landslides also for rock fall records taken out from the landslide inventory of Thiery (2007). This information was merged with the rock fall zones indicated by the PPR of Jausiers (RTM, 2000).
- Avalanches: The CLPA inventory (Les Donnees de la Carte de Localisation des Phéonomènes d'Avalanche, (MEDD) provides information on terrain observations and photo-interpretation results for the south-eastern part of the study area comprising primarily the north-facing slopes (parts of the Bachelard catchment, Galamonds, Bramafan Riou Versant and Abries nearly completely).
- Flood: No spatial information on the extent of past events is available. Thus, the flood risk zones indicated in the different PPRs (RTM, 2000, 2002, 2008) were put together and used for the flood model validation. From the hydrological reports after IDEALP and Hydroetudes (2008), IDEALP and Hydroetudes (2010) information about the 100a discharge values of the Ubaye at five points between Jausiers and Barcelonnette was derived.

4.3. Hazard-modeling - parameter choice

The calibration or parameterization of a model is a very difficult task, especially in a multi-hazard setting. To enable the comparison of the exposure to single-hazards the reference of the analyses has to be synchronized primarily. The reference relates to qualitative or quantitative scenarios as *medium-frequency events*, *events with a 100-year return period*, *high-magnitude events*, *worst-case* or the like. The selection of parameters or the model calibration for such scenarios can either be based on statistical inventory analyses, expert knowledge or on literature review of comparable studies and transfer of the parameter values. A challenge all options share in the multi-hazard environment is the unequal availability of information for the different hazards:

- Inventories hold much more information on frequently occurring hazard types having affected settled areas and might completely underestimate very rare processes.
- Experts have in very few cases a profound background concerning a wide range of different hazards.
- Literature of studies with very similar conditions is not for any constellation and for any hazard equally available.

Although the Barcelonnette basin has been investigated for many years by many scientists, not enough inventory data is available to calibrate all five processes without further detailed literature examination, field surveys and photo interpretation. Thus in this study, in accordance with the objective to facilitate the computation of a fast and simple approximation without high data requirements the computation of *worst-case scenarios*[1] has been chosen. Based on the literature of comparable settings, parameter values are chosen which are related to the largest recorded events or methodologies selected to estimate these parameter values empirically. Consequently, no inventory data is needed for the calibration but can, if available, be fully used for the validation. Scientific journals and reports were searched for the necessary input parameters and always the value (rounded) leading to the largest area identified as threatened was chosen. In the following, the examined literature is presented shortly (see Table 4 for a listing of the, in MultiRISK required, parameters and the values finally selected on basis of the literature review):

Debris flows:

Sources: For the identification of gullies for debris flow initiation a planar curvature of < -2/100 m was adopted as proposed by Horton et al. (2008). Between rare and extreme fitting the second one was chosen because in case of small upslope areas it also assumes the existence of a source without very steep slope angles. Areas of outcropping limestone can, with high probability, be excluded as potential sources.

Run out: Rickenmann and Zimmermann (1993) mapped about 800 debris flow events triggered in the Swiss Alps during intense rainstorms in the summer of 1987 and identified a minimum slope angle of nearly 11°. Bathurst et al. (1997) mention an angle of about 0.2 (~11°) for Japan according to personal communication with Takahashi in 1995. Huggel et al. (2002) established a worst-case angle of reach for debris flows resulting from glacier lake outbursts. Reviewing a quantity of cases in the Alps and Canada, they fitted a curve to the angle of reach as function of the maximum discharge and assessed a threshold angle of 11°. Zimmermann et al. (1997) studied a set of debris flows especially in the Swiss Alps and found a minimum average slope angle of 0.2 (~11°) for coarse and middle-granular debris flows and 0.12 (~7°) for fine-grained debris flows. Prochaska et al. (2008) identified, reviewing a large quantity of investigations, a minimum angle of reach of 6.5°. The lowest value detected, 7° rounded, was adopted for the worst-case modeling.

Rock falls:

Sources: Guzzetti et al. (2003) identified a slope angle threshold of 60° for Cretaceous granitic rocks, including granite, granodiorite and diorite for a 10 m DEM-resolution. Ayala-Carcedo et al. (2003) worked with 45° in a granitic paleozoic zone for 5 m distance elevation lines and Jaboyedoff and Labiouse (2003) determined an angle of 40° for local and 45° for regional analyses for a valley in Vaud, Switzerland, consisting of carbonates. Wichmann and Becht (2003) used an angle of 40° for two catchments in the Northern Limestone Alps, Germany, with a DEM resolution of 5 m and Frattini et al. (2008) applied an angle of 37° for an area composed by sandstones and carbonate rocks intermitted by intrusive and effusive rocks and a DEM resolution of 10 m. Since material and DEM resolution fit, the lowest identified angle of 37° was adopted for the rock fall source modeling under exclusion of outcropping black marls and clays.

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[1] Worst-case is in this study defined as an event of very high magnitude and rather low frequency.

Run out: Rickli et al. (1994) distinguish the angle of reach according to the resistance and the size of the blocks: 33° for small rocks if the resistance is low and the underground smooth or the blocks are larger, resistance is high and the underground is not smooth, 35° for middle to small blocks and 37° for small ones with high resistance and no smooth underground. For the Solà d'Andorra la Vella (granodiorite and hornfels), a statistical analysis of a set of past events resulted in the 90, 99 and 99.9 percentiles at 41.3°, 39.5° and 36.9°, respectively (Copons and Vilaplana, 2008; Copons et al., 2009). Jaboyedoff and Labiouse (2003) applied in their study an angle of reach of 33° (carbonates) and Domaas (1985, cited by Toppe, 1987), detected, that 95% of the rockfalls stop within an angle of 32°. Onofri and Candian (1979, cited in Jaboyedoff, 2003) assume 100% of rock fall events within the 28.5° run out. The lowest slope angle was 28.5° and thus the rounded value of 29° was applied in this study.

Shallow landslides:

Sources: Concerning the parameterization of SHALSTAB, Real de Asua et al. (2000) suggest for comparison purposes standard values of 1,700 kg/m^3 for the bulk density and 45° for the friction angle. With this high friction angle Real de Asua et al. (2000) attempt to compensate the negligence of factors as the root strength of forest and understory as well as for the elimination of cohesion (Real de Asua et al., 2000; Montgomery and Dietrich, 1994; Dietrich et al., 1998). However, for a worst-case scenario, the assumption of area-wide stabilization due to these effects is not meeting the objective of identifying all susceptible areas. Montgomery et al. (1998) applied a friction angle of 33° and Meisina and Scarabelli (2006) used an angle of 28° which was adopted for this study. For the determination of the critical steady state rainfall a study on rainfall thresholds for shallow landslides and debris flows in the Barcelonnette basin carried out by Remaître et al. (2010) has been consulted. Since the landslide threshold values are much more influenced by antecedent rainfall than the debris flow values, Alexandre Remaître (personal communication, 14.02.2011) recommends to use debris flow thresholds and advises daily rainfall values of 30-50 mm/day on basis of a database of past records (Remaître et al., 2010) The lower value of 30 mm/day was adopted for this study. For areas without comparable information the web page of the “Istituto di Ricerca per la Protezione Idrogeologica” (IRPI) gives an overview on general rainfall thresholds and can perfectly serve as first orientation in cases for which no statistical analyses have been carried out.

Run out: The angle of reach is rarely used for the shallow landslide run out computation and only few studies were detected. Corominas (1996) mentions a tangent of the angle of reach of less than 0.8 (about 39°) for all recorded shallow landslides in his inventory. Corominas et al. (2003) assume in their study 26° (30°) for small <800m^3, 22° (25°) for medium 800-2000m^3 and 20° (23°) for large slides >2000m^3 for unobstructed (obstructed) paths. On basis of the scarce literature detected, a constant friction loss angle of 20° was assumed.

Avalanches:

Sources: In accordance with Maggioni (2004) hillsides with a slope between 30° and 60° were chosen while densely forested regions were excluded. Ridges are automatically excluded in MultiRISK.

Run out: According to McClung and Schaerer (1993) the run out angle of avalanches ranges between 15° and 50° while Liévois (2003) mentions a span between 55° and 28-

30°, in exceptional cases even as low as 20° for slush-flows. Lied and Bakkehøi (1980) investigated 423 avalanches and observed values between 18° and 50° with a mean value of 33°. Hereby, 95% show a gradient greater than 23° and about 75% greater than 27°. Mc Clung et al. (1989) investigated four mountain ranges and found for the set of 100 year avalanches a minimum angle of 14° (the Sierra Nevada) and a maximum of 42° (Western Norway). McClung and Lied (1987) investigated 212 avalanches and found a range of 18-49° with a mean of 30.3°. Barbolini et al. (2011) calculated an average slope angle of 27.3° with a standard deviation of 5.1° for an inventory of 2004 extreme avalanches in the Italian mountain range (Alps and Apennines). The lowest detected angle of 14° was adopted for this study.

Flood:

A parameter value choice, as for the previous processes, is not possible in the case of floods because the maximum possible discharge values or inundation depths depend stronger then in case of the previous processes on the specific setting. An equivalent of a worst-case run-out is presumably the probable maximum flood (PMF) which is defined by Francés and Botero (2003; p.223) as the “biggest flood physically possible in a specific catchment”. The PMF can be computed on basis of the probable maximum precipitation and a precipitation-runoff model as proposed in Ely and Peters (1984) or alternatively empirically by means of statistical analyses of discharge time series (Francés and Botero, 2003). An alternative concept to the PMF is the extreme flood, defined by the CEC (2006) and in the Flood Assessment and Management Directive (EP and EC, 2007) as an event of low probability and, as the term indicates, of very high magnitude. The ways to compute extreme floods differ widely but are in general more pragmatic and exhibit lower data requirements than the methods used for the PMF:

- Assumption of a certain return period of the extreme flood: Ruiz Rodriguez + Zeisler et al. (2001) use the 1,250-10,000-year return period for the flood modeling of the Rhine-delta. Bründl (2008) applies for a case study of the river Lonza at the communities Gampel and Steg in the Canton Wallis the 1,000-year event as an extreme flood.
- Increase of a certain flood scenario by a defined inundation depth as *extreme value addition* (Extremwertzuschlag; UVM, 2005): UVM (2005) propose the 100-year or 200-year flood + *x* m, for one partition of the Oder the 200-year flood + 1 m is used (OderRegio, 2006) and for the extreme flood computation for several parts of the Rhine, Ruiz Rodriguez + Zeisler et al. (2001) applied the 200-year flood + 0.5 m.
- Multiplication of a certain discharge scenario by a defined factor: the practitioners having participated in the workshop on risk management of alpine torrents and rivers Klumpp and Hörmann (2010) defined the threshold for acceptable residual risk which corresponds to the extreme event of the EU flood directive to 100-year flood × 1.6. This method is also frequently used for the designing of spillways as shown in the study of the TU Wien (2009) and in rivershed analyses (André Assmann, personal communication). Hydrotec (2009) used for identification of areas beyond the flood protection goal for the Solmsbach the 100-year flood × 1.3.

The methods to assess the PMF are rather sophisticated and data-demanding and for the statistical computation of a very low frequency scenario as e.g. a 10,000-year event an extensive inventory is necessary, if such estimations are, on basis of rather short-period inventories, *possible* at all. The increase of a certain flood scenario by a defined inundation depth depends strongly on the specific morphology and is not really transferable to other regions. Furthermore, this method is also very problematic if channeled and braided river sections alternate as it is the case in the Barcelonnette basin. Therefore, the multiplication of a comparably *frequent* and thus better assessable event (100-year event) with a certain factor was chosen to determine the discharge of the *extreme flood* which is assumed to be a suitable equivalent to the worst-case modeling of the other hazards. The modeling was run for 48 h at the constant discharge of the 100-year flood × 1.6 to achieve a steady state flooding.

In Table 3 an overview of the parameters to be defined in the MultiRISK Modeling Tool and the values assumed for the worst-case analysis in the Barcelonnette basin are compiled.

Table 3 Summary of the parameters to be defined in the software for the modeling of the different hazards and the selection made for the case study

	Source		**Run out**	
	Parameters	Values chosen	Parameters	Values chosen
Debris flow	Planar curvature threshold Slope angle - upslope area threshold Land use/cover & lithological units to be excluded	< -2/100 m^{-1} Extreme fitting Outcropping limestone	Holmgren exponent Angle of reach (= constant friction loss angle)	1 7°
Rock falls	Slope threshold Land use/cover & lithological units to be excluded	37° Outcropping marls & clays	Holmgren exponent Angle of reach	1 29°
Shallow landslides	Soil bulk density Slope threshold (friction angle) Critical rainfall threshold Lithological units to be excluded	1,700 kgm^3 28° 30 mm Outcropping limestone	Holmgren exponent Angle of reach	1 20°
Avalanches	Slope threshold Land use/cover units to be excluded	30-60° Dense forest	Holmgren exponent Angle of reach	1 14°
River flood	Hydrograph, 100-year flood * 1.6, 48 h duration			

4.4. Validation and exposure analysis

The validation has been carried out for the complete susceptible areas by means of the inventory information described in the input data section. No use has been made of the option to validate the sources susceptibilities separately since respective inventory information is lacking.

The exposure analysis has been performed for the available building database while the buildings are treated as entire units. Likewise the exposure of infrastructure and settled areas was examined, however, in these cases the fractions exposed were quantified.

4.5. Results and Discussion

If the input is prepared and the parameters are determined, the setup of the model takes about 5 minutes (definition of the project folder and name, upload of the input files and entering of the parameters). With the choice of the *quick* mode for the run out calculations the modeling ran in total about 50 hours[2] whereof the hazard analysis, and more precisely the run out computation, took most of the time. The duration is dependent on the number of sources identified, e.g. the more source pixels are considered, the longer is the computation time. The *complete* modeling takes much longer as the values in brackets behind the duration of the *quick* analysis indicate (Table 4). Thus with the present computer specifications, it is not a really flexible method while the quick run serves, as comparisons indicated, very well. Hence, the modeling has been carried out in the quick mode. The data preparation, derivative production and source identification of all processes lasted for about 20 min in total. The validation for all five processes took about 5 minutes and the exposure analysis around 5 minutes as well. The preparation of the data for the visualization accounted for another max. 10 minutes.

Hazard analysis

The results indicate the largest susceptible area for snow avalanches with over 200 km^2, directly followed by shallow landslides with almost 200 km^2 (Table 4). Rock falls (~87 km^2) and debris flows (~63 km^2) affect a much smaller region and river floods exhibit the smallest susceptibility zone with only about 11 km^2, however, located in the most densely populated region. This area distribution is partly a result of the repartition between slopes, which occupy the largest proportion and are prone to debris flows, rock falls, shallow landslides and avalanches, and flood plains, prone to river floods, in the study site. However, also the process characteristics are of a major relevance, e.g. debris flows are spatially not as extensive as snow avalanches. Finally also the parameterizations exert a great influence.

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[2] Computer specifications: Intel® Core(TM)2 CPU 6400 @ 2.13GHz, 2.13 GHz, 3.25 GB RAM, Windows XP.

Table 4 Overview over the analysis results for the processes debris flows (DF), rock fall (RF), shallow landslides (SL), avalanches (AV) and floods (FL). TP - true positives, FP - false negatives, FN - false negatives and TN - true negatives.

	Quick (complete) [h]	**Complete area susceptible (% of the whole area)** [m^2]	**Validation of the complete susc. area:** TP, FP, FN, (TN) [m^2]	**Exposure to sources**	**Exposure complete**
				Nr. of buildings [-] -Road length [m] - Settled area [m^2]	
DF	~1 (36) → run out	62,995,900 (17%)	210,936 0.06% 62,784,964 16.90% 42,259 0.01% (308,442,833) 83.03%	1 463 225	1,143 110,911 1,249,831
RF	~4 (11) → run out	86,629,178 (23%)	555,834 0.15% 86,073,344 23.17% 53,328 0.01% 284,798,486 76.67%	10 6,638 4,389	49 40,081 34,765
SL	10 (~336) → run out	195,782,092 (53%)	503,463 0.14% 195,278,465 52.57% 40,394 0.01% (175,658,670) 47.29%	297 104,327 157,803	872 228,825 651,148
AV	~10 (>340) → run out	212,672,507 (57%)	49,144,230 13.23% 163,528,277 44.02% 2,377,168 0.64% (156,431,317) 42.11%	36 18,111 11,628	1,633 254,718 1,684,640
FL	~24	10,447,502 (3%)	3,366,192 0.91% 7,081,310 1.91% 296,430 0.08% (360737060) 97.11%	1,319 64,419 1,902,747	

In Figure 6 examples for the presentation of the results of hazard modeling step in the MultiRISK Visualization Tool are given. The produced information is shown in three different shifts, first the single hazards are displayed, secondly the overlay of three hazards and finally the number of hazards with the option to spatially query the underlying processes. The map depicting the number of overlapping hazards (Figure 6 at the bottom) indicates a high potential of the coincidence of two, three or even four hazards, especially on the slopes. Especially the upper slopes are prone to three or four processes while the torrent channels at lower altitudes unite mostly only two hazards.

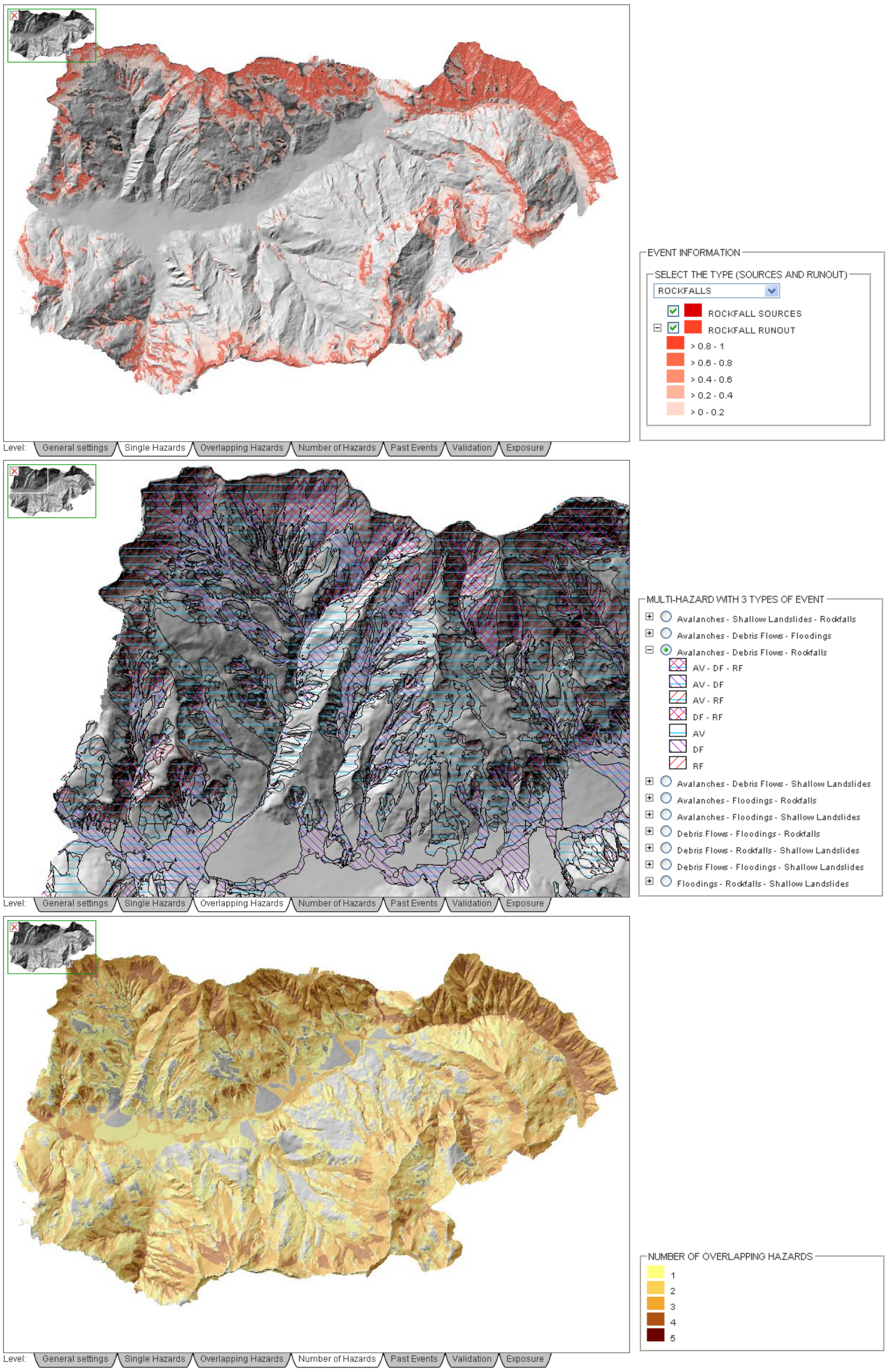


Figure 6 Examples for the presentation of the hazard modeling results in the MultiRISK Visualization Tool (Note: The brown colors in the lower graphic refer to the number of hazards in

Validation

The sensitivity of all five hazards is rather high with at least 83% in case of debris flows and up to 95% for avalanches (Table 5). This means, between 83% and 95% of the recorded events are covered by the corresponding hazard modeling results. However, a very high sensitivity is to be expected in a worst-case analysis which aims at indicating all susceptible areas. In return, a rather low positive prediction power (PPP) can be suspected for worst-case scenarios and indeed the good sensitivity results are relativized by PPP values below 1% for debris flows and rock falls followed by shallow landslides with about 7%. Additionally to the very conservative modeling approach that underlies worst-case studies, the inventories of these three processes are particularly small and result consequently in low proportions of true positives and low PPP.

Table 5 Presentation of the proportions of TN, FP and FN as well as the quality indicators sensitivity (SY) and positive prediction power (PPP) of the modeling results. The highest value for category is marked light grey.

	DF	RF	SL	AV	FL
TP	0.06%	0.15%	0.14%	13.23%	0.91%
FN	0.01%	0.01%	0.01%	0.64%	0.08%
FP	16.9%	23.17%	52.57%	44.02%	1.91%
SY	83.31%	91.25%	92.57%	95.39%	91.91%
PPP	0.33%	0.64%	7.43%	23.11%	32.22%

The positive prediction power of avalanches is with ~23% only exceeded by the flood result with ~32%. The same two processes exhibit also the highest sensitivity values. However, the validation results cannot be interpreted without considering the hazard type and its specific characteristics (cf. Figure 7). The overall area potentially susceptible to e.g. river flooding is probably to a much higher percentage already covered by few records of past events since river floods take place in the mostly definite area of the flood plain. By contrast, the area e.g. susceptible to the occurrence of shallow landslides is much less restricted to a certain region as a flood plain and additionally landslides will not recur but only reactivate.

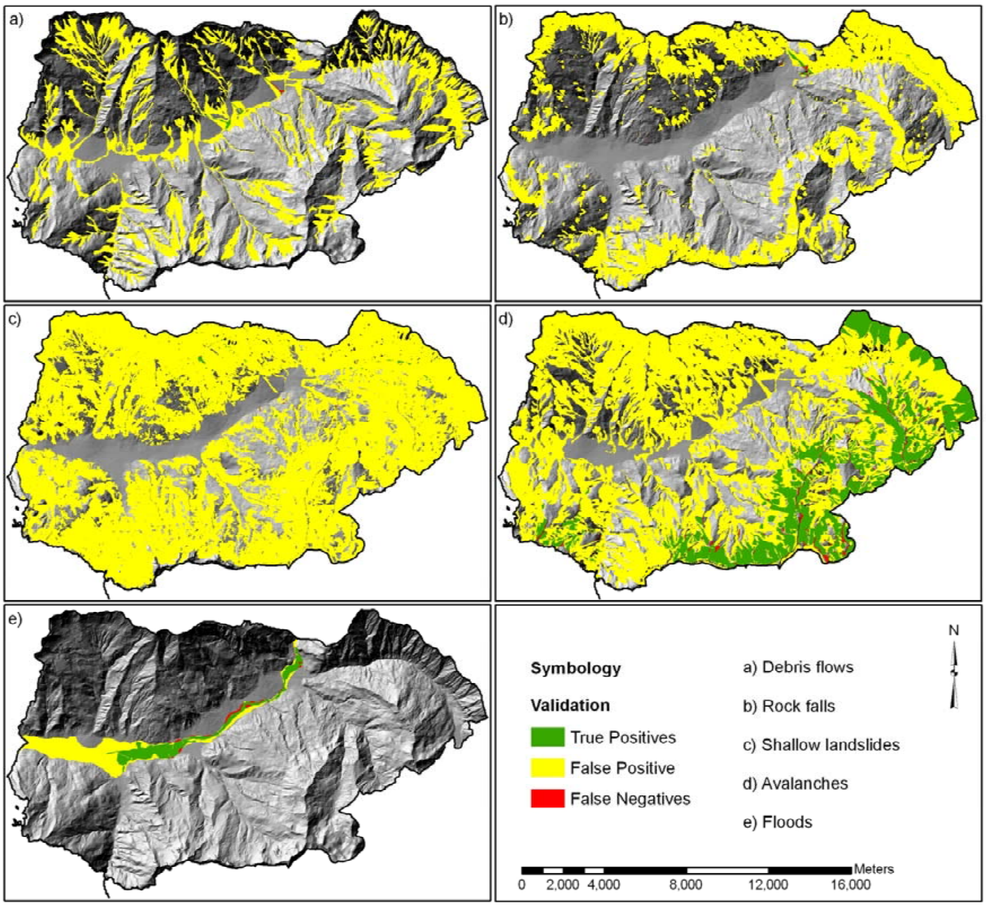


Figure 7 Maps of the validation result

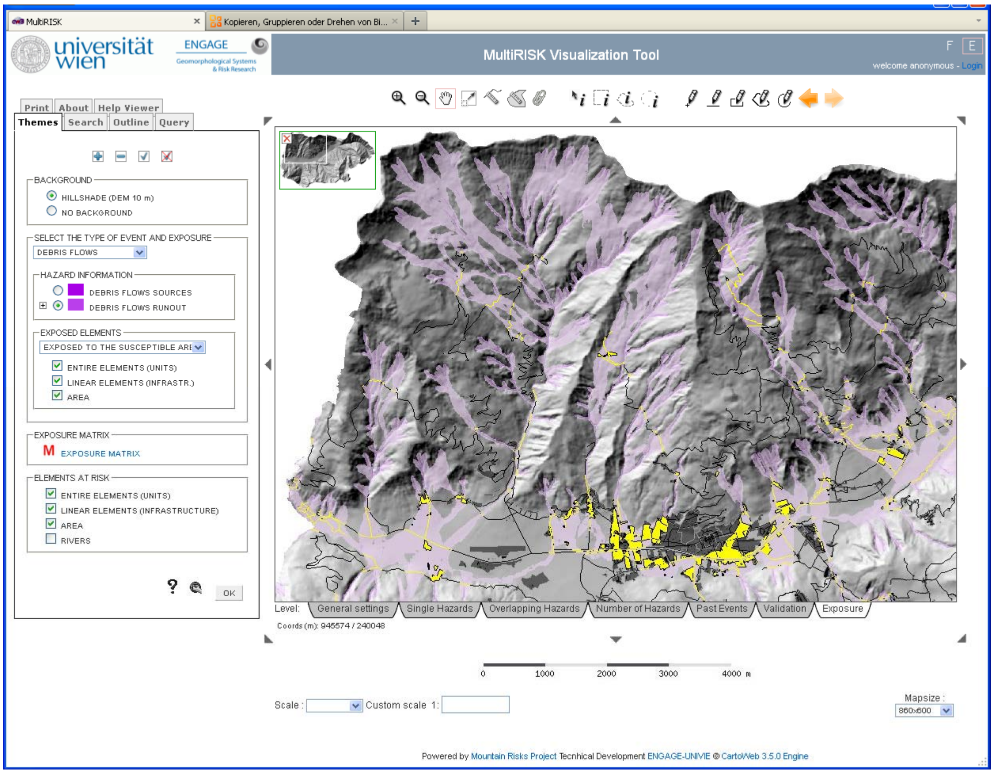
This means, the false positive proportion of shallow landslides is most probably always higher than for floods due to the process characteristics. Consequently, PPP values achievable for flood modeling are probably not realistic for shallow landslide models. Furthermore, floods, avalanches, rock falls and debris flows are, to a greater or lesser extent, recurring events while shallow landslides may be reactivated but do rarely occur in the same or a very similar location as for the first time failure. These different aspects complicate a clear ranking of the modeling result.

For the present study a clear quality difference is notable, at least between the avalanche and flood modeling results with comparatively high sensitivity and the outcome of the rock falls, debris flows and shallow landslides computation. However, a more detailed ranking is difficult and depends on the weighting of sensitivity versus the PPP or the FN versus TP and objective of the analysis procedure, respectively. For all hazards an overestimation of the actually susceptible area can be assumed due to the way the values for the model parameterization were obtained. Especially the susceptibility of 53% and 57% of the study area to shallow landslides and avalanches suggests an unrealistic modeling result. However, the validation based on mostly rather small inventories does not enable a clear judgement.

In summary, confusion matrices proved well-utilizable in a multi-hazard context. However, each single validation result has to be interpreted carefully under consideration of the process specificities, the inventory size etc. and also the comparison between process validations has to be done with caution.

Exposure

The lowest exposure results from rock fall with only ~40 km of roads and paths, 49 buildings and 34,765 m^2 of settled area, respectively (Table 4). In contrast, the highest numbers exhibit debris flows, floods and avalanches with far more than 1,000 buildings exposed. Especially due to river flooding to which only about 3% of the study area is susceptible, a very high exposure arises which originates from the close vicinity of many cities and villages to the river course. On the contrary, shallow landslides cover more than 50% of the area but the exposure concerning buildings and built-up area amounts to less than half of the one of avalanches. In Figure 8 an example for the visualization of the exposures in MultiRISK is given.



BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

SELECT THE TYPE OF EVENT AND EXPOSURE
DEBRIS FLOWS

HAZARD INFORMATION
○ DEBRIS FLOWS SOURCES
● DEBRIS FLOWS RUNOUT

EXPOSED ELEMENTS
EXPOSED TO THE SUSCEPTIBLE ARE
☑ ENTIRE ELEMENTS (UNITS)
☑ LINEAR ELEMENTS (INFRASTR.)
☑ AREA

EXPOSURE MATRIX
M EXPOSURE MATRIX

ELEMENTS AT RISK
☑ ENTIRE ELEMENTS (UNITS)
☑ LINEAR ELEMENTS (INFRASTRUCTURE)
☑ AREA
☐ RIVERS

Coords (m): 945574 / 240048

Mapsize : 860x600

Powered by Mountain Risks Project Tecnhical Development ENGAGE-UNIVIE © CartoWeb 3.5.0 Engine

Figure 8 Screenshot of the visualization of exposed elements in the MultiRISK Visualization Tool - exposure to debris flows.

Summarizing, the analysis of the Barcelonnette case study using the software tool MultiRISK proved much more comfortable, user-friendly and much less error-prone than the separate modeling of all single steps, previous attempts to step by step perform the analysis enabled the authors to come to this conclusion. By means of literature review complemented by few expert advices and statistical analyses a worst-case parameterization followed by hazard model validation and exposure assessment could be carried out. Although an overestimation of the susceptible area has to be strongly assumed, long time- and resource-consuming data acquisition has been avoided. However, the applicability and usefulness of such an approach for a very first approximation of an unknown area has to be examined in future studies together with stakeholders.

5. Overall Discussion and Conclusions

In this study the development of a modeling and a visualization scheme was presented, their automation in software tools outlined and a case study performed. Thereby, many challenges and additional aspects arising in a multi-hazard context were faced. Although, many issues and difficulties could be coped with, this study raised even more new perspectives and questions which will be discussed in the following:

1. The comparability of modeling results is one of the main objectives of the analysis scheme proposed here. To achieve this goal, similar or at least somehow equivalent models should be selected. However, two major problems emerged: a) the existence and detection of similar models and b) the question if similar models assure comparability. (a) Already in the presented set of hazards difficulties arose with the selection of similar models, for instance with respect to methods for source identification: while simple empirical methods are commonly in use for rock falls, debris flows and avalanches, slopes susceptible to shallow landsliding are usually analyzed by statistically and physically based models. Moreover, while two-step approaches of source identification and run out modeling are commonly applied for rock falls, debris flows, shallow landslides and avalanches, the analysis of floods follows completely different procedures, assumptions and decisions. Other processes as earthquakes, storms or forest fires differ even stronger from the processes presented here, not only with respect to the modeling approaches and the spatial extent but also regarding the temporal scale they act at. This leads to difficulties to define common scenarios since e.g. the modeling of the 20-year events may be possible for floods, rock falls or debris flows but such events are of very low relevance in the earthquake context. Likewise, the rock fall or debris flow with a 1000-year return period is a very rough assumption, while much more in use for earthquakes. This does also apply for the worst-case parameterization used for the case study. The inclusion of a process of such low frequencies but extremely high magnitudes with high spatial extent would lead to a distortion of the result due to the dominance of the earthquake threat. (b) Furthermore, the question arises if the utilization of similar or even equal methods for the modeling of distinct hazards as in the case of run out modeling by means of the angle of reach concept does automatically assure comparability of the results. While for debris flows or rock falls a large quantity of studies was detected, in case of shallow landslides only two

articles were found, an indication of the less frequent use of this technique for shallow landslides and possibly a lower suitability of this method. Especially the validation results indicate very well, that differences between hazards due to contrasting characteristics can not simply be overcome and comparability is not automatically assured by the application of the same methodology. Differing suitability and applicability of an approach when used for contrasting processes may result in very distinct model qualities. However, if the previously proposed attempts to achieve comparability do not in any case meet the objective to produce comparable results, then how can comparability be assured? By aiming at similar quality and uncertainties of the models? How can this be measured and is it possible to meet this goal? Or is it sufficient to produce results of the same metrics at a predefined scale and all the differences have only to be considered in the interpretation of the outcome? Especially when the model choice is constrained by data availability this is may be the most realistic strategy.

2. A challenge becoming apparent in the case study is the parameterization or calibration of the models. Despite the fact, that the chosen study area is already investigated for many years by several universities, insufficient inventory information is available to carry out a complete multi-hazard model calibration. A rather simple approach has been chosen with the modeling of worst-case scenarios on the basis of literature information, multiple assumptions and generalizations. Although this approach apparently led to an overestimation of the susceptible areas and the number of exposed elements, it offers the determination of general hazard distributions, overlaps and areas of potential risk without data-demanding calibration. By now a parameter set is available by means of which a very fast approximation of a completely unknown area can be performed and much time can be saved. The actual usefulness of this worst-case scenario parameter set and the resulting grade of overestimation have to be examined in further regions. Nevertheless, the meaningfulness of such a blind analysis depends primarily on the objective and restrictions of the respective study. In areas without any inventory information and previous hazard analyses such a worst-case analysis may offer helpful indications which areas have to be regarded in more detail.

   For better adjusted parameterization or calibration of the models difficulties have to be solved in each single situation individually. This means that solutions have to be found according to the available data and the legislative framework requiring the computation of certain scenarios or the like. Thereby, expert appraisal seems to be an indispensible component in multi-hazard risk analyses. Multi-hazard information, especially regarding inventory data, is probably always fragmentary and has to be complemented and pieced together. Nevertheless, a problem is that only few experts have real multi-hazard experience.
3. Although the presented analysis concept is designed as top-down approach, in this study only the first step is outlined, the regional exposure analysis scheme. Nevertheless, in the elaboration of a local analysis scheme many additional problems will emerge such as the development of a vulnerability analysis scheme. Depending on the type of hazard differing methods are used such as curves, matrices or indicator-based approaches (Kappes et al., in press). For instance, vulnerability curves are frequently applied for flood and earthquake modeling but are still not available for

rock falls. Thus, the question is how to combine different methods or identify one method (e.g. vulnerability matrices) which can be applied for all processes. Moreover the vulnerability is altered by simultaneous or sequential hazard impacts (Kappes et al., in press). Furthermore, local multi-hazard risk analyses require much detailed information and although with the regional analysis zones of special interest are identified, the acquisition of the necessary information for these areas is a challenge.
An extension of MultiRISK towards full-hazard and risk at a local scale is planned to facilitate detailed examination of those areas determined at a regional scale. Moreover, the inclusion of further processes as, for instance, earthquakes and flash floods is under consideration.

4. Aspects not approached in detail in this article are relations and interactions between hazards. Since hazard relations are, until now, not automated in the MultiRISK Modeling Tool, they were not presented in the present study. Nevertheless, ideas and recommendations how to regard for this issue at a regional scale are already presented in Kappes and Glade (2011). Primarily the implementation of feedback loops and the identification of areas susceptible to hazard chains with the overlay of modeling results are proposed.
5. The multi-hazard modeling is followed by the interpretation of the results which includes especially the determination of acceptable and tolerable levels of hazard and risk for certain types of use or the planning of mitigation measures. In Switzerland and France, broad guidelines for the performance multi-hazard analyses and thresholds already exist, directly linked to the implementation of the hazard zones into the spatial planning. However, without the provision of a software tool such analysis guidelines face the challenge of comparability problems between municipalities since distinct methods are used in each administrative unit. The analysis performance is often outsourced to consultants. However, this results in low transparency and information on the modeling procedure and does not offer the option to flexibly compute and examine scenarios, update the analyses, to name some topics only. The linkage with a tool, which has to be adapted to the specific requirements, legislation and other user-specific needs, would accelerate and simplify the procedure and make the results more transparent. Although the first parameterization and adaptation to the specific area and user-needs will always require expert support from outside the tool itself could stay in the hand of the e.g. municipalities and offer flexible and fast rerunning. How realistic the introduction of such a tool in administrative bodies and institutions is depends on the legislation, the duties of the administrative units and many more aspects. However, an interesting example offers HAZUS in the United States, elaborated by and freely available from FEMA. HAZUS is a software tool for flood, hurricane and earthquake modeling which is delivered together with a nation-wide database offering sufficient information to carry out a first overview analysis of any region in the US.

Concluding, multi-hazard settings pose a wide range of challenges. Although several difficulties can be solved by a coherent analysis scheme and the automation of the analysis procedure, many problems persist and require experience in handling and analyzing of multiple hazards but also careful interpretation of analysis results.

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Bibliography

Apel, H., Aronica, G., Kreibich, H., Thieken, A., 2009. Flood risk analyses - how detailed do we need to be? Nat. Hazards 49, 79–98.

Ayala-Carcedo, F., Cubillo-Nielsen, S., Alvarez, A., Domínguez, M., Laín, L., Laín, R., Ortiz, G., 2003. Large scale rockfall reach susceptibility maps in La Cabrera Sierra (Madrid) performed with GIS and dynamic analysis at 1:5,000. Nat. Hazards 30, 325–340.

Bakkehøi, S., Domaas, U., Lied, K., 1983. Calculation of snow avalanche runout distance. Ann Glaciol 4, 24–29.

Barbolini, M., Pagliardi, M., Ferro, F., Corradeghini, P., 2011. Avalanche hazard mapping over large undocumented areas. Nat. Hazards 56, 451–464.

Bathurst, J., Burton, A., Ward, T., 1997. Debris flow run-out and landslide sediment delivery model tests. J. Hydraul. Eng. 123, 410–419.

Bausch, D., 2003. HAZUS: FEMA's GIS-based risk assessment tool. In: Proceedings of the GITA conference (Geospatial Information & Technology Association). http://-www.gisdevelopment.net/proceedings/gita/2003/disman/dism09pf.htm

Beguería, S., 2006. Validation and evaluation of predictive models in hazard assessment and risk management. Nat. Hazards 37, 315–329.

Bell, R., 2002. Landslide and snow avalanche risk analysis - methodology and its application in Bíldur, NW-Iceland. Master's thesis, Rheinische Friedrich-Wilhelms-Universität Bonn.

Bell, R., Glade, T., 2004. Multi-hazard analysis in natural risk assessments. In: International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation. Brebbia, C.A., Rhodes, Greece, pp. 197–206.

Blahut, J., Horton, P., Sterlacchini, S., Jaboyedoff, M., 2010. Debris flow hazard modelling on medium scale: Valtellina di Tirano, Italy. Nat. Hazard Earth Sys. 10, 2379–2390.

Bordonné, M., 2008. Cartographie de laves torrentielles dans le bassin de Barcelonnette. Master's thesis, Université Louis Pasteur, Strasbourg.

Bründl, M., 2008. Risikokonzept für Naturgefahren - Leitfaden. Tech. rep., Nationale Plattform für Naturgefahren PLANAT, Bern, access 24 January 2009. www.riskplan.admin.ch

Bründl, M., Romang, H., Bischof, N., Rheinberger, C., 2009. The risk concept and its application in natural hazard risk management in Switzerland. Nat. Hazard Earth Sys. 9, 801–813.

Carranza, E., Castro, O., 2006. Predicting lahar-inundation zones: case study in West Mount Pinatubo, Philippines. Nat. Hazards 37, 331–372.

CEC, 2006. Proposal for a directive on the assessment and management of floods. Com (2006) 15, Commission of the European Communities.

CEPREDENAC, ISDR, IDB, Worldbank. CAPRA Portal (Central American Probabilistic Risk Assessment). Access 10 February 2010. http://www.ecapra.org/en/

Copons, R., Vilaplana, J., 2008. Rockfall susceptibility zoning at a larger scale: From geomorphological inventory to preliminary land use planning. Eng. Geol.

Copons, R., Vilaplana, J., Linares, R., 2009. Rockfall travel distance analysis by using empirical models (Solà d'Andorra la Vella, Central Pyrenees). Nat. Hazard Earth Sys. 9, 2107–2118.

Corominas, J., 1996. The angle of reach as a mobility index for small and large landslides. Can. Geotech. J. 33, 260–271.

Corominas, J., Copons, R., Vilaplana, J., Altimir, J., Amigó, J., 2003. Integrated landslide susceptibility analysis and hazard assessment in the Principality of Andorra. Nat. Hazards 30, 421–435.

Dai, F. C., Lee, C. F., Ngai, Y. Y., 2002. Landslide risk assessment and management: an overview. Eng. Geol. 64 (1), 65–87.

Dietrich, W., Montgomery, D., 1998. Shalstab: a digital terrain model for mapping shallow landslide potential. Tech. rep., NCASI, access 15 November 2009. http://calm.geo.berkeley.edu/-geomorph/shalstab/index.htm

Dietrich, W. E., de Asua, R. R., Cyle, J., Orr, B., Trso, M., 1998. A validation study of the shallow slope stability model, SHALSTAB, in forested lands of Northern California. Tech. rep., Stillwater Ecosystem, Watershed & Riverine Sciences, access 24 February 2010. http://-www.krisweb.com/biblio/gen_ucb_dietrichetal_1998_shalstab.pdf

Dilley, M., Chen, R.S. Deichmann, U., Lerner-Lam, A., Arnold, M., 2005. Natural disaster hotspots: a global risk analysis. In: Disaster Risk Management Series. No. 5. World Bank.

Ely, P., Peters, J., 1984. Probable maximum flood estimation - Eastern United States. Tech. rep., US Army Corps of Engineers - Hydrologic Engineering Center, access 9 March 2010. http://-www.hec.usace.army.mil/publications/TechnicalPapers/TP-100.pdf

EP, EC, 2007. Directive 2007/60/ec of the European Parliament and of the Council on the assessment and management of flood risks. Official Journal of the European Union 288, 27–34. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:288:0027:0034:EN:PDF

Évin, M., 1997. Géology de l'Ubaye. Sabenca, Association de la Valeia,, Barcelonnette, France.

FEMA, 2008. HAZUS-MH MR3 Patch 2: Release notes. Tech. rep., FEMA.

Flageollet, J.-C., Maquaire, O., Martin, B., Weber, D., 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France). Geomorphology 30, 65–78.

Francés, F., Botero, B., 2003. Proceedings of 2002 PHEFRA workshop—palaeofloods, historical floods and climatic variability: applications in flood risk assessment. Ch. Probable maximum flood estimation using systematic and non-systematic information, p. 223–229. http://-www.ccma.csic.es/dpts/suelos/hidro/images/chapter_34_phefra.pdf

Frattini, P., Crosta, G., Carrara, A., Agliardi, F., 2008. Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. Geomorphology 94 (3-4), 419 – 437, GIS technology and models for assessing landslide hazard and risk.

Fuchs, S., Keiler, M., 2006. Natural hazard risk depending on the variability of damage potential. simulation and hazard mitigation. In: Popov, V., Brebbia, C. (Eds.), Risk Analysis V: Simulation and hazard mitigation. WIT Press, Southampton, UK. WIT Transactions on Ecology and the Environment, pp. 13–22.

Geomer, February 2008. FloodArea - ArcGIS extension for calculating flooded areas: user manual. Geomer GmbH and Ingenieurgemeinschaft Ruiz Rodriguez + Zeisler + Blank. http://-www.geomer.de/fileadmin/templates/main/res/downloads/floodarea_manual_en_9.pdf

Glade, T., van Elverfeldt, K., Vancouver, Canada 2005. Multirisk: an innovative concept to model natural risks. In: Oldrich, H., Fell, R., Coulture, R., Eberhardt, E. (Eds.), International Conference on Landslide Risk Management. Balkema.

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005. Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72 (1-4), 272 – 299.

Guzzetti, F., Reichenbach, P., Wieczorek, G. F., 2003. Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. Natural Hazards and Earth System Science 3 (6), 491–503.

Heim, A., 1932. Bergsturz und Menschenleben. Beiblatt zur Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich.

Holmgren, P., 1994. Multiple flow direction algorithms for runoff modelling in grid based elevation models: an empirical evaluation. Hydrol. Process. 8, 327–334.

Horton, P., Jaboyedoff, M., Bardou, E., May 2008. Debris flow susceptibility mapping at a regional scale. In: 4th Canadian Conference on Geohazards. Université Laval, Québec, Canada.

Horton, P., Jaboyedoff, M., Rudaz, B., Zimmermann, M., in prep. Flow-r, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can. Geotech. J. 39, 316–330.

Hydrotec, 2009. Hochwasserschutzplan Solmsbach. Tech. rep., Regierungspräsidium Gießen. http://www.hessen.de/irj/RPGIE_Internet?cid=f95a2a5d2807b19fc5b9fe2f31e52e62

IDEALP, Hydroetudes, 2008. Etude hydraulique globale de la vallée de l'Ubaye - Diagnostic. Tech. rep., Syndicat mixte contre les crues du bassin Ubaye-Ubayette.

IDEALP, Hydroetudes, 2010. Etude hydraulique globale de la vallée de l'Ubaye - Plan de gestion. Tech. rep., Syndicat mixte contre les crues du bassin Ubaye-Ubayette.

IRPI. Rainfall threshold for the initiation of landslides. online, access 23 February 2011. http://-wwwdb.gndci.cnr.it/php2/rainfall_thresholds/thresholds_all.php?lingua=it

Jaboyedoff, M., 2003. Conefall - user's guide. Open report soft 01, Quanterra.

Jaboyedoff, M., Labiouse, V., 2003. Preliminary assessment of rockfall hazard based on GIS data. ISRM - Technology roadmap for rock mechanics. South African Institute of Mining and Metallurgy, Johannesburg, South Africa.

Kappes, M., 2011. Multirisk: a platform for multi-hazard risk analyses and visualization - users' manual. Tech. rep., University of Vienna.

Kappes, M., Glade, T., 2011. Landslides considered in a multi-hazard context. In: Proceedings of the Second World Landslide Forum. Rome, Italy.

Kappes, M., Keiler, M., Glade, T., 24-26th November 2010. Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence. CERG Editions, Strasbourg, Ch. From single- to multi-hazard risk analyses: a concept addressing emerging challenges, pp. 351–356.

Kappes, M., Malet, J.-P., Remaître, A., Horton, P., Jaboyedoff, M., Bell, R., 2011. Assessment of debris flow susceptibility at medium-scale in the Barcelonnette Basin, France. Nat. Hazard Earth Sys. 11, 627–641.

Kappes, M., von Elverfeldt, K., Glade, T., Keiler, M., subm. Challenges of dealing with multi-hazard risk: a review. Nat. Hazards.

Kappes, M.; Papathoma-Köhle, M., Keiler, M. in press. Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Appl. Geogr.
Keylock, C., 2005. An alternative form for the statistical distribution of extreme runout distances. Cold Reg. Sci. Tecnol. 42, 185–193.

Kienholz, H., Krummenacher, B., 1995. Symbolbaukasten zur Kartierung der Phänomene. Tech. rep., Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bundesamt für Wasser und Geologie (BWG).

Klumpp, E., Hörmann, F. (Eds.), 2010. Arbeitspaket 6: Risikoprävention & Management: Praktiker Workshop - Risikomanagement an alpinen Wildbächen und Flüssen. Alpine Space. http://www.adaptalp.org/-index.php?option=com_docman&task=doc_details&gid=201&Itemid=79

Le Carpentier, C., 1963. La crue de juin 1957 en Ubaye et ses conséquences morphodynamiques. Ph.D. thesis, Université de Strasbourg.

Lied, K., Bakkeh øi, S., 1980. Empirical calculations of snow-avalanche runout distance based on topographic parameters. J. Glaciol. 26, 165–177.

Liener, S., Kienholz, H., 2000. Modellierung von flachgründigen Rutschungen mit dem Modell SLIDISP. In: Internationales Symposium - INTERPRAEVENT. Villach, Austria, pp. 259–269.

Liévois, J., 2003. Guide méthodologique plans de prévention des risques d'avalanches. Tech. rep., Ministère de l'Écologie et du Développement et de l'Aménagement.

Maggioni, M., 2004. Avalanche release areas and their influence on uncertainty in avalanche hazard mapping. Ph.D. thesis, Universität Zürich.

Maggioni, M., Gruber, U., 2003. The influence of topographic parameters on avalanche release dimension and frequency. Cold Reg. Sci. Tecnol. 37, 407–419.

Malet, J.-P., Maquaire, O., Locat, J., Remaître, A., 2004. Assessing debris flow hazard associated with slow moving landslides: methodology and numerical analyses. Landslides 1, 83–90.

Maquaire, O., Malet, J.-P., Ramaître, A., Locat, J., Klotz, S., Guillon, J., 2003. Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Basin, South East France. Eng. Geol. 70, 109–130. http://eost.u-strasbg.fr/omiv/Publications/-Maquaire_et_al_2003_EG.pdf

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M., Di Ruocco, A., Novelli, P., subm. Basic principles of multi-risk assessment: a case study in Italy. Nat. Hazards.

Marzocchi, W., Mastellone, M., Di Ruocco, A., 2009. Principles of multi-risk assessment: interactions amongst natural and man-induced risks. European Commission. http://-www.scribd.com/doc/16902233/Principles-of-MultiRisk-Assessment

Mc Clung, D., Maers, A., Schaerer, P., 1989. Extreme avalanche run-out: data from four mountain ranges. Ann Glaciol 13, 180–184. http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/-nrcc31059/nrcc31059.pdf

McClung, D., Lied, K., 1987. Statistical and geometrical definition of snow avalanche runout. Cold Reg. Sci. Tecnol. 13, 107–119.

McClung, D., Schaerer, P., 1993. The avalanche handbook. The Mountaineers, Seattle, USA.

MEDD. Programmes d'études des avalanches. Access 20 October 2009. http://-www.avalanches.fr/

Meisina, C., Scarabelli, S., 2006. A comparative analysis of terrain stability models for predicting shallow landslides in colluvial soils. Geomorphology 87, 207–223.

Montgomery, D., Dietrich, W., 1994. A physically based model for the topographic control on shallow landsliding. Water Resour. Res. 30, 1153–1171.

Montgomery, D., Greenberg, H., 2009. Dave and Harvey's slope stability package. Access 11 November 2010. http://gis.ess.washington.edu/stability/index.html

Montgomery, D. R., Sullivan, K., Greenberg, H. M., 1998. Regional test of a model for shallow landsliding. Hydrol. Process. 12, 943–955.

Odeh Engineers, Inc, 2001. Statewide hazard risk and vulnerability assessment for the state of Rhode Island. Tech. rep., NOAA Coastal Services Center. http://www.csc.noaa.gov/rihazard/-pdfs/rhdisl_hazard_report.pdf

OderRegio, 2006. Vorsorgender raumordnerischer Hochwasserschutz im Einzugsgebiet der Oder - Transnationales Handlungsprogramm. Tech. rep., INTERREG III B-Projekt OderRegio. http://-www.oderregio.org/download/OR_HP_DE_Web.pdf

Papathoma-Köhle, M., Kappes, M., Keiler, M., Glade, T., 2011. Physical vulnerability assessment for Alpine hazards - state of the art and future needs. 85, 645-680.

Prochaska, A., Santi, P., Higgins, J., Cannon, S., 2008. Debris-flow runout predictions based on the average channel slope (acs). Eng. Geol. 98, 29–40.

Quinn, P., Beven, K., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrol. Process. 5, 95–79.

Real de Asua, R., Bellugi, D., Dietrich, E., 2000. Shalstab - Tools Tutorial. BlueG Software, Stillwater Sciences and the U.C.B. Geomorphology Group, attached to the software.

Reese, S., Bell, R., King, A., 2007. RiskScape: a new tool for comparing risk from natural hazards. Water Atm. 15, 24–25.

Remaître, A., 2006. Morphologie et dynamique des laves torrentielles: applications aux torrents des Terres Noires du bassin de Barcelonnette (Alpes du Sud). Ph.D. thesis, Université de Caen/Basse-Normandie.

Remaître, A., Malet, J.-P., Cepeda, J., 2010. Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence. CERG Editions, Ch. Landslides and debris flows triggered by rainfall: the Barcelonnette basin case study, South French Alps, pp. 141–145.

Rickenmann, D., Zimmermann, M., 1993. The 1987 debris flow in Switzerland: documentation and analysis. Geomorphology 8, 175–189.

Rickli, C., Böll, A., Gerber, W., 1994. Ganzheitliche Gefahrenbeurteilung - Kursunterlagen. Tech. rep., Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft and Forstliche Arbeitsgruppe Naturgefahren.

RTM, 2000. Plan de prevention des risques naturals previsibles - Department des Alpes de Haute-Provence, Commune de Jausiers. Tech. rep.

RTM, 2002. Plan de prevention des risques naturels previsibles - Departement des Alpes de Haute-Provence, Commune de Faucon de Barcelonnette. Tech. rep.

RTM, 2008. Commune de barcelonnette: Plan de prevention des risques naturels previsibles - reglement. Tech. rep., Restauration des Terrains de Montagne, provisoire.

Ruiz Rodriguez + Zeisler, geomer GmbH, PlanEVAL, HASKONING, 2001. Übersichtskarten der Überschwemmungsgefährdung der möglichen Vermögensschäden am Rhein - Abschlussbericht: Vorgehensweise zur Ermittlung der hochwassergefährdeten Flächen, Vorgehensweise zur Ermittlung der möglichen Vermögensschäden. Tech. rep., Internationale Kommission zum Schutz des Rheines (IKSR).

Schneider, P., Schauer, B., 2006. HAZUS - its development and its future. Nat. Hazards Rev. 7, 40–44.

Shaw, S., Johnson, D., October 1995. Slope morphology model derived from digital elevation data. In: Proceedings, Northwest Arc/Info Users Conference. p. 12. http://www.krisweb.com/-biblio/gen_xxxx_shawetal_1995_slopemorph.pdf

Sivan, O., 2000. Torrents de l'Ubaye. Sabenca, Association de la Valeia, Barcelonnette, France.

Slaymaker, O., Embleton-Hamann, C., 2009. Geomorphology and Global Environmental Change. Camebridge University Press, Ch. Mountains, pp. 37–70.

Takahashi, T., 1981. Estimation of potential debris flows and their hazardous zones; soft countermeasures for a disaster. J. Nat. Disaster Sci. 3, 57–89.

Thiery, Y., 2007. Susceptibilité du bassin de Barcelonnette (Alpes du sud, France) aux 'mouvements de versant': cartographie morphodynamique, analyse spatiale et modélisation probabiliste. Ph.D. thesis, Université de Caen/Basse-Normandie.

Thiery, Y., Malet, J.-P., Sterlacchini, S., Puissant, A., Maquaire, O., 2007. Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment. Geomorphology 92, 38–59.

Thiery, Y., Sterlacchini, S., Malet, J.-P., Puissant, A., Remaître, A., Maquaire, O., 2004. Strategy to reduce subjectivity in landslide susceptibility zonation by GIS in complex mountainous environments. In: 7th AGILE Conference on Geographic Information Science.

Toppe, R., 1987. Terrain models - a tool for natural hazard mapping. In: Avalanche formation, movement and effects (Proceedings of the Davos Symposium). pp. 629–638.

TU Wien, 2009. Leitfaden zum Nachweis der Hochwassersicherheit von Talsperren. Tech. rep., Bundesministerium für Land- und Forstwirtschaft.

UN-ISDR, 2009. Global assessment report on disaster risk reduction. Tech. rep., access 1 September 2009. http://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413

UN-ISDR, 2009. UNISDR terminology on disaster risk reduction. Tech. rep., United Nations International Strategy of Disaster Reduction, access 18 November 2009. http://-www.undp.org.ge/new/files/24_619_762164_UNISDR-terminology-2009-eng.pdf

UVM, 2005. Hochwassergefahrenkarten in Baden-Württemberg. Tech. rep., Ministerium für Umwelt, Naturschutz und Verkehr. http://www.uvm.baden-wuerttemberg.de/servlet/is/1253/-HWGK_Leitfaden_DEU.pdf

van Westen, C., Montoya, A., Boerboom, L., Badilla Coto, E., 2002. Multi-hazard risk assessment using GIS in urban areas : a case study for the city of Turrialba, Costa Rica. In: Proceedings of the regional workshop on best practices in disaster mitigation: lessons learned from the Asian urban disaster mitigation program and other initiatives.

Wichmann, V., Becht, M., 2003. Modelling of geomorphic processes in an alpine catchment. In: 7th International Conference on GeoComputation. Southampton, United Kingdom. http://-www.ku-eichstaett.de/Fakultaeten/MGF/Geographie/physisch/Forschung/sedag.en

Wichmann, V., Becht, M., 2006. Rockfall modelling: methods and model application in an Alpine Basin (Reintal, Germany). Göttinger Geographische Abhandlungen 115, 105–116.

Wisner, B., Blaikie, P., Cannon, T., Davis, I., 2004. At risk: natural hazards, people's vulnerability and disasters. Routledge, London, UK.

WMO, 1999. Comprehensive risk assessment for natural hazards. Technical document 955, World Meteorological Organisation.

Zimmermann, M., Mani, P., Gamma, P., 1997. Murganggefahr und Klimaänderung - ein GIS-basierter Ansatz. vdf Hochschulverlag AG, ETH Zürich.

A.5. From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges

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From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges

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ABSTRACT: Natural processes are interacting components of natural systems. Only certain characteristics possibly pose a threat to elements at risk and convert the processes into hazards. In the framework of multi-hazard risk analyses these interactions are mostly not taken into account, however mutual impacts alter the disposition and the triggering of natural hazards and negligence might lead to miss- or underestimation of the actual hazard/risk. In a case study of a medium-scale multi-hazard analysis the interactions concerning the disposition were identified with a matrix, implemented with a feedback loop and determined on a map by overlay of hazard layers. Links concerning the triggering were also identified by a matrix and determined by overlapping. In summary, multi-hazard (risk) analyses consider already multiple processes. This offers the great opportunity to add one further step and identify and integrate the interactions.

1 INTRODUCTION

1.1 *Multi-hazard (risk)*

The term ‘multi-hazard’ emerged in the political international environment associated with the aim of risk reduction and sustainable development (e.g. Agenda 21 and Johannesburg Plan). In this context the analysis of risk from multiple hazards was identified as central aspect and basis for risk management and thus for the reduction of risk and sustainable development. Given these objectives, two fundamental facets of such an analysis evolve: the analysis has to be carried out for the administrative unit in charge of risk management, i.e. for the specific administrative area and yielding the results required for this purpose. And, the hazards under consideration are all natural processes threatening humans, buildings or infrastructure, i.e. all hazards posing a relevant risk. Thus, the analysis of multi-hazard risk is, resuming the most important aspects for a definition for this article, the joint investigation of all relevant hazards in a defined area.

Although hazard and risk analysis methods are already well-established for many natural processes, their joint investigation poses a variety of challenges. Especially, the widely differing characteristics of the single processes as intensity, return period or parameters of influence on elements at risk[1] (Tyagunov et al. 2005), but also the varying procedures to estimate/model (Marzocchi et al. 2009), and units to quantify them complicate multi-hazard (risk) analyses. This leads to the need for an overarching analysis scheme to produce single-hazard (risk) results which are comparable among each other. Widespread qualitative and semi-quantitative approaches are the classification of hazards, vulnerabilities and risks according to an overall scheme adjusted to each single process (e.g. Heinimann et al. 1998, Sperling et al. 2007, Thierry et al. 2008 & Wipulanusat et al. 2009) or the development of an index scheme (e.g. Dilley et al. 2005 & Greiving 2006). For quantitative analyses of risks a clear definition of the considered timeframe and types of damage to be modeled is required to make the single-hazard risks comparable and addable to the overall multi-hazard risk (e.g. annual risk for human life in Marzocchi et al. 2009, or the annual economic risk in Bell & Glade 2004).

Such multi-hazard (risk) analysis schemes assure in first place the combinability and comparability of the single-hazard (risk) analysis results. However, the hazards are usually still considered as independent from each other, which cannot be supported by observations in the field.

1.2 *Natural hazards as interrelated system components*

Natural processes are components of systems (ecosystems, geosystems, etc.) and only certain characteristics which possibly pose a threat to elements at risk convert them into hazards. As components of systems these processes are not independent and se-

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[1] An example is rock fall in comparison with storm hazard. Rock fall is characterized by its impact pressure while storms are mostly represented by the wind force, two measures which are not directly comparable. Furthermore they differ in extent, predictability, time of onset, duration etc.

parated from each other but are linked and connected. In the investigation and modeling of natural hazards, this aspect is still very rarely taken into account but each hazard is studied discretely.

The occurrence of natural processes/hazards depends on the disposition, i.e. the general setting which favors the specific process, and the triggering event which leads to the threshold crossing of a factor relevant for the hazard incidence (Heinimann et al. 1998).

The disposition can be subdivided into basic and variable disposition, which refers to the temporal observation scale: the basic disposition is an, over a longer time period constant or very slowly changing setting, e.g. the relief, climate or the vegetation cover. The variable disposition refers to faster alterations, e.g. seasonal or daily changes (water balance, vegetation period, etc.) which lead, in combination with the general basic disposition, to the current disposition.

In this setting, the exceeding of an internal threshold (triggering) or an external trigger may start the incidence. Processes which pose a possible threat to elements at risk are in most hazard analyses only seen as the threat. However, from a systemic point of view they are components acting within the system and shaping it. By shaping the system they may alter the general setting, i.e. the dispositions of other processes/hazards or act as trigger for other processes/hazards.

In single-hazard analyses the most important processes and parameters concerning disposure and triggering are identified and integrated in the modeling procedure. For most multi-hazard analyses a similar approach is now applied, identifying still separately the important factors to be considered for each single process. After investigating them separately only the results are brought together. However, a multi-hazard analysis would offer the possibility to create a framework containing all considered processes and taking into account additionally the relations and interconnections between them.

We investigated the relationships between potentially hazardous processes and their relevance for the overall risk and risk management, subdivided into relations concerning disposition and triggering.

We will in the first section explain what a system approach in combination with the disposition-triggering model for multi-hazard analyses means and give examples of studies in which hazard relationships are already taken into account.

Furthermore, we will make the transfer to explain why the relations are relevant and to be considered for risk management and reduction and how they could be taken into account. In a second section we will give an example for a medium-scale multi-hazard analysis and the implementation of hazard relations in this framework.

2 MULTI-HAZARD INTERACTIONS IN THE FRAMEWORK OF DISPOSITION AND TRIGGERING

2.1 *Alteration of the disposition*

Each natural process acts in a specific subarea of the system area and exhibits its specific footprint, i.e. the zone in which it operates. Where process footprints (process activity areas) overlap, the processes will influence each other more or less strongly. As long as no direct triggering of one hazard by another or temporally simultaneous occurrence exists, an influence will entail alterations of the basic and variable disposition. One process changes the general setting of another one and thus its disposition towards a possibly occurring trigger event.

Examples: De Graff et al. (2007) mention the “fire-flood cycle” which describes the relation of forest fires and subsequent floods and debris flows due to the loss of vegetation, rapid runoff and increased sediment washout. Detailed investigations suggest a significant increase of debris flow frequency after forest fires (Cannon & de Graff 2009). Wichmann et al. (2009) examine the sediment cascade consisting of several mass moving processes which fall into the category of natural hazards. They model several mass moving processes (e.g. rock fall, full depth avalanches and debris flows) and subdivide each one into the erosion, transport and deposition area. Where the deposition zone of one and the erosion area of another process coincide direct influence of the first process on the disposition of the second one and a coupled material transport can be assumed. Garcin et al. (2008) include the sea level rise into the modeling of storm surges and tsunami hazard for the next 100 years.

Transfer: The consideration of this aspect is of great importance to prevent underestimation of slowly or rapidly evolving hazards. The first step is the identification of influences and links between natural processes/hazards. If these links are determined, the occurrence of one process (A) indicates directly the possible alteration of the disposition of another process (B) and the need for reassessment of the second process’ current hazard level. A very good example is given by de Graff et al. (2007) with the “Burned Area Emergency Response (BAER)”. For the BAER post-wildfire threat (including debris-flow hazard) shall be assessed within seven days after a wildfire to ensure that counter-measures can be organized before the first storm event strikes. I.e. the general relation between fire and debris flows is identified, its severity determined and the necessary reaction defined. To make the second part, the reassessment, more user-friendly, the direct implementation of the links into the modeling framework by relating the models “so that the results of one model could feed into another” was proposed by Bovolo et al. (2009, p. 925). Such an application offers the possibility to test management or model hazard scenarios taking into account the wide-ranging implications they will have.

2.2 Triggering

One hazard inducing one or more other threats which may again provoke further ones is an aspect of multi-hazard studies gaining recently more and more attention. The terminology and definition differs from author to author slightly: Delmonaco et al. (2006, p.10) refer to this phenomenon as domino effect or cascading failure which is a “failure in a system of interconnected parts, where the service provided depends on the operation of a preceding part, and the failure of a preceding part can trigger the failure of successive parts”. Marzocchi et al. (2009, pp. 3 & 9) define them as “coupled events” where “an adverse event triggers one or more sequential events (synergistic event)”. A difficulty with this definition is that the triggering event has to be a hazard. Processes with low magnitudes might act as triggers but not cause damages and other triggers might not be hazards but cause several threats. Thus it seems reasonable to include in general all chains in which two or more hazards are involved, i.e. two or more hazards causally linked by triggering. This would also incorporate two hazards triggered by the same non-hazard event as floods and debris flows due to heavy rainfall, although heavy rainfall itself is not a hazard.

Examples: A prominent event chain is the triggering of mass movements due to earthquakes (e.g. Meyenfeld 2008 & Miles & Keefer 2009). Another frequently occurring cascade starts with a landslide which dams a river or torrent, this dam breaks and the runoff of a mixture of water and debris causes considerable damage (Carrasco et al. 2003, Costa & Schuster 1988 & Dai et al. 2005). Huggel et al. (2003) investigated lake outbursts and the formation of a debris flow due to triggering by ice avalanches or debris flows.

Transfer: An important aspect of hazard chains is the possible amplification of the overall hazard and risk of such causally linked processes in comparison to the aggregation of assumedly independent hazards (Marzocchi et al. 2009). For example, a debris flow resulting from the dam break of a landslide dam might be of a higher magnitude than expected channel or slope debris flows. This possible amplification effect does not only refer to direct chaining of hazards but also to threats induced by one common trigger which results in temporal coincidence and increases the probability of spatial overlapping. Tarvainen et al. (2006, p. 84) state that an “additional hazard potential [… may arise due to] a possible coincidence of different hazards in space and time”. They mention the example of a coincidence of a river flood and a storm surge in the Rhine estuary which would have simultaneously a much higher impact than the pure sum of both. Thus the amplification effect can either be the result of the chaining - one hazard triggering and increasing the next - or a consequence of the spatial and temporal coincidence of both.

Besides the amplification, a second aspect is that the impact of two processes simultaneously or one shortly after the other (a landslide triggered by an earthquake) exhibit a higher impact on humans, buildings or infrastructure than the simple sum of both and alter thereby the risk. An earthquake damaged structure is surely much more vulnerable to the following landslide than it was in the original state. A community under stress due to a flood is already in an altered state when the debris flow occurs.

The third important aspect is the challenge for early warnings and emergency management in a situation of more than one threat. Several events and impacts have to be managed simultaneously, often in a multi-agency cooperation as shown in the case of the Shanghai Multi-Hazard Early Warning System (Tang 2009) which poses a high challenge.

3 CONSIDERATION OF HAZARD RELATIONS IN MEDIUM-SCALE MULTI-HAZARD MODELING

Multi-hazard (risk) analyses aim, in accordance with the description given in the introduction, at the consideration of all natural hazards in a specified administrative unit. Since the data requirements are very high for multiple processes and the occurrence and spatial distribution of several processes is much less clear as in the case of one single process, it seems reasonable to adapt a top-down approach. Starting with a relatively coarse and low data intensive analysis for an overview and the identification of potential risk areas the regions in need for more detailed, local studies can be determined. A coherent analysis scheme is the fundamental precondition for the consideration of multi-hazard relationships. The scheme applied in this study will be mentioned only shortly since the focus is on the consideration of the hazard relations.

The case study is carried out in the Barcelonnette Basin, a valley in the southern French Alps between 1100 m and 3000 m a.s.l. drained by the Ubaye River (for detailed information on the area refer to Flageollet et al. 1999, Maquaire et al. 2003, Remaître 2006, Remaître et al. 2008). The processes considered in the analysis are snow avalanches, rock fall, shallow landslides, debris flows and river floods. Further hazards threatening the valley include flash floods and earthquakes which are at this point not included into the analysis due to the unavailability of models fitting in the set of the other five.

For each process the area affected by a high-magnitude low-frequency event (worst-case scenario) is modeled by means of relatively simple models: the mass movement analyses are split in two parts, the source identification with empirical/heuristic criteria (debris flow sources following Horton et al. 2008; avalanche sources after Maggioni 2004; rock fall sources based on Corominas et al. 2003, and shallow landslide sources referring to Montgomery & Dietrich 1994) and the run out computation primarily with the angle of reach concept (Heim 1932) by means of the model Flow-R (Horton et al. 2008). The flood modeling is carried out with the model FloodArea (Geomer 2008) on basis of hydrograph information. Details about the processes, models and parameter choices for the case study will be published later, thus we will not describe these aspects in the article at hand because of the different focus of this contribution.

The outputs are, as already mentioned, the zones possibly affected in a high-magnitude event by each one of the hazards.

In the following we will outline, how the relations between hazard concerning disposition and triggering are taken into account.

3.1 *Disposition*

A general procedure of two steps is suggested: 1) identification of the influences and links between the different hazards, and 2) the establishment of the links between the hazard models adjusted to the modeling scale and methods used. For a medium-scale multi-hazard analysis the following realization of the two steps was carried out:

1) The links between hazards were identified by means of a matrix opposing all hazards to each other after de Pippo et al. (2008). In the interjacent cells the respective effect is shortly explained (Tab. 1).

Table 1. Matrix for the identification of influences of one process on the disposition of another one. The process in the line is the causing one, the column indicates the affected one.

Avalanche	Influence on vegetation cover (Removal of forest)	Influence on vegetation cover (Removal of forest)	Influence on vegetation cover	-
-	Debris flows	-	-	Change of river bed morphology (acc. & erosion)
Increased slope roughness	Supply of material	Rock falls	Increase of load	Material accumulation in river bed
Alteration of surface roughness	Supply of material	-	Landslides	Change of river course
-	Remobilisation of material	-	Erosion/ saturation of landslide deposits	Floods

2) For the linkage of models (the output of one model used as input for the next model) a practical approach is the listing of all model inputs and the identification which model outcomes can be used to update the input layers and parameters. E.g. the avalanche run out zone can be used to roughly estimate the area of potential forest destruction and thus to update the land cover information (Figure 1).

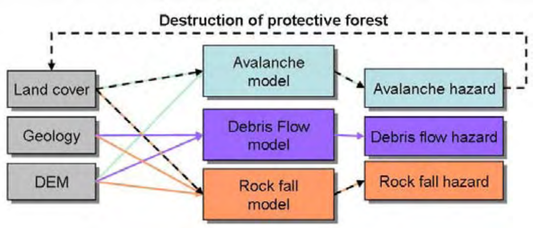

Figure 1. Implementation of the effect of one hazard, in this case avalanche, on the disposition of other processes, in this case rock fall and avalanche hazard itself, due to the effect on an input parameter (land cover). Feedback loop shown with black dashed lines.

This updated information can again be integrated in all models using land cover as input (in this case only the rock fall and the avalanche model itself since e.g. debris flows under forest can, according to our opinion, not be excluded completely) and the new hazard level assessed. However, at such a small scale and with the relatively coarse models and little input data used, most of the relations as e.g. change of river bed morphology (modeling is done on basis of a 10m DEM and volumes are not taken into account) or material provision (volumes are not taken into account) cannot be considered. Such feedback loops allow the consideration of the consequences of a certain event (scenario modeling)

3.2 *Triggering*

As well as for the relations concerning the disposition also in the case of triggering a two-step procedure is convenient consisting of the 1) identification and 2) establishment of links between hazards.

Table 2. Matrix opposing all considered hazards towards the range of identified triggers and hazards taken into account to identify triggering relations.

	AV	DF	RF	LS	FL
Avalanches (AV)					x
Debris flows (DF)					x
Rock falls (RF)					x
Landslides (LS)					x
Floods (FL)				x	
Heavy rainfall	x	x		x	x
Earthquake	x		x	x	

(1) We propose a matrix based on de Pippo et al. (2008) as in the previous section, now for the determination possible triggering effects and complemented by the list of all possible non-hazard triggers (Tab. 2).

(2) While for detailed local studies event trees (e.g. Egli 1996 or Marzocchi et al. 2009) are a useful method to describe the complete chain with the respective probabilities, its application on a small scale is not possible since a huge amount of data and information would be necessary. However, these event trees have to be designed for areas prone to the occurrence of hazard chains and this information can be gained in a medium-scale study by overlaying the modeled hazard areas of possibly linked hazards. In case of floods, landslides might be triggered by undercutting of slopes. The flooded zone can be overlaid with landside prone regions and where both hazards overlap or occur in a distance lower as the range of influence of the flood (due to rising ground water table etc.) a possible cascading can be assumed. For the case of one non-hazard trigger inducing two or more hazards likewise the hazard zones can be overlaid (e.g. for the case of heavy rainfall the process areas of debris flow, shallow landslide and flood). First, the overall area possibly threatened during/shortly after heavy rainfall can be identified and secondly the regions perhaps affected by more than one hazard simultaneously or sequentially with potentially amplifying effect can be determined for further detailed studies by means of event trees.

4 CONCLUSIONS

Natural systems are not just the sum of its components but are a net of interacting parts and we are not able to understand and even less to model them entirely. The natural processes we perceive as hazards form part of these systems. In single-hazard analyses we create subsystems we can handle to model the threat “satisfactorily” and according to the data availability. The same procedure is applied for multi-hazard analyses - still creating for each single process one subsystem and only the results are combined and compared. However, hazards are, as natural processes, part of the same overall system, influence each other and interact. Thus, multi-hazard risk contains emergent properties: It is not just the sum of single-hazard risks since their relations would not be considered and this would lead to unexpected effects. The relations can, for analysis purposes, be subdivided in alteration of the disposition and triggering (cascades and related triggering).

Multi-hazard (risk) analyses offer the great advantage to consider a slightly larger part of the overall system than regarded in merged single-hazard analyses. The major step herein is to identify the relations and establish the respective links. This can be done in a very simple way by merely identifying which hazards could be interlinked or happening at the same time but can also include sophisticated event trees and probabilistic what-if scenarios. However, the beginning is the decision to include the relationships and starts with their identification. In the future, amplification towards the perspective of complex system research would be desirable since also the system theory has its short-comings. Complex systems imply two fundamental conditions: (1) The system consists of multiple interactive components and (2) these interactions give rise to emergent forms and properties which are not reducible to the sum of the individual components of observed system (Bründl et al. 2010, Keiler in press). Both conditions were highlighted in this study for multi-hazard and a new perspective of complex systems research will offer new concepts and methodologies to deal with multi-hazard and multi-risk.

REFERENCES

Bell, R. & Glade, T. 2004. Multi-hazard analysis in natural risk assessments. *Pp. 197–206 of: International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation*. Rhodes, Greece: Brebbia, C.A.

Bovolo, C. I., Abele, Simon J., Bathurst, J.C., Caballero, D., Ciglan, M., Eftichidis, G., & Simo, B. 2009. A distributed framework for multi-risk assessment of natural hazards used to model the effects of forest fire on hydrology and sediment yield. *Computers & Geosciences*, 35(5), 924 – 945.

Bründl, M., Bartelt, P., J., Schweizer, Keiler, M., & Glade, T. 2010. *Geomorphological hazards and disaster prevention. Camebridge* University Press. Chap. *Snow avalanche risk analysis - review and future challenges*, 49–61.

Cannon, S.H., & de Graff, J. 2009. Landslides - disaster risk reduction. Berlin Heidelberg, Germany: Springer Verlag. Chap. *The increasing wildfire and post-fire debris-flow threat in Western USA, and implications for consequences of climate change*, 177–190.

Carrasco, R.M., Pedraza, J., Martin-Duque, J.F., Mattera, M., Sanz, M.A., & Bodoque, J.M. 2003. Hazard zoning for landslide connected to torrential floods in the Jerte Valley (Spain) by using GIS techniques. *Natural hazards*, 30, 361–381.

Corominas, J., Copons, R., Vilaplana, J.M., Altimir, J., & Amigó, J. 2003. Integrated landslide susceptibility analysis and hazard assessment in the Principality of Andorra. *Natural Hazards*, 30, 421–435.

Costa, J.E., & Schuster, R.L. 1988. The formation and failure of natural dams. *Geological Society of America Bulletin*, 100, 1054–1068.

Dai, F. C., Lee, C.F., Deng, J.H., & Tham, L.G. 2005. The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, Southwestern China. *Geomorphology*, 65, 205–221.

de Graff, J.V., Cannon, S.H., & Gallegos, A.J. 2007. Reducing post-wildfire debris flow risk through the burned area emergency response (BAER) process. *In: Proceedings of the 1st North American Landslide Conference, AEG Special Publication no. 23*.

de Pippo, T., Donadio, C., Pennetta, M., Petrosino, C., Terlizzi, F., & Valente, A. 2008. Costal hazard assessment and mapping in Northern Campania, Italy. *Geomorphology*, 97, 451–466.

Delmonaco, G., Margottini, C., & Spizzichino, D. 2006. *ARMONIA methodology for multi-risk assessment and the harmonisation of different natural risk maps*. Deliverable 3.1.1. ARMONIA.

Dilley, M., Chen, R.S. Deichmann, U., Lerner-Lam, A.L., & Arnold, M. 2005. Natural disaster hotspots: a global risk analysis. *In: Disaster risk management series*. World Bank.

Egli, T. 1996. *Hochwasserschutz und Raumplanung. Schutz vor Naturgefahren mit Instrumenten der Raumplanung - dargestellt am Beispiel von Hochwasser und Murgängen*. vdf Hochschulverlag AG, ETH Zürich. ORL-Bericht 100.

Flageollet, J.-C., Maquaire, O., Martin, B., & Weber, D. 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France). *Geomorphology*, 30, 65–78.

Garcin, M., Desprats, J.F., Fontaine, M., Pedreros, R., Attanayake, N., Fernando, S., Siriwardana, C.H.E.R., de Silva, U., & Poisson, B. 2008. Integrated approach for coastal hazards and risks in Sri Lanka. *Natural Hazards and Earth System Sciences*, 8, 577–586.

Geomer. 2008 (February). *FloodArea - ArcGIS extension for calculating flooded areas: user manual*. Geomer GmbH and Ingenieurgemeinschaft Ruiz Rodriguez + Zeisler + Blank.

Greiving, S. 2006. Integrated risk assessment of multi-hazards: a new methodology. Pp. *75–81 of:* Schmidt-Thomé, Philipp (ed), *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions*, vol. 42. Geological Survey of Finland. Available at: http://arkisto.gtk.fi/sp/SP42/1_alkus.pdf.

Heim, A. 1932. *Bergsturz und Menschenleben*. Beiblatt zur Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich.

Heinimann, H.R., Hollenstein, K., Kienholz, H., Krummenacher, B., & Mani, P. 1998. *Methoden zur Analyse und Bewertung von Naturgefahren*. Umwelt-Materialien Nr. 85. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern, Switzerland.

Horton, P., Jaboyedoff, M., & Bardou, E. 2008 (May). Debris flow susceptibility mapping at a regional scale. *In: 4th Canadian Conference on Geohazards*. Université Laval, Québec, Canada.

Huggel, C., Kääb, A., Haeberli, W., & Krummenacher, B. 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. *Natural Hazards and Earth System Sciences*, 3, 647–662.

Keiler, M. in press. Geomorphology and complexity - inseparably connected? *Zeitschrift für Geomorphologie*.

Maggioni, M. 2004. *Avalanche release areas and their influence on uncertainty in avalanche hazard mapping*. Ph.D. Thesis, Universität Zürich.

Maquaire, O., Malet, J.-P., Ramaître, A., Locat, J., Klotz, S., & Guillon, J. 2003. Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Basin, South East France. *Engineering geology*, 70, 109–130.

Marzocchi, W., Mastellone, M.L., & Di Ruocco, A. 2009. *Principles of multi-risk assessment: interactions amongst natural and man-induced risks*. European Commission.

Meyenfeld, Horst. 2008. *Modellierung seismisch ausgelöster gravitativer Massenbewegungen für die Schwäbische Alb und den Raum Bonn und Erstellen von Gefahrenhinweiskarten*. Ph.D. thesis, University of Vienna.

Miles, S.B., & Keefer, D.K. 2009. Evaluation of camel - comprehensive areal model of earthquake-induced landslides. *Engineering Geology*, 104, 1–15.

Montgomery, D.R., & Dietrich, W.E. 1994. A physically based model for the topographic control on shallow landsliding. *Water Resources Research*, 30, 1153–1171.

Remaître, A. 2006. *Morphologie et dynamique des laves torrentielles: applications aux torrents des terres noires du Bassin de Barcelonnette (Alpes du Sud)*. Ph.D. Thesis, Université de Caen/Basse-Normandie.

Remaître, A., van Asch, T.W.J., Malet, J.-P., & Maquaire, O. 2008. Influence of check dams on debris-flow run-out intensity. *Natural Hazards and Earth System Sciences*, 8, 1403–1416.

Sperling, M., Berger, E., Mair, V., Bussadori, V., & Weber, F. 2007. *Richtlinien zur Erstellung der Gefahrenzonenpläne (GZP) und zur Klassifizierung des spezifischen Risikos (KSR)*. Tech. rept. Autonome Provinz Bozen.

Tang, Xu. 2009. Meeting the needs of users in China - the Shanghai experience. *In: Improving weather, climate and hydrological service delivery, and reducing vulnerability to disasters in Central Asia and Caucasus - Regional Workshop*.

Tarvainen, T., Jarva, J., & Greiving, S. 2006. Spatial pattern of hazards and hazard interactions in Europe. *Pp. 83–91 of:* Schmidt-Thomé, Philipp (ed), *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions*, vol. 42. Geological Survey of Finland. Available at: http://arkisto.gtk.fi/sp/SP42/6_spa_patt.pdf.

Thierry, P., Stieltjes, L., Kouokam, E., Nguéya, P., & Salley, P. M. 2008. Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon. *Natural Hazards*, 45, 429–456.

Tyagunov, S., Heneka, P., Stempniewski, L., Zschau, J., Ruck, B., & Kottmeier, C. 2005. CEDIM: From multi-hazards to multi-risks. *In: Proceedings of the 1st ARMONIA conference*.

Wichmann, V., Heckmann, T., Haas, F., & Becht, M. 2009. A new modelling approach to delineate the spatial extent of alpine sediment cascades. *Geomorphology*, 111, 70–78.

Wipulanusat, W., Nakrod, S., & Brabnarong, P. 2009. Multi-hazard risk assessment using GIS and RS applications: a case study of Pak Phanang basin. *Walailak Journal of Science and Technology*, 6, 109–125.

A.6. Landslides considered in a multi-hazard context

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Landslides in a Multi-Hazard context

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Abstract

Landslides and other hazards are components of natural systems and thus are often related to each other. Since these relationships may result in unexpected effects, an approach to account for these relationships in a regional multi-hazard study is proposed. Subdivided into relations concerning disposition alteration and hazard chains in which one process triggers another process, the hazard links are identified and studied by means of GIS-based methods. Two techniques are used for the implementation of relations into the analysis procedure, the establishment of feedback loops and the overlay of hazard areas to determine overlaps. Such a regional analysis enables in the first place the definition of those areas possibly affected by unexpected effects due to hazard relations and indicates the spots to be studied in detail by local and detailed methods to quantify the potential consequences.

Keywords multi-hazard, interaction, hazard chains, disposition and triggering.

Introduction

For many years "system theory" has attempted to account for the continuous nature of the world and the complex relations between components (Chorley and Kennedy 1971). One prime example of the implementation of a systems approach in geomorphology is the concept of debris or sediment cascades (Chorley and Kennedy 1971). In these cascading systems "the output of one subsystem forms the input of another" (Schneevoigt and Schrott 2006, p. 182). Processes as rock falls, debris flows or shallow landslides form part of these systems. Due to "certain characteristics which possibly pose a threat to elements at risk" these, primarily natural, processes may convert to natural hazards (Kappes et al. 2010, p. 351). Although this does not change anything concerning their affiliation to geomorphic systems, natural hazards and among them also the previously mentioned processes are still commonly regarded, analyzed and managed separately. However, interactions cause consequences, lead to modifications, for example of hazard levels and result in unexpected incidences. Thus, a reductionist approach is not able to account for such effects and thus not advisable. An example for hazard relations is the Jubaguerra event: a debris slide blocked the Arroyo de Jubaguerra gorge resulting in a damming of the stream. As a consequence of the subsequent dam break a flood wave rushed down the river and reached the mouth of the watershed (Carrasco et al. 2003). Costa and Schuster (1988) present a range of examples on formation and dam failure events of which several resulted in unexpected incidences with high numbers of fatalities.

The consideration of multiple hazards jointly and the inclusion of cascade and interaction effects is still an emerging research field. One pioneer project which addressed the topic from a geomorphic and system theoretic approach rather than from a hazard approach is SEDAG (SEDiment cascades in Alpine Geosystems). One main objective of SEDAG was to better understand the sediment pathways (Wichmann et al. 2009). However, Wichmann and Becht (2003) mentioned that the applied models might also be used for hazard assessments. By investigating source, transport and deposition areas of each process and the identification where these zones overlap the sediment routing can be determined (e.g. rock fall deposition in locations of debris flow erosion leads to cascading propagation of the sediment).

A practical approach coming from a hazard assessment background is proposed by Kappes et al. (2010). According to this concept, two types of influences between hazards can be distinguished: (1) the alteration of hazard dispositions by a hazardous event, e.g. the accumulation of material by rock falls and the subsequent availability of this material for debris flows or an increase of the load on a slope which destabilizes the slope and the disposition to a failure, and (2) the triggering of one or more hazards by another hazard, e.g. the triggering of rock falls by an earthquake or of lahars by a volcanic eruption hitting a glacier. Likewise, the triggering of at least two hazards by a process which does not classify as hazard, e.g. the triggering of debris flows and landslides by heavy rainfall, falls into this category.

In this study, the practical consideration and implementation of interactions in a regional study are presented, subdivided into disposition alteration and triggering (according to Kappes et al. 2010). For the performance of the hazard modelling, the multi-hazard risk analysis tool MultiRISK Kappes et al. (in prep) was used and the case study is carried out in the Barcelonnette valley, located in the South-eastern French Alps.

Consideration of interactions in a regional context

Multi-hazard analyses suffer several limitations. The extended requirements of soil, infiltration, geology, precipitation, discharge data and further information are often limiting factors. Inventories of past events are of particular relevance for the calibration and validation of hazard models. However, high quality multi-hazard inventories are extremely scarce. A second challenge in a multi-hazard setting is the multi-disciplinarity of the topic. Seldom is one expert proficient with all processes. Thus a first evaluation of the multi-hazard situation, including areas of potential overlay and the occurrence of relations and interactions between them is much more difficult than the determination in a single-hazard environment. Both issues call for a top-down approach in multi-hazard investigations. As a first step, an approximation of the patterns is obtained. This is done by simple methods with low data requirements to ensure its applicability as approximation and avoid extensive and time-consuming data acquisition. On this basis, the resources can then be applied specifically to detailed local analyses in the areas identified as potentially prone to hazard interactions and risk.

The medium-scale analysis scheme

Kappes et al. (in prep) present a simple, GIS-based analysis scheme based on low data requirements (Fig. 1). It is designed as the first step of a top-down approach for multi-hazard exposure analyses. From a digital elevation model (DEM), land use/cover and lithological information (dark grey boxes at the left side of Fig. 1) multiple derivatives are deduced (medium grey boxes). These serve as input for the models and GIS operations (light grey boxes with rounded edges). With this input the areas of potential rock fall, shallow landslide, debris flow and avalanche sources and areas affected by the run out as well as the zone susceptible to river flooding are modelled. The analysis scheme has been automated in the software tool MultiRISK. Herein, the intermediate steps such as the computation of derivatives, required format changes etc. are automatically computed. The software interface guides the user through the modelling process and guarantees user-friendly, faster, less error-prone and reproducible multi-hazard modelling (for further details concerning the analysis scheme and MultiRISK refer to Kappes et al. in prep). The consideration of hazard relations is still not automated in MultiRISK. However, the joint analysis of multiple hazards and the option of a fast re-calculation form a solid basis for *external* examinations of hazard cascades, feedback loops and other effects.

To illustrate the application of the concept of dealing with hazard interactions, a case study has been carried out in the Barcelonnette basin. This high mountain valley is prone to a multitude of landslide types and other natural hazards. In Kappes et al. (in prep) a worst-case analysis of shallow landslides, rock falls, debris flows, snow avalanches and river floods has been carried out and the obtained susceptibility zones form the basis for the hazard relation analysis which is presented in this study.

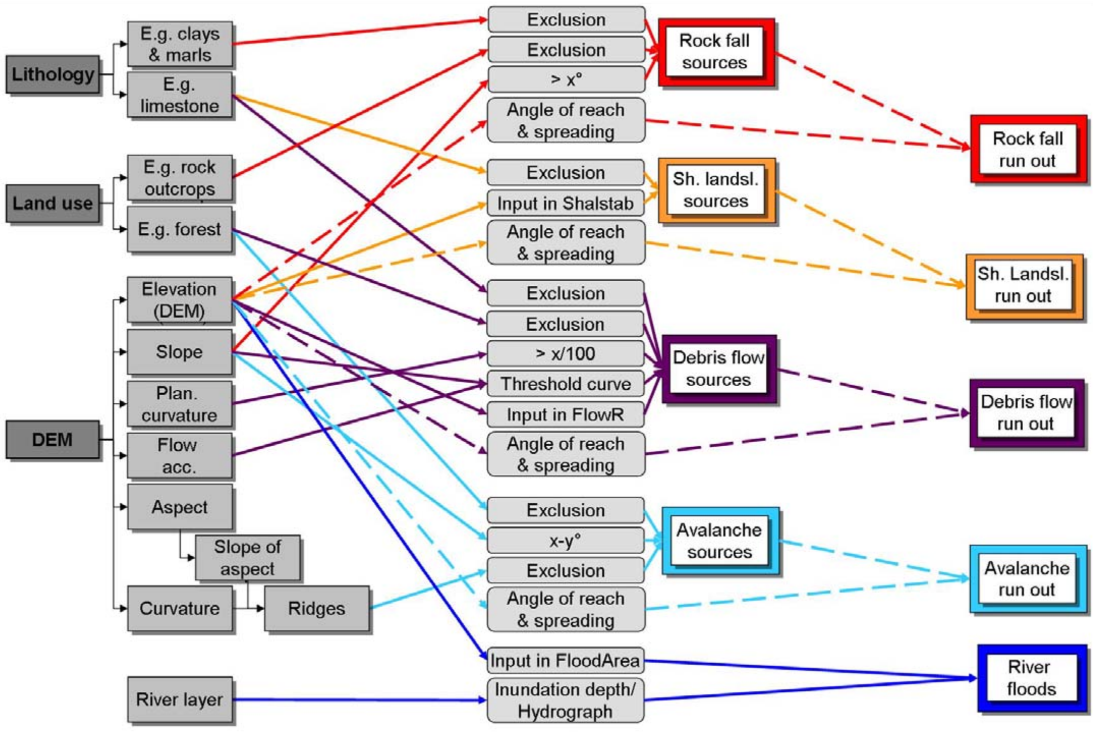

Figure 1 Analysis scheme for medium-scale multi-hazard analyses according to (Kappes et al. in prep)

The Barcelonnette valley

The Barcelonnette valley is situated in the “Département Alpes des Haute Provence” in the South-eastern French Alps. The altitude ranges between 1100 and over 3000 m a.s.l. Autochtonous black marls underlie allochtonous flysch in a geological window (Maquaire et al. 2003) and a multitude of torrents at the north- and south-facing mountain sides is drained by the Ubaye River. For more detail on the area refer to Kappes et al. (in prep).

The environmental characteristics give rise to several landslide types such as rock falls (e.g. RTM 2000), rotational and translational landslides (Thiery et al. 2004), mud flows (Malet et al. 2004) and debris flows (Remaître 2006). Other hazards comprise flash floods (Remaître 2006), river floods (Le Carpentier 1963, Sivan 2000), earthquakes (CETE 1987) and snow avalanches (MEDD).

Consideration of disposition alteration

An option to account for an alteration of the disposition has already been presented in Kappes et al. (2010). The potential influences are identified in a matrix (Tab. 1). Those influences relevant at the respective scale are determined and the implementation in the modelling procedure is designed.

Table 1 Matrix for the identification of disposition alterations between hazards. The hazard in the line causes and the hazard in the column receives the influence (modified after Kappes et al. 2010).

Ava-lances	Land cover	Land cover		
	Debris flows			River bed morphology
Slope roughness	Material supply	Rock falls		River bed morphology
Surface roughness	Material supply		Landslides	River course
	Material supply		Erosion/ saturation	River floods

In the case of a medium-scale analysis and with the input parameters proposed in Fig. 1, the alteration of the land cover by snow avalanches, e.g. the destruction of forest which protects from rock falls and debris flows but also from further avalanches, is the only type of disposition alteration which can be considered. River bed morphology, erosion processes or material supply are parameters which are not represented in the input information of this rather generalised modelling approach. By means of a feedback loop the influence of avalanches on the land cover can be accounted for as shown in Fig. 2.

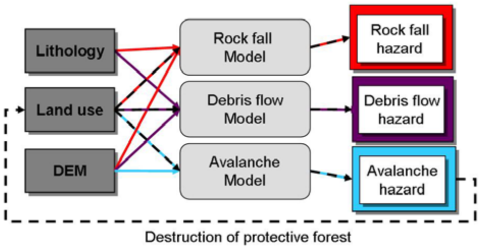

Figure 2 Feedback loop (indicated by dashed lines) implemented in the (simplified) modelling procedure (modified after Kappes et al. 2010).

After having modified the land use, the three processes depending on this input (rock falls, debris flows and snow avalanches - refer to Fig. 2) are re-calculated. This is a fast and user-friendly procedure with the MultiRISK software although the feedback loop itself is not automated.

Consideration of triggering

Within the set of hazards under consideration in this study only two major hazard cascades have been identified: (1) landslides damming rivers or torrents with the potential to cause upstream flooding and dam break with downstream flooding (e.g. Costa and Schuster 1988), and (2) torrent and river floods undercutting slopes and leading to a slope failure. If this leads to a damming of the river or torrent, the same potential consequences as previously described can also be expected.

The study of Carrasco et al. (2003) is very instructive concerning a method to identify spots where such cascading events could take place: based on a landslide susceptibility analysis, Carrasco et al. (2003, p. 361) determined those slopes that are "connected to streams and torrents (gorges)" as *restrictedly susceptible*, i.e. susceptible to a relation between slope and stream processes. This approach is broadly adopted with modifications. In the following, the adjusted method and the GIS operations used for this study are presented and applied to the Barcelonnette basin:

1. Undercutting of a slope:

By using the flood hazard analysis result and overlying it with the potential source areas of shallow landslides, zones potentially destabilized by high water can be identified. However, influences can not only be expected in the overlap of both processes but also interferences due to for instance water saturation of the slope toe and consequently changes are likely in the slope hydrology. This means, the influence may reach beyond the area of actual overlap. Simply, this effect can be accounted for by introducing a buffer around the flooded area. The main challenge is the definition of the buffer width, especially the scale, resolution of the DEM and specific characteristics of the area are of importance in this decision.

Example from Barcelonnette

For the Barcelonnette study a digital elevation model of 10 m was available thus a buffer of 10 m and 20 m was applied to the flooded area (Fig. 3). However, a definite decision about the buffer width can only be made after observations in the field.

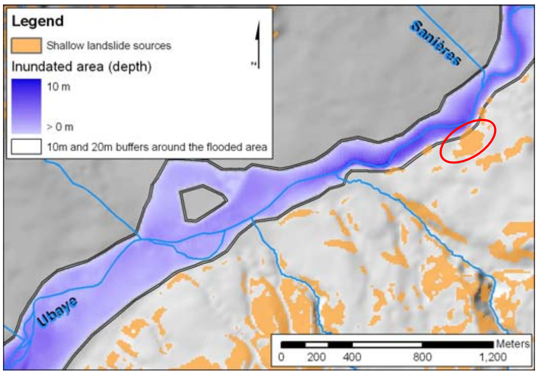

Figure 3 Identification of zones of potential slope undercutting. The area marked with the red ellipse is shown in photograph of Figure 4

As shown in Fig. 3 several locations were identified as susceptible to undercutting. In a field survey multiple spots were examined and proved to be prone to undercutting. An example is given in Fig. 4 depicting the area situated in the red ellipse of Fig. 3.

Figure 4 Area of potential undercutting of the slope, situated at the Ubaye river close to the confluence of the Sanières torrent with the Ubaye (area located in the red ellipse of Fig. 3).

2. Damming of a torrent/river by a landslide:

To identify those torrent and river sections which could possibly be dammed by landslide material the river and torrent network is overlaid with the landslide run out. However, only in “gorge-type” valleys can a damming be expected (at least for moderate debris volumes) whereas in wide valleys the sliding material is most probably not sufficient to block the whole riverbed (Carrasco et al. 2003). In Carrasco et al. (2003) gorge-type valleys are valleys with a bottom not wider than 25 m and identified with a neighbourhood analysis. Since Carrasco et al. (2003) do not provide sufficient detail to reproduce the presented methodology, the landform classification after Jenness (2006) has been applied in this study. The landform classification is based on the topographic position index (TPI) proposed by Guisan et al. (1999) and Weiss (2001). The TPI operates by “calculating the difference between the elevation of the cell and the mean elevation calculated for all cells of a moving circular window centered in the cell of interest” (Guisan et al. 1999, p. 110). The application of thresholds for the TPI values allows the identification of different topographic positions such as ridge, slope, valley, etc. The TPI depends strongly on the size of the neighbourhood taken into account: the larger the considered neighbourhood, the larger are the classified forms. In contrast, small neighbourhoods lead to small-scale classification. For the identification of certain landforms Jenness (2006) combines two TPIs which differ in the size of the neighbourhoods considered for the TPI calculation and defines thresholds at both scales for the different landforms.

When defining the parameters for the landform classification, an important aspect is that the size of the valleys potentially blocked by landslide masses depends on the volume of the slide. This means, large slides can block wider valleys whereas the material from small slides may not fill the full width of the riverbed. Thus, the definition of the TPI neighbourhoods already implies to a certain degree an assumption on the volume of the sliding mass.

The gorge-like torrent partitions are determined by overlay of the valleys with the water courses. By a further overlay of these partitions with the area susceptible to be hit by shallow landslides the areas of potential river/torrent damming are identified.

Example from Barcelonnette

Based on expert judgement, the landform classification of Jenness (2006) was carried out with a smaller neighbourhood of 3×3 and a larger neighbourhood of 6×6 pixels. With this combination, areas known by the authors as valleys with steep slopes and small bottoms were determined as best. Fig. 5 shows the result for one catchment, the Riou Bourdoux, situated in the western part of the Barcelonnette basin.

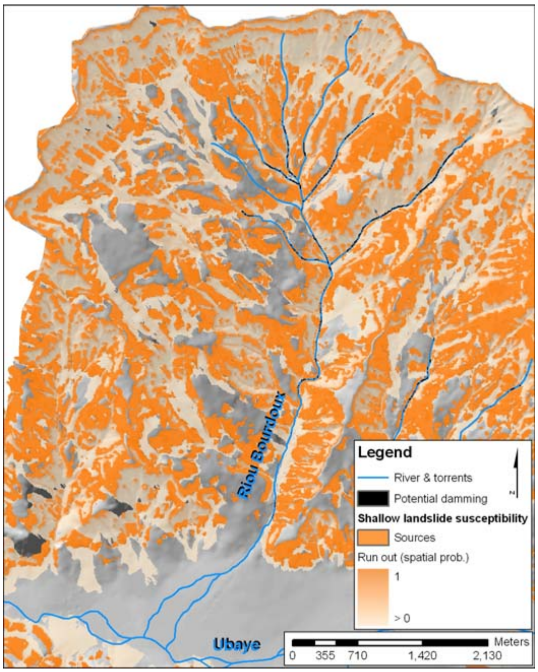

Figure 5 Areas of potential damming of the torrent by landslide masses, example of the Riou Bourdoux.

Apart from the explicit cascades also the triggering of multiple hazards by one event which is not necessarily a hazard (e.g. prolonged rainfall) or a process not included in the multi-hazard analysis should be considered. In this study, this would primarily include floods, debris flows and shallow landslides as a consequence of precipitation or rock falls and shallow landslides triggered by an earthquake.

Example from Barcelonnette

Concerning the triggering by precipitation the rainfall patterns have to be considered. For the Barcelonnette Basin Remaître et al. (2010) identified heavy daily rainfall as trigger for debris flows whereas cumulative rainfall, i.e. rainy periods of about 30 days, may rather lead to shallow landslide events. However, heavy rainfall after antecedent precipitation could lead to a combination of landsliding and debris flows. In contrast, river floods of the Ubaye, are the result of prolonged rainfall in autumn or related to very rapid snow melts in spring (Sivan 2000). Consequently, the creation of one map with all three rainfall triggered hazards would not be realistic but a splitting into short heavy and long cumulative rainfalls is advisable. In Fig. 6 an example is given for the case of heavy rainfall with the potential to trigger shallow landslides and debris flows. The areas susceptible to the effect of one or both are identified.

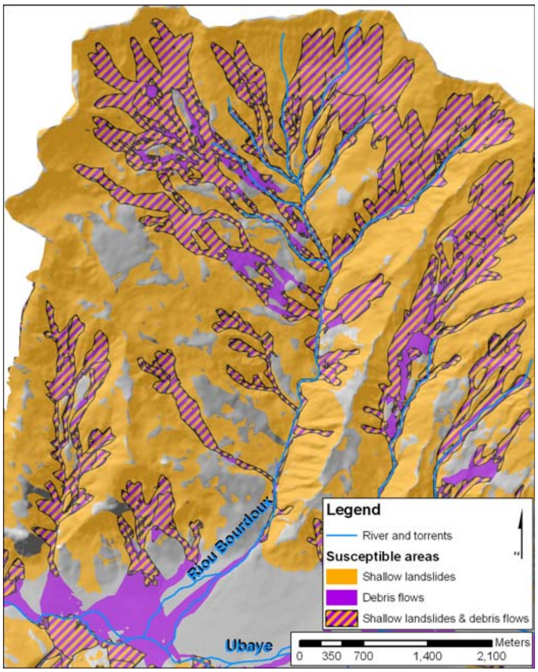

Figure 6 Identification of the area susceptible to being affected shallow landslides and / or debris flows triggered by heavy rainfalls in the Riou Bourdoux catchment.

Conclusions

The integration of hazard relations into hazard analyses is necessary to avoid facing unexpected effects in the aftermaths arising from cascades or feedbacks. The way this can be done depends on the scale level, the methods and models chosen and the hazards combined. However, by means of general identification techniques as matrices a general overview over potential effects can be gained. On this basis, methods suitable to account for relations relevant at the respective scale can be chosen. In this study an example is given for the regional scale at which primarily an identification of spots of potential relations can be performed. However, this is an important starting point for subsequent detailed and time- and data-intensive analyses of the full cascades and effects possibly resulting at these points.

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References

Carrasco, R., Pedraza, J., Martin-Duque, J., Mattera, M., Sanz, M., and Bodoque, J. (2003). Hazard zoning for landslide connected to torrential floods in the Jerte Valley (Spain) by using GIS techniques. Natural Hazards, 30:361-381.

CETE (1987). Commune de Barcelonnette: plan d’exposition aux risques naturels. Technical report, Centre d’Etudes Techniques de l’Equipement, Aix en Prevence.

Chorley, R. and Kennedy, B. (1971). Physical geography - a systems approach. Prentice-Hall International Inc., London, UK.

Costa, J. and Schuster, R. (1988). The formation and failure of natural dams. Geological Society of America Bulletin, 100:1054-1068.

Guisan, A., Weiss, S., and Weiss, A. (1999). GLM versus CCA spatial modeling of plant species distribution. Plant Ecology, 143:107-122.

Jenness, J. (2006). Topographic Position Index v. 1.2. Technical report, online available under: http://www.jennessent.com/downloads/TPI_Documentation_online.pdf, last accessed 08.05.2011.

Kappes, M., Gruber, K., S., F., Bell, R., Keiler, M., and Glade, T. (in prep.). A multi-hazard exposure analysis tool: the MultiRISK Platform. Geomorphology.

Kappes, M., Keiler, M., and Glade, T. (2010). Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence, chapter From single- to multi-hazard risk analyses: a concept addressing emerging challenges, CERG Editions, Strasbourg, pp. 351-356.

Le Carpentier, C. (1963). La crue de juin 1957 en Ubaye et ses conséquences morphodynamiques. PhD thesis, Université de Strasbourg.

Malet, J.-P., Maquaire, O., Locat, J., and Remaître, A. (2004). Assessing debris flow hazard associated with slow moving landslides: methodology and numerical analyses. Landslides, 1:83–90.

Maquaire, O., Malet, J.-P., Ramaître, A., Locat, J., Klotz, S., and Guillon, J. (2003). Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Basin, South East France. Eng Geol, 70:109-130.

MEDD. Programmes d’études des avalanches. URL: http://www.avalanches.fr/, last accessed 20.102009.

Remaître, A. (2006). Morphologie et dynamique des laves torrentielles: applications aux torrents des Terres Noires du bassin de Barcelonnette (Alpes du Sud). PhD thesis, Université de Caen/Basse-Normandie.

Remaître, A., Malet, J.-P., and Cepeda, J. (2010). Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence, chapter Landslides and debris flows triggered by rainfall: the Barcelonnette basin case study, South French Alps, CERG Editions, pp. 141-145.

RTM (2000). Plan de prevention des risques naturals previsibles - Department des Alpes de Haute-Provence, Commune de Jausiers. Technical report.

Schneevoigt, N. and Schrott, L. (2006). Linking geomorphic systems theory and remote sensing. Geographica Helvetica, 61:181-190.

Sivan, O. (2000). Torrents de l’Ubaye. Sabenca, Association de la Valeia, Barcelonnette, France.

Thiery, Y., Sterlacchini, S., Malet, J.-P., Puissant, A., Remaître, A., and Maquaire, O. (2004). Strategy to reduce subjectivity in landslide susceptibility zonation by GIS in complex mountainous environments. In 7th AGILE Conference on Geographic Information Science.

Weiss, A. (2001). Topographic position and landforms analysis. ESRI User Conference, poster presentation.

Wichmann, V. and Becht, M. (2003). Modelling of geomorphic processes in an alpine catchment. In 7th Internation Conference on GeoComputation, Southampton, United Kingdom.

Wichmann, V., Heckmann, T., Haas, F., and Becht, M. (2009). A new modelling approach to delineate the spatial extent of alpine sediment cascades. Geomorphology, 111:70-78.

A.7. Assessing physical vulnerability for multi-hazards using an indicator-based methodology

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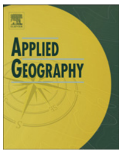

Assessing physical vulnerability for multi-hazards using an indicator-based methodology

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Keywords:
Physical vulnerability
Vulnerability indicators
Multi-hazard
Decision-making

A B S T R A C T

Globally, many built-up areas are threatened by multiple hazards which pose significant threat to humans, buildings and infrastructure. However, the analysis of the physical vulnerability towards multiple hazards is a field that still receives little attention although vulnerability analysis and assessment can contribute significantly to risk reduction efforts. Indicator-based vulnerability approaches are flexible and can be adjusted to the different hazards as well as to specific user needs. In this paper, an indicator-based vulnerability approach, the PTVA (Papathoma Tsunami Vulnerability Assessment), was further developed to be applicable in a multi-hazard context. The resulting multi-hazard version of the PTVA consists of four steps: the identification of the study area and relevant hazards as well as the acquisition of hazard information, the determination of vulnerability indicators and collection of data, the weighting of factors and vulnerability assessment and finally, the consideration of hazard interactions. After the introduction of the newly developed methodology a pilot application is carried out in the Faucon municipality located in the Barcelonnette basin, Southern French Alps. In this case study the vulnerability of buildings to debris flows, shallow landslides and river flooding for emergency planning and for general risk reduction purposes is assessed. The implementation of the methodology leads to reasonable results indicating the vulnerable buildings and supporting the priority setting of different end-users according to their objectives. The constraints of the presented methodology are: a) the fact that the method is not hazard-intensity specific, thus, vulnerability is measured in a rather qualitative and relative way and b) the high amount of data required for its performance. However, the advantage is that it is a flexible method which can be applied for the vulnerability analysis in a multi-hazard context but also it can be adjusted to the user-specific needs to support decision-making.

Q1

Introduction and aims

Many places worldwide such as alpine areas, volcano vicinities or coastal regions are threatened by multiple hazards. Disasters occur when potentially damaging natural processes interact with elements at risk and their associated physical, social, economic and environmental vulnerability (Birkmann, 2006). Therefore, an important aspect for disaster risk reduction is a better understanding of the following factors and their interactions: a) the hazards causing a significant threat and b) the vulnerabilities of the society, the economy and built and natural environment (Birkmann, 2006; UN-ISDR, 2005). The main focus in research and management until recently was on the hazard assessment, however, in the past two decades, vulnerability assessment has also emerged as an important research field. Yet, the Hyogo framework recognises as a *key activity* to develop "systems of indicators of disaster risk and vulnerability at national and sub-national scales" (UN-ISDR, 2005, p. 7). These indicators will provide decision-makers with methodologies to assess the potential impact of disasters on social, economic and environmental conditions. Currently, the existing methods to assess vulnerabilities towards distinct processes vary widely and yet no standard method is applicable for all hazards (cf. Papathoma-Köhle, Kappes, Keiler, & Glade, 2010; Walker and Deeming, 2006). The vast majority of vulnerability assessment methods concern single hazards although the importance of a multi-hazard approach to risk management has been often stressed in the recent past (e.g. Greiving, Fleischhauer, & Lückenkötter, 2006; Kappes, Keiler, & Glade, 2010; Marzocchi Mastellone, & Di Ruocco, 2009). The importance of a multi-hazard approach has been also stressed by the UNEP (1992) that called already for "[u]ndertaking complete multi-hazard research into risk and vulnerability of human settlements and settlement infrastructure […] as one type of risk reduction may increase

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vulnerability to another (e.g., an earthquake-resistant house made of wood will be more vulnerable to wind storms)" in the Agenda 21 (UNEP, 1992, paragraph 7.61 a). Moreover, in the Johannesburg Plan from 2002 is stated that an integrated, multi-hazard risk assessment, which it also includes a vulnerability analysis, and comprehensive disaster management "is an essential element of a safer world in the twenty-first century" (UN, 2002, p. 20). However, multi-hazard risk analyses pose a wide range of challenges - not only concerning the multi-hazard assessment but - also regarding the investigation of the vulnerability towards multiple hazards (Kappes, von Elverfeldt, Glade, & Keiler, in press). Hazards exhibit very different characteristics such as, time of onset, duration, extent and the resulting impact on humans and elements at risk which have to be considered for a multi-hazard vulnerability assessment.

Considering the highlighted challenges the main objective of this paper is to present and discuss a newly developed GIS-based approach that allows coherently assessing hazard-specific physical vulnerability towards multiple hazards. The method proposed here is based on the selection of element characteristics which can serve as vulnerability indicators. In this study, we consider the physical vulnerability of buildings[1] and include information on the distribution and characteristics of people to assist the decisions-makers e.g. in guiding an effective response strategy or even planning preparedness and mitigation measures. However, this information remains within the boundary of physical vulnerability while socio-economic aspects such as income, level of education, level of public awareness, health etc. are not included.

In the following sections a brief overview on vulnerability and indicators considering definitions and methods is presented (Section 2) and the PTVA approach, on which the newly developed multi-hazard vulnerability methodology is based, is described (Section 3). Section 4 introduces the newly developed methodology and Section 5 demonstrates the application of this methodology in the Faucon municipality located in the Barcelonnette Basin, France. This case study illustrates its applicability for several hazards and users. The final sections of the paper provide an analysis and discussion on the results including the advantages, limitations and future developments of the method (Section 6) and a final conclusion (Section 7).

Vulnerability and indicators

The term vulnerability is used diversely, therefore, scientists from various disciplines have an ongoing debate regarding its definition. In a study reviewing vulnerability assessment methods for alpine hazards, Papathoma-Köhle et al. (2010) stated that the vast majority of the authors with natural sciences and/or technical background define physical vulnerability as "[t]he degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)" (UNDRO, 1984). Nevertheless, other scientists (e.g. Birkmann, 2006; Fuchs, 2009), including the authors of this paper, argue that vulnerability should not be reduced only to the degree of damage, although damage assessments can act as important sources of information regarding physical vulnerability. A more integrative but less strict delimited definition would be: "vulnerability is a characteristic of human behaviour, social and physical environments, describing the degree of susceptibility (or resistance) to the impact of e.g. natural hazards" (CENAT, 2004; online glossary). From this perspective, assessing vulnerability should focus on the identification of the variables that influence and change the vulnerability of an element at risk, the so-called *vulnerability indicators* (Birkmann, 2006). According to Birkmann (2006, p. 57) a vulnerability indicator in the context of natural hazards is defined as "a variable which is an operational representation of a characteristic or quality of a system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of an albeit ill-defined event linked with a hazard of natural origin".

Three major approaches are commonly used for the analysis of physical vulnerability: vulnerability curves, damage matrices and vulnerability indicators.

The so-called vulnerability-, fragility- or damage-curves are a widespread approach among natural scientists and engineers (cf. Merz, 2006). These curves are usually building type-specific and link the intensity of a hazard to the expected damages or the cost of these damages related to the total value at risk. The disadvantage of this type of approach is the restriction to only one characteristic of the building, mainly the building type, without considering other factors that contribute to the vulnerability of the elements at risk (such as number of floors, windows or age of the building). Furthermore, the development of vulnerability curves requires information on a large number of damaged buildings. For this reason, they are often used for hazards that impact large areas such as earthquakes, floods or storms (e.g. Grünthal et al., 2006) and rarely for hazards that impact a limited number of buildings such as rock falls or landslides (Menoni 2006).

In contrast to curves, damage matrices are a simpler and more widely applicable method (i.e. applicable for more hazards types). They are composed by classified intensities and stepwise damage levels (Menoni, 2006). The advantage of vulnerability curves and matrices is the quantitative and semi-quantitative result, respectively. However, they also generalise strongly by only distinguishing between certain building types and neglecting the properties of the element at risks that also contribute to their vulnerability. Consequently, neither curves nor matrices are suitable for giving indications on how to reduce risks.

An alternative, mostly rather qualitative, approach is the use of vulnerability indicators. In the socio-economic field, indicators are already widely used to consider the multiple characteristics of humans (age, wealth, health, education level etc.), institutions and/or societies that contribute to their overall vulnerability. Increasingly, this even includes multi-hazard settings as for example in the studies of Collins, Grinseki, and Romo Aguilar (2009); Cutter, Mitchell, and Scott (2000); Lazarus (2011) or Wisner Blaikie, Cannon, and Davis (2004). However, since vulnerability is primarily regarded as a characteristic of the element at risk, only in very few cases hazard-specific vulnerabilities are assessed (hazard-specific examples are Schneiderbauer and Ehrlich (2006), the Disaster Risk Index - DRI (UNDP, 2004)), the Disaster Hotspots (Dilley, Chen, Deichmann, & Lerner-Lam, 2005) or the Global Risk and Vulnerability Index Trends per Year - GRAVITY (Dao and Peduzzi, 2003). By contrast, significantly less experience with vulnerability indicators has been acquired in the physical vulnerability context. This may be related strongly to the fact, that in this field vulnerability is regarded to be hazard-specific. Thus, the development of an overall multi-hazard approach is much more difficult due to the differences between hazards as well as the contrasts between applied vulnerability analysis methods.

An example for an application of indicators in the field of physical vulnerability is the study of Granger, Jones, Laiba, and Scott (1999). They use indicators in the context of a suitability evaluation of buildings to serve as shelters from multiple threats. However, Granger et al. (1999) do not follow up this method to derive a vulnerability index or measure but they offer only a qualitative

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[1] The methodology is applied in this study to analyse the vulnerability of buildings, however, it is transferable to further elements at risk as infrastructures or agricultural land.

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Table 1
Indicators for the building vulnerability according to Papathoma and Dominey-Howes (2003) and Papathoma-Köhle et al. (2007).

	Tsunamis	Landslides
Material of the building	X	X
Number of floors of the building	X	X
Warning signs on buildings		X
Characteristics of the slope side wall (windows or only wall)		X
Condition of the ground floor	X	
Building surroundings (e.g. walls)	X	X
Row of the building	X	
Presence of sea-defence	X	
Width of intertidal zone in front of the building	X	

overview of building characteristics and their relative vulnerability towards different hazards. Another example of the application of indicators in the physical context is given by Puissant, Malet, and Maquaire (2006). In this study the relative damage potential of the exposed elements is evaluated on basis of some kind of damage or vulnerability indicators. One of the few methods that take into consideration a set of vulnerability indicators to carry out an actual physical vulnerability analysis is the PTVA method (Papathoma Tsunami Vulnerability Assessment, Papathoma (2003); Papathoma and Dominey-Howes (2003)). The PTVA method was originally developed for vulnerability analyses in coastal areas susceptible to tsunami using a weighted multi-indicator approach (Papathoma, Dominey-Howes, Zong, & Smith, 2003) and was later on modified for landslide hazard areas (Papathoma-Köhle, Neuhäuser, Ratzinger, Wenzel, & Dominey-Howes, 2007). The method considers characteristics of the elements at risk themselves as well as their surroundings. The successful application of this methodological concept to two different processes indicates a high potential to transfer and adapt the method to multi-hazard vulnerability context. Hence, the PTVA was chosen as the basis for the methodology presented in this paper and adjusted to the requirements of a multi-hazard vulnerability analysis.

The PTVA methodology

The PTVA model was developed using information from historic tsunami records, post-event surveys and damage assessments (Papathoma, 2003; Papathoma and Dominey-Howes, 2003). Papathoma (2003) identified and ranked on basis of expert judgement, a series of attributes, i.e. indicators (Table 1), responsible for controlling the type and severity of tsunami damage to buildings. The methodological steps of the PTVA method are shown in Fig. 1.

The 2004 Indian Ocean event provided data for the method to be validated and improved (Dominey-Howes and Papathoma, 2007) and further application and testing has recently been carried out in the United States (Dominey-Howes, Dunbar, Varner, & Papathoma-Köhle, 2010). In more detail (Dominey-Howes, Dunbar, Varner, & Papathoma-Köhle, 2010), tested the PTVA-2 Model, an improved updated version of the PTVA, in the Cascadia subduction zone (Seaside, Oregon, US). In this case study, the model was used to calculate Probable Maximum Losses (PMLs) within a 500-year tsunami inundation zone in Oregon (USA), demonstrating the flexibility and usefulness of the PTVA approach. A further improved version of the method has also been used for tsunami vulnerability assessment in Sydney, Australia (Dall'Osso, Gonella, Gabbianelli, Withycombe, Dominey-Howes, 2009) and at the Aeolian islands in Italy (Dall'Osso et al., 2010).

The first attempt to apply the PTVA method on a different type of hazard took place in 2007 (Papathoma-Köhle et al., 2007). The authors, having recognized the gap in research concerning landslide vulnerability assessment, modified the PTVA method for landslide related disasters and integrated it in a wider "framework for assessing the vulnerability of communities to landslides" (Papathoma-Köhle et al., 2007, p. 765). The modified PTVA method was applied on the village of Lichtenstein in the Swabian Alb, Germany. The limitations of the study included data availability, lack of information regarding the actual process, lack of information regarding other phenomena that could trigger landslides (such as earthquakes) or occur at the same time (e.g. floods). The study stressed the need for the identification of the factors that contribute to the vulnerability of communities to alpine hazards and the importance of taking multiple hazards into consideration when looking at the vulnerability of alpine communities. In Table 1 the vulnerability indicators for buildings susceptible to tsunami hazard and landslides are presented.

An indicator-based vulnerability assessment methodology for multi-hazards

The four steps of the original PTVA method were slightly modified and generalised to fit to the multi-hazard setting (Fig. 2). The modifications primarily include merging the third and fourth step of the original PTVA and adding the examination of the effect of hazard interactions on the vulnerability. In this study, focus is put on the vulnerability of buildings, however, the approach is transferable to other elements at risk as infrastructure or agricultural areas.

Step 1: Determination of the study area, identification of the relevant hazards and acquisition of hazard information

Determining the objective of the study and the area to be considered is the first step. Practitioners often focus on administrative units (e.g. municipalities, regions, or countries (c.f. Fleischhauer, Greiving, & Wanczura, 2006)) or on specific areas within the administrative boundaries (for instance for the risk prevention plans in France only the settled area within a municipality is considered; refer to RTM, 2002). Within these units and according to the objective of the vulnerability analysis (e.g. risk prevention, mitigation, event management or reconstruction) all

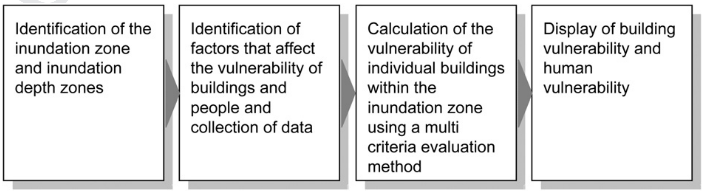

Fig. 1. Steps of the PTVA after Papathoma and Dominey-Howes (2003).

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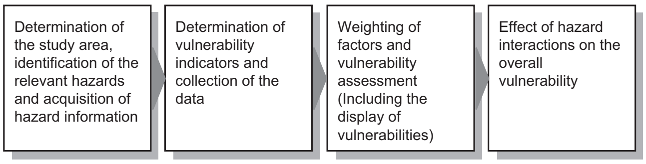

Fig. 2. Steps of the multi-hazard version of the PTVA.

relevant hazards have to be identified based on historical information, records or already available hazard analyses. If hazard analyses are not yet available the necessary investigations have to be conducted within this first step by means of field surveys, aerial-photo-interpretation or inventories which form the basis for heuristic, statistical, deterministic or probabilistic assessment or modelling (Heinimann, Hollenstein, Kienholz, Krummenacher, & Mani, 1998; Van Westen, van Asch, & Soeters, 2006).

Step 2: Determination of vulnerability indicators and collection of the data

Characteristics of elements at risk and their surroundings influencing the physical vulnerability have to be identified. Furthermore, the importance of each indicator towards the different hazards has to be assigned. Although very few studies offer information on indicators and their role in the overall physical vulnerability of the elements at risk, documentation focussing on damage assessment and descriptions of past events can provide this information.

For a multi-hazard vulnerability analysis of buildings in an alpine environment three major groups of vulnerability indicators are proposed:

Building-specific information

This information is related to the characteristics of the building such as its material, construction type and maintenance, number of floors and other characteristics that influence more or less the vulnerability to a specific hazard. Some indications on the role of these characteristics are already given in a few post-event analyses and used for the development of vulnerability curves corresponding to different construction types (Borter and Bart, 1999; Keiler et al., 2006; Romang, 2004; Wilhelm, 1997). Furthermore, information on building characteristics can be extracted from the building codes in some countries. For example, following the introduction of the legally binding hazard zone maps in Austria, buildings in the red and in the yellow hazard zone have to fulfil special construction requirements to reduce vulnerability and, consequently, possible damage (Keiler et al., 2006). Moreover, the role of some building characteristics in reducing or increasing physical vulnerability towards a range of natural hazards, can be found in the literature.

As far as floods are concerned, Granger et al. (1999) suggest that floor height is the most important characteristic for structural (physical) vulnerability, followed by the number of stories, the building age, the wall material and the existence of large unprotected windows as well as the plan regularity. Regarding the building material, Menoni et al. (2006) discuss the differences in the vulnerability of masonry and non-masonry constructions to floods.

Regarding rock falls hazards, Holub and Hübl (2008) mention the strength of the outer wall and the existence, size (smaller size reduces vulnerability) and height of windows above the ground level (height also reduces vulnerability) as key indicators for the building vulnerability. The surface of buildings towards the slope (the smaller the better) and the strength of intermediate ceilings are also considered very important aspects.

In the case of avalanches, Bertrand, Naaim, and Brun (2010) suggest that the physical vulnerability of a building primarily depends on its geometry, the mechanical properties of its material, the anchorage of its foundations and the existence of openings in the wall facing the flow. Thus, the construction types of the buildings are of high importance for the vulnerability assessment (Keiler et al., 2006).

For landslides, Glade and Crozier (2005) discuss the direct and indirect impact on elements at risk without emphasising the importance of building characteristics for the increase or reduction of its vulnerability. Dai, Lee, and Ngai (2002) recognise that the vulnerability of a building to landslides depends on its technical resistance which is subject to its type, nature, age and height. For debris flow Fuchs, Heiss, and Hübl (2007) and Totschnig, Sedlacek, and Fuchs (2011) refer to construction materials, number of stories, existence of a basement and local protection measures such as reinforced outer walls and sheltered openings as key indicators of physical vulnerability.

Holub and Hübl (2008) provide a list of the resistance of different building and opening materials to different processes (avalanche, debris flow, rock fall, floods) and offer thus the possibility to compare the level of importance between hazards.

Building surroundings

The surrounding of buildings is still rarely taken into account although it may play an important role by offering protection from a range of hazards (Holub and Hübl, 2008). In this category also local structural protections have to be considered which may strongly decrease the physical vulnerability (Egli, 1999; Holub and Fuchs, 2008). Holub and Fuchs (2009) stress for example the significance of protection forests whereas Meusburger and Alewell (2008) mention the role of the land cover in general in the occurrence of landslides. Furthermore, the role of neighbouring buildings should not be ignored, as buildings can protect other buildings by reducing the force of water, debris, rocks or snow (Papathoma et al., 2003). However, single trees, small levees or walls around a house can usually not be considered with the DEM or land use information. Nevertheless, they can have a significant positive or negative effect on the vulnerability of neighbouring structures and therefore they have to be considered in another way. According to the PTVA this is done by integration of the building surrounding as vulnerability indicator.

Human-related information

Once the physical vulnerability of the individual buildings has been assessed and its spatial pattern has been illustrated, the next step is the collection of information regarding the distribution and the characteristics of the population of the area, which is essential especially for emergency planners and the civil protection (Cutter, 2003; King, 2001).

After having determined the indicators to be used for the vulnerability assessment, the information on each of them has to be

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Table 2
Vulnerability indicators for several alpine hazards (avalanche (AV), rock fall (RF), flood (FL), shallow landslides (SL), debris flow (DF), flash floods (FF)) and their relative[2] importance for each hazard (black: high importance, grey: medium importance, light grey: low importance and white: no importance).

	AV	RF	FL	SL	DF	FF
Building-specific information						
Material	■	■	░	■	■	▨
Floors	▨	░	■	░	■	■
Condition	■	■	░	■	▨	▨
Openings towards slope (size and condition)	■	■		▨	■	▨
Height of lowest opening			■		▨	▨
Presence of warning signs of landslides (jammed doors, cracks, broken utility lines, etc.)				▨		
Basement			■	░	■	■
Roof material	▨	▨		░		
Foundation type	░		░	■	■	▨
Building surroundings						
Building row (towards slope)	■	■		■	■	▨
Building row (towards river)			▨		▨	▨
Protection by vegetation	░	▨		░	■	░
Protection measures	▨	▨	▨	▨	▨	▨
Movable objects that can be carried away by water or snow	▨		░	░	▨	▨
Human-related characteristics						
Use	▨	▨	▨	▨	▨	▨
Vulnerable pop. (hospitals/schools etc.)	■	■	■	■	■	■
Population density (winter/day)	▨	▨	▨	▨	▨	▨
Population density (winter/night)	▨	░	░	░	░	░
Population density (summer/day)		▨	▨	▨	▨	▨
Population density (summer/night)		▨	▨	▨	▨	▨

collected for each element at risk (at least within the hazardous area) in order to create a GIS database that will be available for the end-users. Although the local authorities are usually the main data providers, field surveys and analysis of aerial photos may be also required.

Step 3: Weighting of indicators and vulnerability assessment

The importance hierarchy of the indicators collected in the previous step varies significantly between hazards as it depends on

- The type of hazard. For example, the height of the building is of great importance during a flood, but not of the same importance in case of a rock fall.
- The priorities of the user. The purpose of the study can influence the weighting of the factors. For example, the height of a building may be important for the emergency management because it enables vertical evacuation, however, when the focus of the study is not the threat to life but the economic loss, the height of the building might be less important than the percentage of the building which is affected.

In Table 2 a qualitative assessment of their relative importance for the vulnerability towards different hazards is provided. While several indicators show almost the same level of importance for all processes as e.g. the material or the building condition, others, such as the roof material or the presence of a basement, are relevant only to some hazards[2].

For each indicator a weight has to be defined which quantifies the level of importance this indicator has on the vulnerability of the elements at risk. For every single indicator, again, scores are assigned to each value this indicator may attain. The scores contain the information to what degree a certain characteristic (one-, two- or three-storey building) contributes to the vulnerability of the building. While the vulnerability scores are supposed to be only hazard- but not user-specific, the weights are hazard- and user-specific. This is based on the assumption, that e.g. a single-floor building is always more vulnerable to floods than a two-floor building but that the number of floors is of higher importance in an emergency management context (vertical evacuation is possible) than in relation to spatial planning. For example, emergency services need to locate potential victims as soon as possible, therefore, buildings housing vulnerable population groups such as elderly, children etc. and buildings not offering opportunity for vertical evacuation (one floor buildings) are of high importance. On the other hand, in the preparedness phase, local authorities need to know where they should focus their mitigation efforts. Therefore, they need to locate non-reinforced buildings with little or no protection from their surroundings. Concerning hazards for which short-time warning and evacuation is nearly impossible, as in case of rock fall, structural and non-structural measures as protections nets or room use in the building (no bedrooms towards the slope etc.) have to be adapted. Insurance companies are additionally interested in the vulnerability of the content of a building. Thus, information regarding the use of the ground floor and the existence of large windows on the slope or river side (depending on the hazard) is relevant for this investigation. According to the PTVA method, the vulnerability computation is done by means of the weighted linear combination method (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003; Papathoma-Köhle et al., 2007): multiplying each factor with a weight and assign a Building Vulnerability (BV) to each element at risk. In the present study, the building vulnerability is computed as a Relative Vulnerability Index (RVI) of each single-hazard according to the scheme shown in Fig. 3 and using the following formula:

$$\mathrm{RVI} = \sum_{1}^{m} w_m \cdot I_m S_n \qquad (1)$$

With the weights $w_1 – w_m$ (with $\sum_1^m w_m = 1$) for the different indicators ($I_1 – I_m$) and the influence to vulnerability ($I_1 s_1 – I_m s_n$, with a value between 0 and 1). This Relative Vulnerability Index is not dependent on the hazard intensity but it rather expresses a relative vulnerability for each building for different hazards and user defined objectives.

After the vulnerability computation - using e.g. a GIS software for the whole database to calculate the vulnerability of all elements at risk - those elements actually at risk are identified by means of overlay with the hazard information. In the case of time- or data-constraints the overlay of hazard zones and buildings can be done in advance to carry out the vulnerability analysis only for the exposed elements. However, this impedes the analysis of multiple hazard scenarios since the necessary vulnerability information on newly exposed elements may be lacking.

Step 4: Effect of hazard interaction on the overall vulnerability

Where hazards overlap, elements may be exposed to multiple hazards or even suffer the simultaneous impact of two events. Since this may lead to an alteration of the vulnerability, the relation of multiple hazards has to be considered. This refers to the spatial (overlap) as well as to the temporal coincidence (simultaneous occurrence). The merging of the spatial and the temporal component of hazard coincidences leads to four possible combinations (cf. Table 3): elements are located in zones of only spatially (1), neither spatially nor temporally (2), spatially and temporally (3) or only temporally coinciding hazards (4). In more detail:

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[2] Relative between the hazards listed in this table. This appraisal is no final evaluation but an example to illustrate the hazard-specific importance of the indicators.

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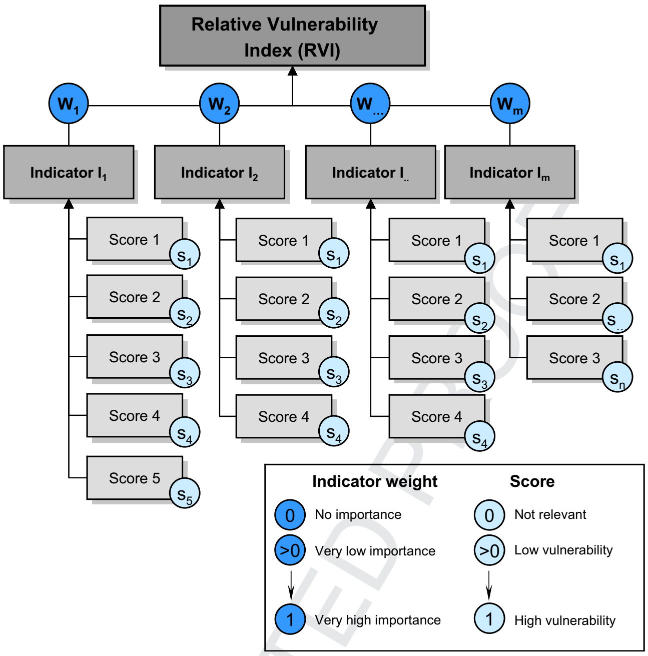

Fig. 3. Vulnerability computation framework.

Type 1 has implications for building codes and design of mitigation measures etc. The loads due to different hazards can be contradictory, for instance, a measure to reinforce an element at risk towards one hazard might destabilise it towards another (Gibbs, 2003). In the framework of the indicator-based approach proposed here, contradictory characteristics can be identified when assigning the scores to the different categories of each indicator and further consideration of this aspect can be encouraged. However, the inclusion of this aspect into the presented methodology is restricted to the identification, while more detailed engineering knowledge is necessary to develop building codes.

Type 2 is of no importance to physical vulnerability. However, for the awareness and education of the population and their behaviour this aspect might be of interest. The consideration of this aspect in the presented approach is neither necessary nor possible.

Type 3 is the result of several hazards caused by the same trigger, one hazard triggering the next or completely coincidental occurrence of various hazards at the same time or timely close with additional spatial overlapping (Kappes et al., 2010). For the resulting vulnerability a distinction has to be made between sequential and simultaneous hazards. According to Zuccaro, Cacace, Spence, and Baxter (2008, p. 417), the timely close occurrence of events (a so-called event-sequence) has the effect of “a progressive diminution of the resistance characteristics of the buildings”. For example, an earthquake, having caused damage to a number of buildings, can have triggered landslides. These landslides will have a larger impact on the already affected buildings than on intact ones since the physical vulnerability of the buildings has been increased due to earthquake damages (Zuccaro et al., 2008). In order to examine the effect of such sequences a matrix may be developed. In this matrix, a first hazard is opposed to a potentially sequential second hazard, and the way the impact of the first event could alter the vulnerability of a building towards a second process is identified (Table 4).

The simultaneous impact of two events provokes a cumulative vulnerability that is potentially different from the sum or sequence of the vulnerabilities of both single events. An example is the impact of an earthquake on a snow covered building which leads to a higher vulnerability of the structure as the sum of both individually occurring events (Lee and Rosowsky, 2006). However, the investigation of the resulting overall vulnerability is an engineering problem and cannot be solved by the method proposed here. Nevertheless, it should be kept in mind, that the simultaneous impact of two hazards on a building in most cases will not only cause more damage than the two processes would cause if they would occur individually.

Type 4 is a challenge for the emergency planners since two incidences within e.g. an administrative unit have to be coped with simultaneously. Likewise, the reactions of the affected inhabitants

Table 3
Types and effects of hazard relations on the resulting vulnerability.

	Spatially overlapping	Spatially not overlapping
Not simultaneous	Elements are affected by different hazards at different times (1)	Different elements within the area under consideration are affected by different hazards at different times (2)
Simultaneous or timely close	Element are affected by two hazards at the same time (3)	Different elements are affected at the same time by different hazards (4)

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Table 4
Matrix to identify the effect of hazard event sequences on building vulnerabilities. The column indicates the first, the row the second hazard.

	Earthquake	Landslide	Flood	Storm
Earthquake		Cracks and especially structural damages may increase the vulnerability to the second impact → Alteration of the condition indicator	Destabilisation of the underground due to the water-saturated soil/erosion → Alteration of the condition & foundation indicator.	
Landslides (including rock fall)	Structural damages may increase the vulnerability to the second impact → Alteration of the condition indicator		Destabilisation of the underground due to the water-saturated soil/erosion → Alteration of the condition & foundation indicator	A storm may unroof a building and "open" the building towards an impacting rock → Alteration of the roof characteristics
Flood		Cracks and damages increase the vulnerability → Alteration of the condition and the lowest opening		
Storm		Cracks and damages increase the vulnerability → Alteration of the condition indicator		

will be altered by two simultaneous events. However, the purely physical vulnerability is not modified and this aspect is therefore not included in the methodology proposed in this paper.

In the following section, the presented methodology is tested in a case study.

Application of the methodology in the Faucon municipality, Barcelonnette Basin, France

The chosen area for the application and testing of the proposed methodology is the municipality of Faucon in the Barcelonnette valley, Alpes des Haute Provence, France.

In France, the development of risk prevention plans (Plan de prevention des risques naturels previsibles, PPR - or previously PER, Plans d'exposition au risques) at the municipal level is obligatory in areas which are threatened by natural hazards. The prefect of the "Département" is responsible for defining which municipalities have to elaborate a PPR. The area considered in such a plan is confined to the settled parts of the municipality. The PPRs designate three types of risk zones, red, indicating high risk, blue, for medium risk and white, for zones of no significant risk. However, the individual vulnerabilities of the single buildings are not considered but a kind of standard building is assumed to define the risk level. The objective of this pilot study is to assess the vulnerability of the buildings situated in the official high and medium hazard zones of the Faucon municipality and demonstrate its spatial pattern.

The case study area

The Barcelonnette Basin (Vallée de l'Ubaye) is situated in the department "Alpes-de-Haute-Provence", located in the South French Alps. The valley stretches between about 1100 m at the lowest point to over 3000 m on the surrounding peaks and is drained by the Ubaye river which is fed by numerous torrents (Flageollet, Maquaire, Martin, & Weber, 1999). Geologically, it constitutes a structural window with autochtonous black marls underlying allochtonous Eocene thrust sheets which are composed by limestones, sandstones and flyschs (Évin, 1997, p. 32; Maquaire et al., 2003; Remaître, Malet, Maquaire, & Ancey, 2003a). The geological setting gives rise to the specific morphology of the slopes: the upper slopes above 1900 m on the thrust sheets are very steep with over 45° while the lower-lying area below 1900 m in the black marls exhibits gentle slopes of 10–30° (Remaître, 2006).

Despite the generally dry and mountainous Mediterranean climate with mean annual rainfall of 700–800 mm, heavy rainfalls during summer storms and spring rains on deep snow cover lead to high discharges (Flageollet et al., 1999; Maquaire et al., 2003). The area is exposed to a high number of freeze–thaw cycles with about 130 freezing days per year (Maquaire et al., 2003).

These boundary conditions give rise to a variety of natural hazards such as shallow landslides (Thiery, Malet, Sterlacchini, Puissant, & Maquaire, 2007), large earthflows (e.g. Poche, La Valette and Super Sauze, (Malet, Maquaire, Locat, & Remaître, 2004)) as well as high debris flow and flash flood activity (Remaître et al., 2003b). After nearly complete deforestation which started in the 17th century and entailed increasing torrent activity, reforestation and construction of mitigation measures, particularly check-dams, were initiated in 1864 (Remaître and Malet, 2010).

Due to the risk posed by the different hazards, all municipalities of the Barcelonnette basin are obliged to elaborate risk prevention plans. The "Commune de Faucon de Barcelonnette" is one of the eight municipalities forming the Community of Communes "Vallée de l'Ubaye" (Fig. 4). The last damaging event was a debris flow in the Faucon catchment in 2003 that affected nine houses and led to a closure of the main road through the valley for several hours. In 2002, the local risk prevention plan (Plan de prevention des risques naturels previsibles, PPR) was elaborated (RTM, 2002).

Although avalanches and rock falls endanger certain zones of the basin, the settled part of the municipality Faucon is not affected by these processes. In contrast, landsliding, torrential processes as debris flows, flash floods (especially in the Faucon and Bourget catchments) and river floods (Ubaye) pose a significant threat.

Application of the methodology

Step 1: Determination of the study area, identification of the relevant hazards and acquisition of hazard information

The hazard information is taken from the PPR of Faucon and accordingly the area under consideration refers to the built-up zone. For endangered areas three different risk zones are distinguished: the red (high risk), blue (medium risk) and white (no significant risk) zone and, thus, this classification is used in this study. The difference between high and medium risk is not attributed to changes in vulnerability or the value at risk but to different levels of hazard. Thus, for the high risk zone a high hazard level and likewise for the medium risk zone a medium hazard level can be assumed. The different zones are described as followed: the red zones are defined as those regions in which no effective and economically acceptable protection measures are possible for this hazard level. Therefore, further construction is

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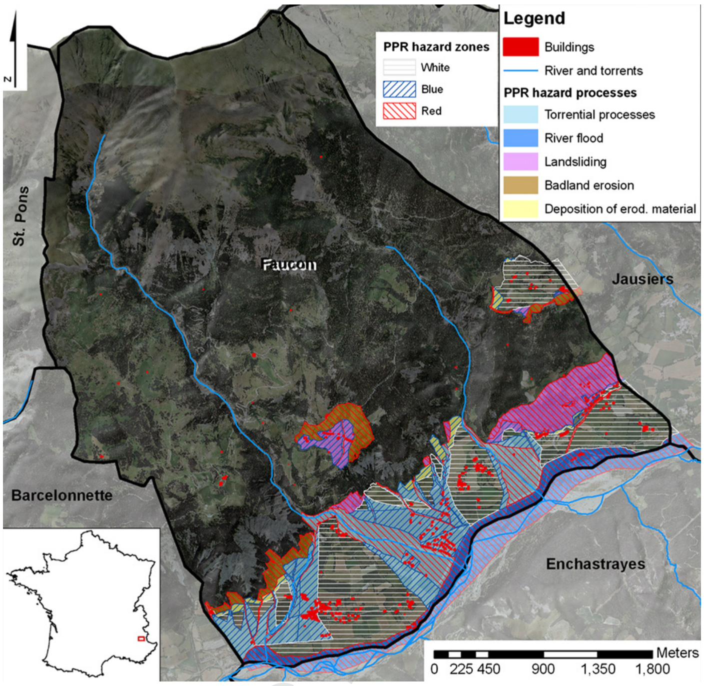

Fig. 4. The municipality «Faucon de Barcelonnette» lying between the municipalities Jausiers, Enchastrayes, Barcelonnette and St. Pons.

prohibited in this area. The blue zone exhibits medium level risk and preventive measures can be applied effectively. For the construction of further buildings certain requirements (building codes) are imposed in accordance to the type of hazard. Finally, the white zone indicates areas where no significant risk was identified (the seismic threat is considered at national level and not included in the PPRs), thus no building codes concerning natural hazards are applied in these areas. Finally, although these risk or hazard zones, respectively, do not indicate exact hazard intensities, they offer information on high and intermediate hazard for multiple processes which can be used for a relative vulnerability analysis within the zones.

Step 2: Determination of vulnerability indicators and collection of the data

In this case study, we focus on building vulnerability. Indicators from Table 1 which were already available or rather easy to obtain were chosen (Table 5). Building-specific information was available from the LIVE Institute (Laboratoire Image, Ville, Environment) of CNRS, University of Strasbourg. Information on the building

Table 5
Indicators chosen for the vulnerability analysis.

Indicator	Source of information	Values
Building-specific information		
Type of building	LIVE	Apartment buildings Residential houses Hut/Cottage Storage buildings or Hangars Monuments (e.g. churches)
Use	LIVE	Agricultural Emergency services Garage Groundwater extraction Industrial/technical Lodging Public administration Pumping station Recreational Religious Residential Transformators
Building condition (This indicator is a combination of age and maintenance)	LIVE	Good Medium Bad Ruin (partly destroyed or very bad shape)
Material	LIVE	Concrete Metal Mixed Traditional brick wall Wood
Floors (Including the cellar)	LIVE	Number
Building surroundings		
Row towards the slope	Orthophoto interpretation	First Second Third ≥ Fourth
Row towards the river	Orthophotos interpretation	First Second Third ≥ Fourth or far from the river
Row towards torrents	Orthophotos interpretation	First Second Third ≥ Fourth or far from any torrent
Trees towards the slope	Orthophotos interpretation	No trees Few trees Closed tree line Located in the forest
Trees towards the river	Orthophotos interpretation	No trees Few trees Closed tree line Located in the forest
Trees towards torrents	Orthophotos interpretation	No trees Few trees Closed tree line Located in the forest

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surroundings was obtained by means of aerial-photo-interpretation of images from 2000.

Step 3: Weighting of factors and vulnerability assessment

The application of the methodology will be demonstrated through the production of several vulnerability maps for three different hazard types (debris flows, shallow landslides and river flooding). Two exemplary users are considered: first, emergency services and rescue teams having evacuation-planning as their focus (later on referred to as emergency scenario). Secondly, local authorities, insurance companies or even private individuals such as house owners that focus on reinforcement of buildings in order to reduce vulnerability (later on referred to as general scenario). The definition of the vulnerability scores and the indicator weighting for each hazard (debris flow, flood and shallow landslide) for the different users was done on basis of expert appraisals and is presented in Fig. 5. According to these schemes, the relative vulnerability index was calculated for each building for the three hazards (debris flow, river flood and shallow landslides). The results for each hazard and user are presented in Fig. 6. The buildings were classified in three classes (high, medium, low vulnerability) using the quantile classification method (equal number of buildings per class but only concerning those buildings situated in the respective hazard zones). Thus, this classification provides assistance for the prioritisation of buildings for evacuation or vulnerability reduction measures. In this study, we assess the vulnerability of all buildings including also buildings which are located in the risk/hazard zones. Although this is not relevant for identifying hotspots but it might be necessary for the assessment of future scenarios. Especially the buildings located close to the hazard zones should be considered for future scenarios.

In Fig. 6 the maps illustrate the spatial patterns of the physical vulnerability for debris flows (Fig. 6a and b), river floods (Fig. 6c and d) and landslides (Fig. 6e). The maps in Fig. 6a/c/e result from assigning the weights by considering the ability of the building to withstand the impact of the process. The resulting information may be used by local authorities, individual building owners or insurance companies for the planning of vulnerability reduction measures and reinforcement of buildings. Regarding debris flows (Fig. 6a), especially for four buildings located very close to the torrent (Faucon) and on the border to the red zone the results indicate a strong recommendation to specific measures for reducing the vulnerability. Actually, these buildings were affected during the 2003 debris flow in the Faucon torrent. In contrast, the buildings located further down the torrent or in the second or third building row benefit from the shadowing effect of the structures and show lower vulnerabilities. It becomes evident that, for this group of buildings, the indicator on building location (in relation to the other buildings) captures and influence the relative vulnerability index since the buildings are very similar as far as the rest of their characteristics are concerned (all two-storey houses except two three-storey houses). More detailed information, such as size and height of windows towards the slope or reinforcement of walls, could give a more nuanced picture of their physical vulnerability. The vulnerability pattern of the buildings towards river flooding (Fig. 6c) suggests that two buildings (assigned to the high vulnerability class and marked in red) should be clearly the priority when planning measures to reduce the vulnerability. Thus, the four buildings that display intermediate and low vulnerability should be given lower priority. However, the risk zone (red) indicates a high hazard level and, therefore, a nevertheless high need for risk reduction measures. For landslides, Fig. 6e shows a rather heterogeneous picture for both, hazard and vulnerability levels. This pattern complicates the prioritization of buildings for which vulnerability reduction measures have to be applied since the ranking between buildings belonging to different hazard zones is not possible. Due to the very general hazard information available from the PPR it is not possible (without making assumptions) to rank a building of high vulnerability located in a blue risk zone with a building of medium vulnerability in the red risk zone. However, since fewer buildings are situated in the red zone (especially buildings with high vulnerability) there is no doubt about the priority ranking. For vulnerability reduction, the buildings classified as highly vulnerable that are located within the landslide hazard zones should be considered for protection measures such as reinforcement or protections walls. Moreover, the function of these buildings should be known and controlled, thus, it should be ensured that no vulnerable groups use these buildings (e.g. children, elderly, disabled).

The weighting for the vulnerability assessment in Fig. 6b/d aims at highlighting the most important buildings for the emergency services. In other words, indicators relevant e.g. for the vertical evacuation in case of a flood such as the number of floors have received higher weights. According to this procedure, the rescue teams may prioritise their actions in the response phase following a disastrous event. The emergency scenario map depicting the vulnerability towards debris flows (Fig. 6b) illustrate only minor differences compared to the general scenario (Fig. 6c). Several additional buildings exhibit high vulnerability and would need immediate support in case of an event (e.g. the building situated north of the four buildings with high vulnerability (red) located in the red zone close to the torrent). However, in general, the prioritization is very similar to the one suggested for general risk reduction and protection measures. There are no dramatic differences between the vulnerability maps for general and emergency scenarios. This can be explained by the fact that the available indicators for the pilot study were limited. Especially the inclusion of information on the characteristics of the population would highly increase the usefulness of the emergency scenario. Having more indicators available could lead to two very different maps, one showing clearly the buildings that should be reinforced and the other showing the buildings that the rescue teams and emergency services should concentrate on in the response phase.

The municipality of Faucon already identified risk/hazard zones (blue and red) for a range of different hazards. However, Fig. 6a, b, c, d, e illustrate the physical vulnerability to all the relevant hazards of the buildings in the entire area and not only in the hazard zones. A municipality with limited resources may limit the vulnerability assessment of buildings within the hazard zones, identifying in this way the hotspots and focus on specific buildings that will most likely experience the impact of a process. Although, in order to use vulnerability assessment for disaster risk reduction strategies for future scenarios we ought to consider that these hazard zones are supposed to represent the hazard levels based on past events but they do not represent possible future scenarios. Especially in the context of climate and global environmental change, future scenarios of processes behaviour have to be considered and, therefore, also hazard frequency and magnitude will change in the settled run-out area indicated as hazard zones (cf. Keiler, Knight, & Harrison, 2010). For example, in Fig. 6d highly vulnerable buildings are located only a few metres away from the border of the hazard zone. A similar situation can be observed in Fig. 6e where highly vulnerable buildings (orange) are located a few metres south of the landslide hazard zone border. The local authorities and rescue teams will have access to this information also if in the future an event has a larger impact than expected.

Step 4: Effect of hazard interactions on the overall vulnerability

Since the PPR of Faucon does not indicate spatially overlapping hazards the effect of hazard interactions on the vulnerability cannot be considered within this case study.

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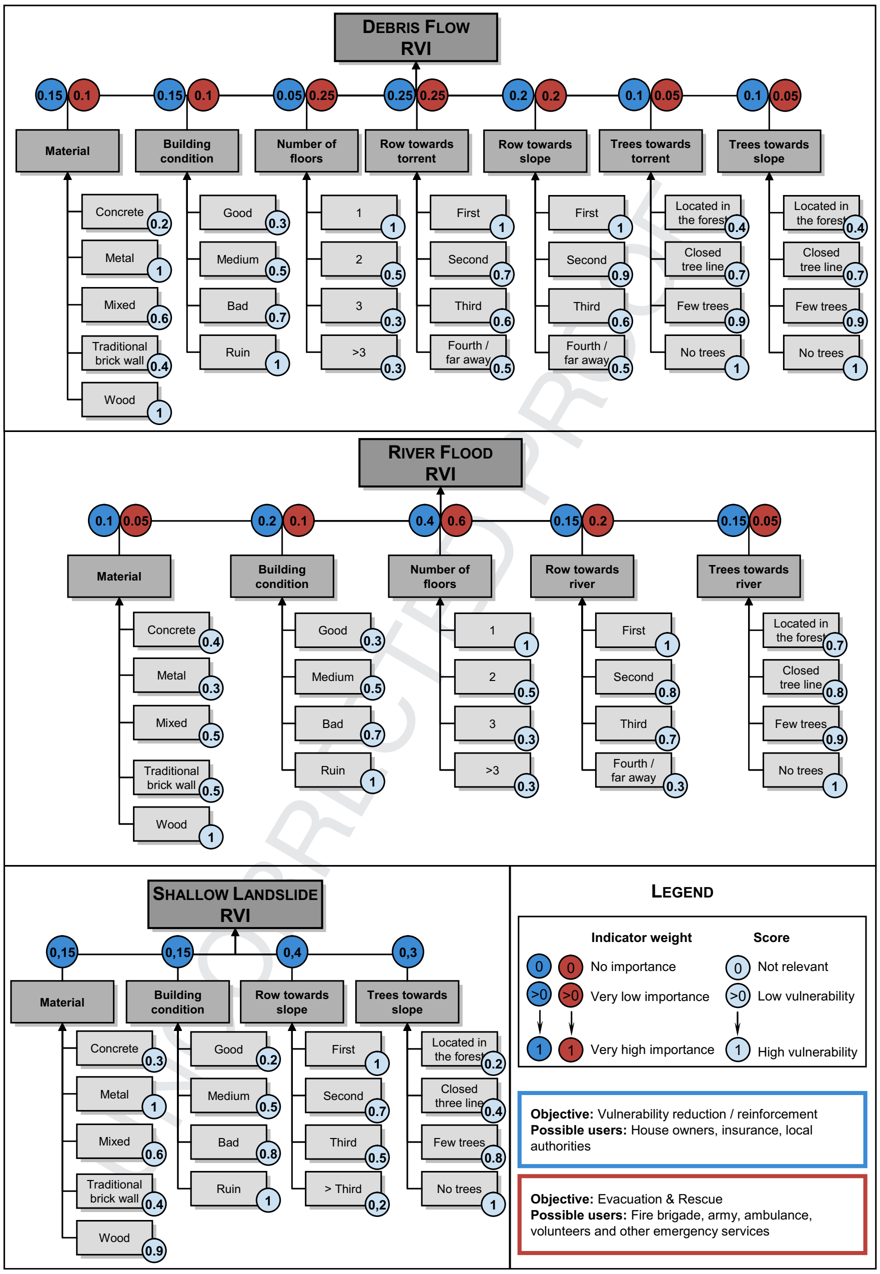

Fig. 5. The vulnerability indicators, the weighting and score for debris flows, river floods and shallow landslides for two different objectives (vulnerability reduction & reinforcement (blue) and evacuation & rescue (red)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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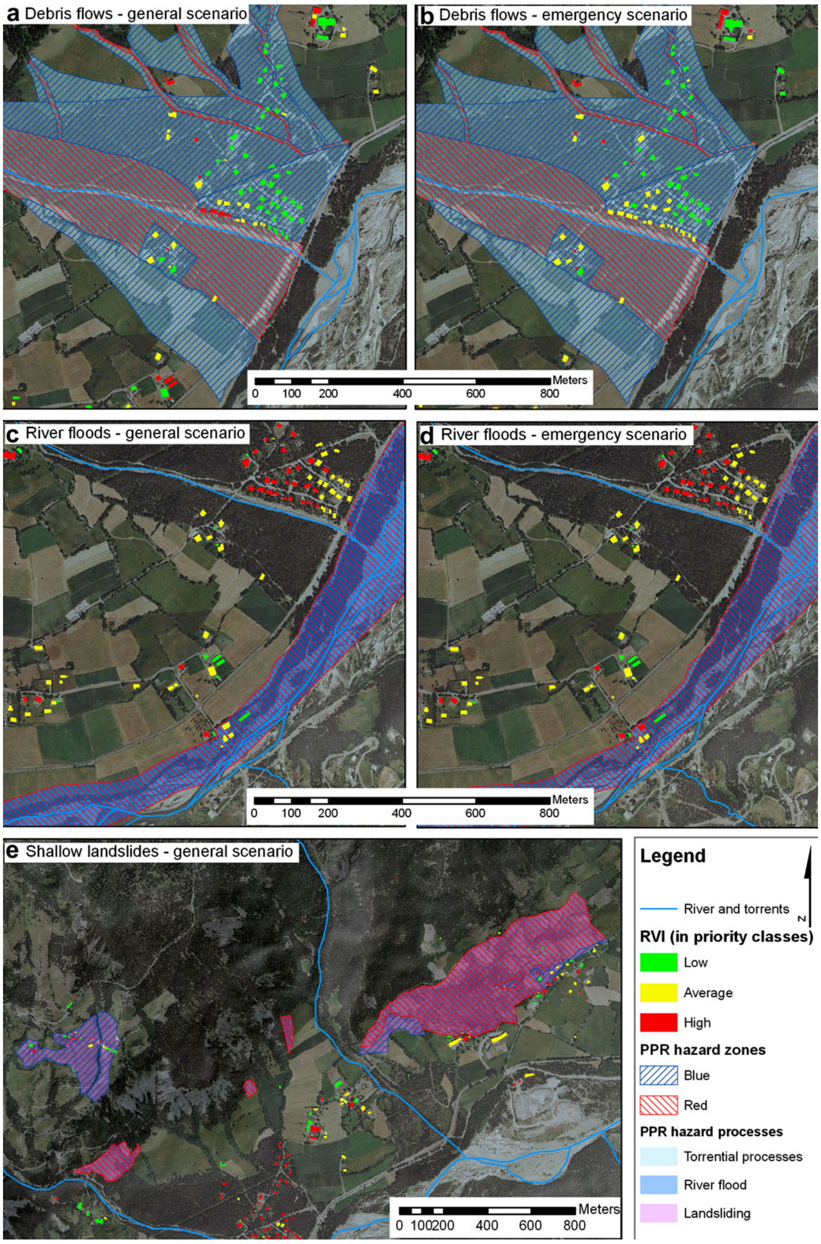

Fig. 6. Physical vulnerability maps.

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Advantages, limitations and future developments

In this paper a newly developed GIS-based approach that allows coherently assessing hazard-specific physical vulnerability towards multiple hazards is presented. This approach is based on the selection of element characteristics which serve as vulnerability indicators. A pilot study in Faucon, France demonstrated the advantages of the method but also its limitations. Moreover, a range of possible future developments are proposed here that could improve and strengthen an already valuable tool for planners and decision-makers.

Advantages

The method presented herein is a valuable tool in the hands of decision-makers offering a common platform for various users to use according to their needs and objectives. The advantages of the newly developed methodology are described in the following paragraphs.

Indicators: The innovation of the methodology lies on the fact that multi-hazard vulnerability indicators are used. All the building characteristics considered as relevant in a multi-hazard context can be taken into account in the assessment of its vulnerability, in contrast to other vulnerability methods that consider only one (e.g. building type).

Flexibility: A major advantage of the method is its flexibility. There is no standard and inflexible weighting of the indicators. Each user can adjust the weighting according to his/her objectives needs and priorities. Moreover, the method can be used for different types of hazards assisting in this way the decision-making in a multi-hazard setting.

Not hazard-intensity specific: The methodology can work also in absence of hazard intensity information. The “relative” vulnerability index enables prioritization of risk reduction actions although it does not assign an absolute vulnerability value to each building.

GIS: The use of GIS makes the database easy to update and to extend by including indicators for more hazard types or additional indicators (e.g. socio-economic data). Moreover, it can be accessed by various end-users and it enables the visualisation of the results.

Future scenarios: The database containing the vulnerability indicators includes all buildings and not only the ones that are located within the hazardous zones. In this way, the vulnerability of the buildings for future scenarios that consider also climate and environmental change can be also assessed, as the impact of future events can be larger than expected.

Local scale: The unit for the vulnerability assessment is the individual house and not building blocks or entire regions as in other vulnerability assessment methods. Working on a local scale is appropriate not only for decision-making but also for emergency planning and vulnerability reduction prioritisation.

Limitations and future developments

The modification of the PTVA for multi-hazards and the implementation of the methodology in a pilot study area was a challenging task. Some of the main limitations of the method are listed below.

Hazard zones: The method we proposed in this article is a first attempt to consider multi-hazard vulnerability in a hazard-specific way. However, this poses a wide range of challenges, among others the link to the hazard intensity. It is understood that buildings that are vulnerable to a process of a specific intensity might be less or not vulnerable when the same process occurs having a lower intensity. Ideally, the hazard zones should include information regarding the intensity/magnitude and the probability of occurrence of each process. However, in this study due to lack of relevant data and in the interest of applicability and transferability the vulnerability of each element at risk is assigned as a relative vulnerability index rather than as an absolute score that expresses the vulnerability of the element to a specific intensity.

Availability of data: In order to implement the proposed methodology a large amount of detailed data at local scale is required that is not always available to the local authorities or cannot be collected by orthophotos or other remote sensing methods. Therefore, applying the methodology includes a considerable amount of time-consuming fieldwork that could make the methodology unattractive to potential users. For this reason, the minimum of data necessary to derive useful results has to be identified and furthermore alternative methods of data collection should be considered.

Weighting of factors: The weighting of factors in this study has been done on basis of expert appraisal. Better documentation of events and damage assessment would provide more information regarding the impact of physical processes on buildings that at the moment is not available.

However, the assumptions and limitations listed above may be used constructively in order to improve and strengthen the methodology. The main points which have to be considered for a future development of the presented indicator-based vulnerability assessment for multi-hazard research are:

Alternative methods of data collection and additional data: One of the major drawbacks of our methodology is the lack of data. Conducting such a study requires a great amount of detailed data that cannot always be collected on site or are not always available by the authorities. In this case, alternative methods of data collection should be considered such as the use of street views (e.g. google street view if available) or questionnaires that should be completed by the inhabitants of the hazardous areas. This could be part of a public education and awareness program. Complementary data would improve the vulnerability assessment considerable. This could include:

- Data regarding open spaces such as the use of the open space and the population density when this is in use (e.g. camping sites) and whether it is paved or not.
- Data regarding the accumulation of movable objects (car parks, machinery, etc.) that could be carried away from water and cause additional damage to infrastructure and people.
- Data regarding infrastructure and agricultural areas: infrastructure and agriculture are very important for a community. Disruption of transport routes and lifelines can make the work of rescue teams very difficult. Damages on agriculture will have a significant impact on the economy of the area. For this reason, in a future development of the present methodology, data regarding the physical vulnerability of infrastructure and agriculture should be included.
- Socio-economic data: the database can be also populated with socio-economic data that would determine the social vulnerability of the population which in combination to the physical vulnerability would constitute valuable information for decision-makers.

Improvement of the weighting of indicators and validation of results: The weighting of the indicators in the present study has been based in expert judgement and for this reason it bears many uncertainties. An interesting future development would be to base the weighting on documentation of past events. This would require detailed information on the characteristics of the buildings, the damage that the building has suffered and the intensity of the event on the specific building. Based on this information, the importance of the indicators can be identified by looking at the damages of

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buildings that, although they experience the same intensity of a process, they suffered different degree of damage. It is understood that in order to conduct such a study documentation containing detailed information on the damage of individual buildings is needed which is rarely available. Detailed damage assessment for individual buildings following an event can provide valuable information regarding the vulnerability of the structure and for this reason it has to be improved and optimised where needed.

Physical Vulnerability Index for multi-hazard: Last but not least, an ambitious development of this study would be the development of a Physical Vulnerability Index for areas exposed to multiple hazards which could combine all these indicators and determine the overall vulnerability to multi-hazards.

Conclusion

In this paper a new vulnerability assessment method for multi-hazards in alpine environments is introduced. The specific methodology is based on an existing methodology for tsunami vulnerability assessment (PTVA) and it was modified to include a multiple alpine hazards. The main idea was to create an indicator-based methodology for physical vulnerability assessment that also enables assessing building vulnerability for multi-hazards perspective. A further innovative aspect of the methodology is that not only vulnerability "to" different hazards (hazard-specific) but also vulnerability "for" a range of users (user-specific) is considered. In other words, the indicators database can be applied by a range of end-users adapting the methodology according to their objectives. The results of this study show that the proposed methodology make it possible: (a) to assess comparable physical vulnerability for multi-hazards (e.g. debris flows, shallow landslides and river flooding) and to (b) to provide information to different stakeholders in order to identify hotspots and focus their efforts in specific buildings and areas. The presented approach is a flexible method which can be applied for the vulnerability analysis in a multi-hazard context but it can also be adjusted to the user-specific needs to support decision-making processes. These advantages and a further improvement of the method will help to meet the challenges for vulnerability as well as risk assessment arising from global change under the consideration of changing natural systems and social systems as well as complex interaction between both systems. Nevertheless, the results also demonstrate the requirement for data regarding the indicators themselves and a better documentation of damage assessment. Better damage documentation could provide further information concerning the importance of each indicator for the vulnerability assessment towards a range of hazard types.

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References

Bertrand, D., Naaim, M., & Brun, M. (2010). Physical vulnerability of reinforced concrete buildings impacted by snow avalanches. *Natural Hazards and Earth System Sciences, 10*, 1531–1545.

Birkmann, J. (2006). Indicators and criteria for measuring vulnerability: theoretical bases and requirements. In J. Birkmann (Ed.), *Measuring vulnerability to natural disasters* (pp. 55–77). United Nations University Press.

Borter, P., & Bart, R. (1999). *Risikoanalyse bei gravitativen Naturgefahren - Fallbeispiele und Daten*. Umwelt-Materialien 107/II. Bern, Switzerland: Bundesamt für Umwelt, Wald und Landschaft (BUWAL).

CENAT. (2004). *Glossary - Monte Verità workshop: Coping with risks due to natural hazards in the 21st century*. Online under. http://www.cenat.ch/index.php?navID=824&userhash=41529&l=e last access 25.07.2010.

Collins, T., Grinseki, S., & Romo Aguilar, M. (2009). Vulnerability to environmental hazards in the Ciudad Juárez (Mexico)–El Paso (USA) metropolis: a model for spatial risk assessment in transnational context. *Applied Geography, 29*, 448–461.

Cutter, S., Mitchell, J., & Scott, M. (2000). Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina. *Annals of the Association of American Geographers, 90*, 713–737.

Cutter, S. (2003). GI Science, disasters, and emergency management - review article. *Transactions in GIS, 7*, 439–445.

Dai, F. C., Lee, C. F., & Ngai, Y. Y. (2002). Landslide risk assessment and management: an overview. *Engineering Geology, 64*(1), 65–87.

Dall'Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., & Dominey-Howes, D. (2009). A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage. *Natural Hazards and Earth System Sciences, 9*, 1557–1565.

Dall'Osso, F., Maramai, A., Graziani, L., Brizuela, B., Cavaletti, A., Gonella, M., et al. (2010). Applying and validating the PTVA-3 model at the Aeolian Islands, Italy: assessment of the vulnerability of buildings to tsunamis. *Natural Hazards and Earth System Sciences, 10*, 1547–1562.

Dao, H., & Peduzzi, P. (2003). *Global risk and vulnerability index trends per year (GRAVITY) - phase IV: annex to WVR and multi risk integration*. Technical report, UNEP.

Dilley, M., Chen, R. S., Deichmann, U., Lerner-Lam, A., & Arnold, M. (2005). Natural disaster hotspots: a global risk analysis. In *Disaster risk management series*. World Bank, number 5.

Dominey-Howes, D., & Papathoma, M. (2007). Validating a tsunami vulnerability assessment model (the PTVA Model) using field data from the 2004 Indian Ocean tsunami. *Natural Hazards, 40*, 113–136.

Dominey-Howes, D., Dunbar, P., Varner, J., & Papathoma-Köhle, M. (2010). Estimating probable loss from Cascadia tsunami. *Natural Hazards, 53*, 43–61.

Egli, T. (1999). *Richtlinie Objektschutz gegen Naturgefahren*. Technical report, Gebäudeversicherungsanstalt des Kantons St. Gallen.

Évin, M. (1997). *Géology de l'Ubaye*. Barcelonnette: Sabença, Association de la Valeia. pp. 32.

Flageollet, J. C., Maquaire, O., Martin, B., & Weber, D. (1999). Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France). *Geomorphology, 30*, 65–78.

Fleischhauer, M., Greiving, S., & Wanczura, S. (2006). *Natural hazards and spatial planning in Europe*. Technical report, Armonia.

Fuchs, S., Heiss, K., & Hübl, J. (2007). Towards an empirical vulnerability function for use in debris flow risk assessment. *Natural Hazards and Earth System Sciences, 7*, 495–506.

Fuchs, S. (2009). Susceptibility versus resilience to mountain hazards in Austria - paradigms of vulnerability revisited. *Natural Hazards and Earth System Sciences, 9*, 337–352.

Gibbs, T. (2003). Multi-hazard design - contradictions and synergies. In *Leaders: International course on development and disasters with a special focus on health*. Paper presented at Leaders: International course on development and disasters with a special focus on health.

Glade, T., & Crozier, M. (2005). The nature of landslide hazard and impact. In T. Glade, M. Anderson, & M. Crozier (Eds.), *Landslide hazard and risk* (pp. 43–74). Chichester: Wiley.

Granger, K., Jones, T., Laiba, M., & Scott, G. (1999). *Community risk in Cairns: a multi-hazards risk assessment*. Technical report, Australian Geological Survey Organisation (AGSO).

Greiving, S., Fleischhauer, M., & Lückenkötter, J. (2006). A methodology for an integrated risk assessment of spatially relevant hazards. *Journal of Environmental Planning and Management, 49*(1), 1–19.

Grünthal, G., Thieken, A., Schwarz, J., Radtke, K., Smolka, A., & Merz, B. (2006). Comparative risk assessment for the city of cologne - storms, floods, earthquakes. *Natural Hazards, 38*(1–2), 21–44.

Heinimann, H., Hollenstein, K., Kienholz, H., Krummenacher, B., & Mani, P. (1998). *Methoden zur Analyse und Bewertung von Naturgefahren*. Umwelt-Materialien Nr. 85. Bundesamt für Umwelt, Wald und Landschaft (BUWAL).

Holub, M., & Fuchs, S. (2008). Benefits of local structural protection to mitigate torrent -related hazards. In C. Brebbia, & E. Beriatos (Eds.), *Risk analysis VI* (pp. 401–411). Southampton: WIT Press.

Holub, M., & Fuchs, S. (2009). Mitigating mountain hazards in Austria-legislation, risk transfer and awareness building. *Natural Hazards and Earth System Sciences, 9*, 523–537.

Holub, M., & Hübl, J. (2008). Local protection against mountain hazards - state of the art and future needs. *Natural Hazards and Earth System Sciences, 8*, 81–99.

Kappes, M., Keiler, M., & Glade, T. (2010). From single- to multi-hazard risk analyses: a concept addressing emerging challenges. In J. P. Malet, T. Glade, & N. Casagli (Eds.), *Mountain risks: Bringing science to society. Proceedings of the international conference, Florence* (pp. 351–356). Strasbourg: CERG Editions.

Kappes, M., von Elverfeldt, K., Glade, T., Keiler, M.. (in press). Challenges of dealing with multi-hazard risk: a review. *Natural Hazards*.

Please cite this article in press as: Kappes, M. S., et al., Assessing physical vulnerability for multi-hazards using an indicator-based methodology, *Applied Geography* (2011), doi:10.1016/j.apgeog.2011.07.002

Keiler, M., Sailer, R., Jörg, P., Weber, C., Fuchs, S., Zischg, A., et al. (2006). Avalanche risk assessment - a multi-temporal approach, results from Galtür, Austria. *Natural Hazards and Earth System Sciences, 6*, 637–651.

Keiler, M., Knight, J., & Harrison, S. (2010). Climate change and geomorphological hazards in the eastern European Alps. *Philosophical Transactions of the Royal Society A, 368*, 2461–2479.

King, D. (2001). Uses and limitations of socioeconomic indicators of community vulnerability to natural hazards: data and disasters in Northern Australia. *Natural Hazards, 24*, 147–156.

Lazarus, N. (2011). Coping capacities and rural livelihoods: challenges to community risk management in Southern Sri Lanka. *Applied Geography, 31*, 20–34.

Lee, K. H., & Rosowsky, D. V. (2006). Fragility analysis of woodframe buildings considering combined snow and earthquake loading. *Structural Safety, 28*, 289–303.

Malet, J. P., Maquaire, O., Locat, J., & Remaître, A. (2004). Assessing debris flow hazard associated with slow moving landslides: methodology and numerical analyses. *Landslides, 1*, 83–90.

Maquaire, O., Malet, J. P., Ramaître, A., Locat, J., Klotz, S., & Guillon, J. (2003). Instability conditions of marly hillslopes: towards landsliding or gullying? The case of the Barcelonnette Basin, South East France. *Engineering Geology, 70*, 109–130.

Marzocchi, W., Mastellone, M., & Di Ruocco, A. (2009). *Principles of multi-risk assessment: interactions amongst natural and man-induced risks*. Project Report, European Commission.

Menoni, S., Galderisi, A., Ceudech, A., Federico, N., Delmonaco, G., Margottini, C., et al. (2006). *Harmonized hazard, vulnerability and risk assessment methods informing mitigation strategies addressing land-use planning and mangement*. Deliverable 5.1, Armonia.

Menoni, S. (2006). *Integration of harmonized risk maps with spatial planning decision processes*. Deliverable 5.1, Armonia.

Merz, B. (2006). *Hochwasserrisiken - Grenzen und Möglichkeiten der Risikoabschätzung*. Stuttgart: Schweizerbart'sche Verlagsbuchhandlung (Nägele und Obermiller).

Meusburger, K., & Alewell, C. (2008). Impacts of anthropogenic and environmental factors on the occurrence of shallow landslides in an alpine catchment (Urseren Valley, Switzerland). *Natural Hazards and Earth System Sciences, 8*, 509–520.

Papathoma, M., & Dominey-Howes, D. (2003). Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece. *Natural Hazards and Earth System Sciences, 3*, 733–747.

Papathoma, M., Dominey-Howes, D., Zong, Y., & Smith, D. (2003). Assessing tsunami vulnerability, an example from Herakleio, Crete. *Natural Hazards and Earth System Sciences, 3*, 377–389.

Papathoma, M. (2003). Tsunami vulnerability assessment using a geographic information system with special reference to Greece. PhD thesis, *Coventry University*.

Papathoma-Köhle, M., Neuhäuser, B., Ratzinger, K., Wenzel, H., & Dominey-Howes, D. (2007). Elements at risk as a framework for assessing the vulnerability of communities to landslides. *Natural Hazards and Earth System Sciences, 7*, 765–779.

Papathoma-Köhle, M., Kappes, M., Keiler, M., & Glade, T. (2010). Physical vulnerability assessment for Alpine hazards - state of the art and future needs. *Natural Hazards*, online first.

Puissant, A., Malet, J.P., Maquaire, O. (2006). Mapping landslide consequences in mountain areas: a tentative approach with a semi-quantitative procedure. *Paper presented at the SAGEO conference*.

Remaître, A., & Malet, J. P. (2010). The effectiveness of torrent check dams to control channel instability: example of debris flow events in clay shales. In C. Conesa García, & M. Lenzi (Eds.), *Check dams, morphological adjustments and erosion control in torrential streams* (pp. 211–237). Nova Science Publications.

Remaître, A., Malet, J.-P., Maquaire, O., Ancey, C.. (2003a). Study of a debris-flow event by coupling a geomorphological and a rheological investigation, example of the Faucon stream (Alpes-de-Haute-Provence, France). *Paper presented at the third international conference on Debris-Flow Hazard Mitigation: Mechanics, Prediction and Assessment, Davos*, pp. 375–385.

Remaître, A., Malet, J.-P., Maquaire, O., Laigle, D., Ancey, C., Locat, J. (2003b). Torrential hazard assessment using a debris-flow runout model. The case of the Faucon stream. *Paper presented at the international conference on fast slope movements: Prediction and prevention for risk mitigation, Napoli*.

Remaître, A.. (2006). Morphologie et dynamique des laves torrentielles: applications aux torrents des Terres Noires du bassin de Barcelonnette (Alpes du Sud). PhD thesis, *Université de Caen/Basse-Normandie*.

Romang, H. (2004). *Wirksamkeit und Kosten von Wildbach-Schutzmassnahmen*. Bern: Verlag des Geographischen Instituts der Universität Bern.

RTM. (2002). *Plan de prévention des risques naturels previsibles - Departement des Alpes de Haute-Provence, Commune de Faucon de Barcelonnette*. Technical report, RTM.

Schneiderbauer, S., & Ehrlich, D. (2006). Social levels and hazard (in) dependence in determining vulnerability. In J. Birkmann (Ed.), *Measuring vulnerability to natural hazards - towards disaster resilient societies* (pp. 78–102). New Delhi: TERI Press, chapter.

Thiery, Y., Malet, J.-P., Sterlacchini, S., Puissant, A., & Maquaire, O. (2007). Landslide susceptibility assessment by bivariate methods at large scales: application to a complex mountainous environment. *Geomorphology, 92*, 38–59.

Totschnig, R., Sedlacek, W., & Fuchs, S. (2011). A quantitative vulnerability function for fluvial sediment transport. *Natural Hazards*, online first.

UN. (2002). *Johannsburg plan of implementation of the world summit on sustainable development*. Technical report, United Nations.

UNDP. (2004). *A global report: reducing disaster risk - A challenge for development*. Technical report, United Nations Development Programme.

UNDRO. (1984). Disaster prevention and mitigation - a compendium of current knowledge. *Preparedness Aspects, 11*, New York.

UNEP (1992). Agenda 21. *Technical report, United Nations environment programme*.

[UN-ISDR2005] UN-ISDR (2005). Hyogo framework for action 2005-1015: building the resilience of nations and communities to disasters. In *World conference on disaster reduction, Kobe, Hyogo, Japan*.

Van Westen, C., van Asch, T., & Soeters, R. (2006). Landslide hazard and risk zonation - why is it still so difficult? *Bulletin of Engineering Geology and the Environment, 65*, 167–184.

Walker, G., & Deeming, H. (2006). *Functional and technical architectural design of a decision-support system for risk informed spatial planning*. Deliverable 5.2, ARMONIA.

Wilhelm, C. (1997). *Wirtschaftlichkeit im Lawinenschutz*. Davos: Eidgenössisches Institut für Schnee- und Lawinenforschung.

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). *At risk: Natural hazards, people's vulnerability and disasters*. New York: Routledge.

Zuccaro, G., Cacace, F., Spence, R., & Baxter, P. (2008). Impact of explosive eruption scenarios at Vesuvius. *Journal of Volcanology and Geothermal Research, 178*, 416–453.

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A.8. MultiRISK - Modelling Platform: User's Manual

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MultiRISK

a Platform for Multi-Hazard Risk Analyses

User's Manual

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Developed in the framework of the Mountain Risks project

PREFACE

MultiRISK is a multi-hazard risk platform consisting of the MultiRISK Modeling Tool and the MultiRISK Visualization Tool to enable rapid, consistent, user-friendly and easily reproducible multi-hazard risk analyses and clear visualization of the results. This platform has been developed in the framework of the Mountain Risks Project, a Marie Curie Research and Training Network, 7th Framework Programme, 2007-2010, Contract number MCRTN03598.

IN SHORT: THE MULTIRISK PLATFORM…

… is a software consisting of a Modeling and a Visualization Tool.

… consists of four steps: (1) hazard modeling, (2) hazard model validation, (3) exposure analysis and (4) visualization of the results.

THE MODELING TOOL

… is a software for the analysis of multiple hazards jointly. The processes currently included are debris flows, rock falls, shallow landslides, floods and snow avalanches.

… includes three of the four steps the MultiRISK Platform consists of, namely (1) hazard modeling, (2) model validation and (3) exposure analysis.

… offers a fast computation and rapid & easy recalculation.

… is designed as top-down approach.

… is based on ArcGIS, programmed in Python and includes several single-hazard models in one framework.

THE VISUALIZATION TOOL

… offers a user-friendly visualization with a clear and lucid layout.

… is a web-application elaborated in CartoWeb and based on MapServer 4 Windows (free of charge).

TABLE OF CONTENT

Introduction

Risk analysis and management strategies are often reactive and restricted to single hazards. However, for a coherent reduction of the overall risk posed by all relevant natural hazards affecting an area, a complete multi-hazard approach is necessary. While the analysis of single hazards and risks is for most processes already rather well established, multi-hazard analyses are still rare, pose a range of additional challenges and can therefore not be computed by just summing the single-hazard risks (cf. Kappes et al. subm). The main challenge is the huge differences between the characteristics of different hazards. This comprises e.g. the scale at which hazards act, their predictability, return period, extent etc. Furthermore it affects the metric in which hazards are measured: impact pressure of rocks, inundation depth of floods or peak ground acceleration of earthquakes. Consequently, also the methods to assess the hazards are very diverse. Last but not least, the scale at which hazards and risks have to be assessed depends on the objective and requirements defined by the end-users who need the information for decision-making purposes in the framework of risk management.

The Multi-Hazard Risk Modeling Tool “MultiRISK” is a software application for the analysis of mountain hazards consisting of the MultiRISK Modeling Tool and the MultiRISK Visualization Tool. MultiRISK follows a top-down approach where a general regional overview to identify areas at high hazard risk is followed by more detailed analyses of these zones. This first MultiRISK version does currently consist of the regional scale analysis of the hazards rock fall, debris flows, shallow landslides, avalanches and river floods. More hazards and detailed local scale models will be implemented in a following version of the MultiRISK Modeling Tool.

The Modeling Tool is programmed in Python and running on basis of ArcGIS for the joint analysis of the hazard susceptibilities and the elements which are exposed. It consists of an assemblage of GIS-based methodologies (e.g. the source identification of avalanches according to Maggioni), ArcGIS extensions (e.g. Shalstab and FloodArea) and stand-alone models (Flow-R running on Matlab) which are connected by means of the Python script. It is an application with the aim to simplify the joint analysis of multiple hazards and risks by carrying out preparative and intermediate steps automatically (as the computation of DEM derivatives, the conversion of formats etc.). This reduces possible errors and makes the analyses clearer and faster.

The MultiRISK Modeling Tool is connected to the MultiRISK Visualization Tool which offers a clearly structured display of the previously produced results. The Visualization is designed in CartoWeb on a MapServer engine acting as local host and shows the results in a browser window (preferably Firefox).

1. Theoretical background of the Modeling and Visualization Tool

The first step in the development of a multi-hazard risk analysis tool is the development of an analysis concept. However, before entering into the topic a short definition of the most important terms is provided:

BRIEF DEFINITION OF THE BASIC TERMS (c.f. Kappes et al. prep):

Exposure: is according to (UN-ISDR 2009, p. 6) defined as "[p]eople, property, systems, or other elements present in hazard zones that are thereby subject to potential losses". In this manual the definition is extended from elements lying in hazard (i.e. full-hazard) zones to susceptibility zones as well. The decisive difference to risk is the negligence of hazard intensity specific vulnerability of the elements.

Hazard: is "[a] dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UN-ISDR 2009, p. 7. However, in a technical context hazard refers often to quantitative information of "likely frequency of occurrence of different intensities for different areas, as determined from historical data or scientific analysis" (UN-ISDR 2009, p. 7. In a multi-hazard context both definitions of hazard are needed: hazard according to a general definition is needed when referring to the totality of multiple potentially threatening processes and the technical one is needed to describe the level of information available for a certain process (in contrast to susceptibility). To be able to distinguish between the two meanings the second (technical) definition will be called *Full-Hazard* in the following.

Risk: relates to the "[e]xpected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period" (WMO 1999, p. 2).

Susceptibility: refers in contrast to full-hazard to the purely spatial information, i.e. indicating areas possibly hit by a certain threatening natural process offering only spatial probabilities without (detailed) information about temporal probabilities.

MultiRISK is based on a top-down approach. Top-down refers to the performance of a simple, rough large scale and fast analysis which is followed by a more detailed, local and sophisticated analysis. The large-scale analysis shall serve as overview over a certain area and support the identification of threat hotspots where more detailed local analyses have to be carried out (c.f. Kappes et al. prep). This assumption is first underpinned by the fact that multi-hazard analyses exhibit very high data requirements and a step-wise analysis enables an efficient concentration of resources on those areas actually at high threat. Second, in a multi-hazard concept the overlap of hazards and potential interactions in the overlapping areas are an aspect which shall not be neglected and finds more and more attention in the recent literature (Tarvainen et al. 2006, Marzocchi et al. 2009, Kappes et al. 2010, European Comission 2011). Overview analyses offer a very good opportunity to identify the respective zones and indicate where interactions have to be analyzed in detail.

The MultiRISK Modeling Tool consists at the present state of the regional analysis for a first overview and the inclusion of local models will be done in a second step. The data requirements for an overview analysis have to be kept down to ensure the effectiveness of a top-down approach. Important aspects in this context are the decisions to model full-hazard or only susceptibility and exposure or risk. Hitherto, MultiRISK has in first place been developed to model susceptibility and analyze (Kappes et al. prep).

However, the single models exhibit the potential to be applied for full-hazard. E.g. the flood model is anyways designed for full-hazard modeling and for rock fall, debris flows, avalanches and shallow landslides certain assumptions could enable the user to compute full-hazard as well (e.g. Blahut et al. 2010).

1.1. Flow chart of the analysis/modeling scheme

The analysis scheme is the background concept of the software. It was developed under consideration of the need to compute comparable hazards and risks on basis of well-available spatial data to enable a fast and easy analysis without the necessity for time-consuming field work and data acquisition (for a more detailed description refer to (Kappes et al.prep).

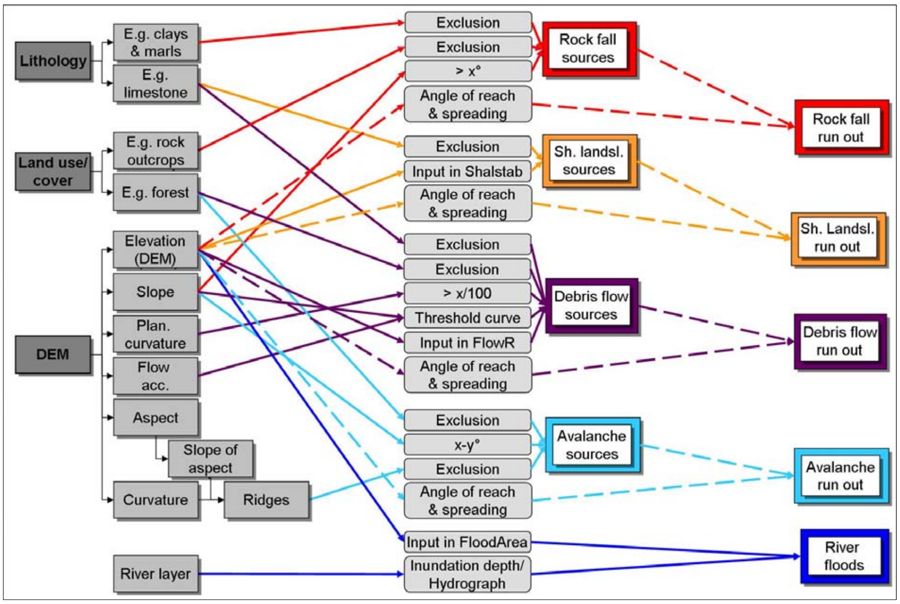

Figure 1: Flow chart of the analysis/modeling scheme

The required input for the MultiRISK Modeling Tool is a digital elevation model (DEM) and optionally land use/cover and lithology information of which a number of derivatives is computed as e.g. planar curvature, forest cover or limestone outcrops (Figure 1). These information layers form the actual input for the modeling. The modeling is done either by external models, by ready-to-use ArcGIS extensions for the modeling of certain hazards or by methodologies which are implemented directly in ArcGIS by means of the basic tools in the toolbox.

1.2. Data input (original data)

INFORMATION ON THE DATA REQUIREMENTS:

Scale: Regional ~1:25.000 (max. range 1:10.000 - 1:50.000)

Resolution of the rasters: 10m (MultiRISK is currently adjusted to a resolution of 10m although it could as well be adapted to 20m and potentially still to 30m. The resolution is restricted by the run out model Flow-R which requires a raster resolution which is divisible by 10)

Data/Information:

Spatial data:	DEM (raster file) Land use/cover (polygon shape file) Lithology (polygon shape file) Drainage network (raster file)
Non-spatial information:	Hazard information: to calibrate the single models information is necessary for each process. Details will be given in the following sections. Inventory data (if an automatic validation shall be carried out. Alternatively to data on past events, areas mapped on basis of expert appraisal could be entered into the validation as well. Alternatively other validation approaches as a field survey are also possible. Elements at risk (if an exposure analysis shall be carried out). Potential options are points, lines or polygons (e.g. buildings) which will be treated as units (already a partial exposure leads to the indication of the label *exposed*), lineal elements as infrastructure of which the exposed stretch will be identified and finally polygons (e.g. land use units) of which the exposed part will be determined.

1.3. Processing

In the first processing step, the DEM is resampled to a resolution of 10m and adjusted to coordinates divisible by 10[1].

An exception is the input for the model FloodArea for river flood modeling: the elevation differences in floodplains are rather low but significant and a resampling to 10m (if the resolution of the original DEM is better) means a loss of detail. Therefore, as input for FloodArea, the original DEM is only processed with „fill sinks" but no resampling to a 10m resolution etc. is carried out.

The shape file inputs (land use/cover, lithology and the rivers) are converted into rasters exactly aligned to the processed DEM raster. The elevation information is assigned to the pixels of the river raster as input for the flood model FloodArea.

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[1] Coordinates divisible by 10 are needed for the model Flow-R by means of which the run out of rock fall, avalanches, debris flows and landslides is computed. Flow-R itself is (in the MultiRISK independent version) applicable at a resolution of 10, 20 or 30m, however, the way it is included in MultiRISK (this refers especially to the data preparation) offers currently only the 10m application. For the modeling with a resolution of 20m or 30m MultiRISK would have to be readjusted!

1.4. Computation of derivatives (model input)

The following derivatives are computed with the default algorithms of ArcGIS (see Figure 1):
DEM: slope [°], planar curvature [m^{-1}], flow accumulation [m^2] and ridges (derived on basis of curvature and slope (change) of aspect).
The class information of land use/cover and lithology are reclassified according to decisions made by the user (e.g. the exclusion of dense forest for the avalanche initiation leads to a classified file indicating the existence of forest 1/noData).

1.5. Hazard modeling methods

In the following the methods and models used for the hazard analyses are described.

1.5.1. Avalanche sources

The source identification is carried out according to the methodology proposed by Maggioni and Gruber (2003) and simplified by Barbolini et al. (2009). The basic assumptions are:

→ Where enough snow accumulates (on ridges or too steep terrain this is mostly not possible) and can, due to a sufficiently high slope angle, get into movement and is not stabilized by dense forest an avalanche can possibly be initiated. Translated to modeling criteria the following three parameters have to be considered:

1. Slope: A range between around 30° and 60° can be assumed as potentially avalanche producing since below a certain angle the slope is too flat to start the movement and above a specific angle the snow is not accumulating. The exact thresholds are defined by the user.
2. Land use/cover: Specific land use/cover types as e.g. dense forest can usually be excluded as possible source for avalanches.
3. Ridges: Due to the exposed situation and the effect of wind-induced snow-drift, ridges are excluded as possible sources. Ridges are, according to Maggioni (2004), identified by the slope of aspect of >40° and positive curvature values >1/100m. This is done automatically and cannot be modified by the user.

1.5.2. Shallow landslide sources

The sources are identified with the model Shalstab (Montgomery and Dietrich 1994) in the version of the slope stability package (a script running in ArcGIS 8.x & 9.x) after Montgomery and Greenberg (2009) which is included in MultiRISK. Shalstab couples a “hydrological model to a limit-equilibrium slope stability model to calculate the critical steady-state rainfall necessary to trigger slope instability at any point in a landscape” (Montgomery et al. 1998, p. 944) till obtaining the following equation for the critical steady-state rainfall (Qc):

$$Q_c = \frac{T \sin\theta}{a/b}\left[\frac{\rho_s}{\rho_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\right] \qquad \text{Equation 1}$$

with the soil transmissivity T [m^2/day], the hillslope angle θ [°], the drainage area [m^2] a and the outflow boundary length b [m], the water bulk density ρ_w [kg/m^3], the soil bulk density ρ_s [kg/m^3] and the angle of internal friction ϕ [°].

Shalstab can be used without specific calibration or can be calibrated in detail. Without specific calibration, it indentifies the “areas with equal topographic control on shallow landslide initiation” (Montgomery et al.1998), p. 945). The following data and parameters, respectively, have to be entered:

1. DEM: the digital elevation model is directly (after the general pre-processing) inputted into Shalstab which computes the necessary derivatives *a*, *b*, θ and performs the susceptibility computation.
2. The soil bulk density ρ_s (one value for the whole area has to be defined). Dietrich and Montgomery (1998) propose the assumption of a value between 1600 and 2000 kg/m^3 for the use without specific calibration.
3. The angle of internal friction (friction angle) θ has to be inputted.
4. The critical steady state rainfall has to be determined for which the unstable areas are computed.
5. After the susceptibility analysis in Shalstab, identified unstable areas lying in certain lithological units which generally do not lead to landsliding as e.g. outcropping limestone can be excluded.

→ Where the material is adequate and the topography favorable, possible landslide sources are identified.

1.5.3. Rock fall sources

Rock falls initiate at rock walls / outcropping rocks which exhibit usually rather steep slopes. Rock fall initiation is thus strongly correlated to steep slopes and a common method to identify potential sources is the classification of the slope gradient (derived from a DEM) with a threshold angle above which rock detachment and fall is assumed (Wichmann and Becht 2006). This applies especially for certain lithological units as limestone or granite while e.g. clays and marls do usually not produce significantly large and stable blocks with far movement (Corominas et al. 2003).

In total, three criteria are used within MultiRISK for the rock fall source identification:

1. Slope: the area exhibiting a slope angle above a certain threshold which has to be defined by the user is assumed to possibly produce rock fall. For Information on slope angles used in scientific studies see for example Corominas et al. (2003), Wichmann and Becht (2006), Guzzetti et al. (2003), Ayala-Carcedo et al. (2003), Jaboyedoff and Labiouse (2003) or Frattini et al. (2008).
2. Lithology: certain lithological units which most probably do not lead to significant rock fall as clays and marls can be excluded.
3. Land use/cover: the usefulness of this layer depends on the detail and information content offered. Outcropping bedrock, sealed areas or dense forest could give valuable information for inclusion and exclusion, respectively, according to the effect on rock fall initiation.

→ Where the slope angle is high enough and neither the land use/cover nor lithology information indicate an exclusion as possible source the zone is marked as possible rock fall source.

1.5.4. Debris flow sources

The source identification was done according to the methodology proposed by Horton et al. (2008) and carried out with the model Flow-R which is operated by MultiRISK. The following criteria are used for the source identification (Horton et al. 2008):

1. Slope in combination with upslope area: A certain slope angle is necessary to put material and water in movement, however, the availability of these two components is strongly influenced by the size of the drainage area. Therefore, slope and upslope area can be considered as dependent and related variables, respectively. For rather big upslope areas moderately steep slopes are sufficient to start a movement (high material and water availability) while for small contribution zones only rather steep slopes lead to mass displacement (Figure 2). One of the two curves, the rare or the extreme fitting, can be chosen for the debris flow modeling.

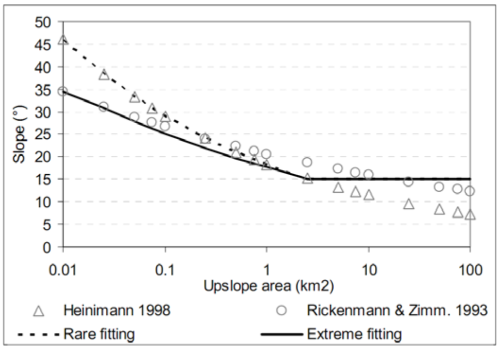

Figure 2: Slope threshold in dependence on the upslope area

2. Planar curvature: the existence of a concave shape is assumed to be an important factor for the accumulation of material and water for the formation of debris flows as well (Delmonaco et al. 2003). The user defines a planar curvature threshold below which an area is identified as gully which may lead to material and water accumulation and contributes in further consequence as one parameter to debris flow formation.
3. Lithology: Potential sources lying in certain lithological units as e.g. outcropping limestone which is assumed to not be susceptible to debris flow initiation can be excluded as possible sources.
4. Land use/cover: Units as e.g. dense forest can be excluded, if a respective indication gives rise to the assumption that below dense tree cover no debris flows are initiated in this area.

→ Concave and steep areas with a sufficiently big upslope area to accumulate enough material and water and explicit stabilitzation due to certain land use/cover or lithological characteristics are designated as potential debris flow sources.

1.5.5. Run out modeling for debris flows, rock falls, shallow landslides and avalanches

The run out computation is done by means of the model Flow-R. Flow-R combines three algorithms, two flow direction and one run out distance algorithm:

1. The flow direction is primarily based on the multiple flow direction method after Quinn et al. (1991) which was enhanced by Holmgren (1994) resulting in the following formula:

$$f_i = \frac{(\tan \beta_i)^x}{\sum_{j=1}^{8} (\tan \beta_j)^x} \qquad \text{for all } \tan \beta > 0 \qquad \text{Equation 2}$$

with *I,j* the flow directions (1..8), f_i the flow proportion (1..0) in direction *i*, $\tan \beta_i$ the slope gradient between the central cell and cell in direction *i* and *x* an exponent introduced by Holmgren (1994) (for more detail on the model see Horton et al. (2008), Kappes et al. (2011) or Blahut et al. (2010)). For $x = 1$ it converts into the basic multiple flow direction after Quinn et al. (1991) and for $x \to \infty$ it turns into a single flow.
2. The flow direction is influenced by the persistence of the flow which describes its inertia to changes of the flow direction. It is a function of the change in angle from the last flow direction (Horton et al. 2008).
3. The run out distance is delimited by means of a constant friction loss angle. For each transition of the mass from one pixel to the next the kinetic energy is computed while the angle of constant

friction loss is subtracted. This is done by the subtraction of the constant friction loss angle from the angle between the two pixels. The kinetic energy is thus computed by the following equation:

$$E_{kin}^{i} = E_{kin}^{i-1} + \Delta E_{pot}^{i} - E_{loss}^{i} \qquad \text{Equation 3}$$

with the time step *i*, the kinetic energy E_{kin}, the change in potential energy ΔE_{pot} and the constant loss E_{loss}. The flow stops when the kinetic energy drops below zero.

1.5.6. River floods

For the river flood modeling the ArcGIS extension FloodArea developed by Geomer (2008) is implemented in MultiRISK. FloodArea offers a number of modeling options and model parameters of which only the following two options are included in MultiRISK:

1. Modeling of the water level (static flood modeling): On basis of a DEM, the drainage network and a specific water level above the elevation of the drainage network, the extent of the water surface is computed with the corresponding water depth in each pixel.
   “Using the option *Water level* (elevation of a drainage network) assumes that flooding is initialized by the entire drainage network, meaning from all grid cells other than NoData). Water levels can vary spatially but remain temporally constant during the simulation process” (Geomer 2008, p. 12).
2. Modeling by means of hydrograph information (static or dynamic flood modeling): On basis of a DEM and one or more hydrographs at various points the spatial and temporal course of the flooding can be modeled. “Using the option *Hydrograph* (input by single cell) water enters the model at defined locations. This option makes temporal variation (hydrograph) of water levels possible” (Geomer 2008, p. 12).

1.6. Hazard model validation

If inventories of past events exist or mapping of e.g. areas susceptible to landsliding can be mapped a validation can be carried out[2]. For the validation step confusion matrices are chosen which are based on an overlay of the modeling results with either expert assessment from the field or aerial photos / records of past events (Beguería 2006). The result is subdivided into four classes, the True Positives, True Negatives, False Positives and False Negatives (Table 1).

Table 1: Confusion matrix, numbers either in [m^2] or [%]

	Modeled	Not Modeled
Event	True Positive	False Negative
No Event	False Positive	True Negative

This method gives an indication which area / percentage of area has been modeled correctly (true positives), i.e. the positive modeling result can be confirmed by recorded events. Likewise it shows with the false negatives which percentage of past events could not be identified by the model. The false positives have to be interpreted as areas which will possibly fail in the future. The true negatives are the ones most difficult to evaluate since inventories contain normally only areas affected by hazards but not areas surely not affected (i.e. safe). Thus they are indeed no “true negatives” because no recorded “negatives” are mapped and entered into the validation process.

In summary, especially the true positives and the false negatives are valuable measures to assess the quality of the procedure. The percentage of false positives to the overall area modeled might furthermore give an impression if the model does strongly overestimate the as possibly threatened marked area. However the extent of the inventory has to be taken into account. If only few events are available for the validation, a “high overestimation” is to be expected while in the case of a very extensive inventory the “overestimation” shall be lower. Thus, although the confusion matrix method does not require a certain minimum amount of recorded events, the number/area of the records influences the true positive rate in comparison to the false positive rate strongly.

1.7. Multi-hazard exposure/risk analysis

By means of overlaying the susceptibility zones with the elements at risk those e.g. buildings, roads or areas which are exposed are identified.

1.8. Concept of the visualization

The result of a multi-hazard risk analysis consists of a multitude of single files: the single susceptibilities (sources and run out) and the exposure to the different hazards, but also the overlaps of hazards. The visualization of all these single files is not only a time-consuming work by assigning each one of them color and design but should furthermore follow cartographic rules to assure clearness and facilitate the understanding of the content. This means in first place to not overload a map with too much information which makes it confusing and the message unclear but also to follow the cartographic principles

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[2] Alternatively a validation based on expert appraisal of the resulting maps or with the maps in the field is possible

concerning the layout of a map etcetera. To communicate the susceptibility and exposure information the following three steps were set up:

1. General setting: Provision of general information on the study - among others e.g. land use/cover and lithology, slope and planar curvature, components of the models and contributing to the modeling results.
2. Single hazards: Each hazard is visualized separately and in detail. This option shall give the user the possibility to recognize hazard patterns for each single process and get familiar with the distribution of each single one.
3. Overlaying hazards: Up to three hazards can be overlaid to identify the areas where they overlap and possibly interact.
4. Number of overlapping hazards: Here the number of processes lying one above the other is visualized. This is an extension of the previous visualization mode but the information on the type of processes overlapping is taken out to.
5. Past events: Visualization of the recorded past events which are the basis for the validation.
6. Validation: The validation result (True Positives, False Negatives and False Positives) are shown.
7. Exposure: Highlighting of the exposed elements.

The colors for the visualization of the hazards are chosen according to the “Symbolbaukasten”, a symbol kit for the mapping of natural hazards after Kienholz and Krummenacher (1995).

2. The implementation: MultiRISK - the Modeling Tool

2.1. Installation (Read-me file)

DESCRIPTION:

The MultiRISK Modeling Tool is a software for the analysis of the hazards rock fall, debris flows, shallow landslides, avalanches and river floods at a regional scale.

ATTENTION

Space-characters as well as specific symbols are not allowed in any path used in the program! Furthermore, names must not start with a number!

REQUIREMENTS:

- ArcGIS 9.3 with ArcInfo license and ArcInfo Workstation (incl. Python)
- FloodArea + FloodArea Toolbox
- wxPython - Download: http://wxpython.org/download.php
  (wxPython2.8-win32-unicode-py25 for windows 32 bit and python 2.5)
- MCRInstaller - Download:
  ftp://igar.org/Flow-R/Matlab%20Compiler%20Runtime/v%207.11%20(2009b)/

INSTALLATION (The requirements have to be installed already!!!)

Unzip MultiRISK.zip (e.g. to C:\Programs) Space-characters are not allowed in the Path!

- Browse the location of Toolboxes in the ArcGIS installation and change the path in MultiRISK.py (it is located in the MultiRISK folder, open it with e.g. notepad or the like) in line 17.
- Browse the location of FloodArea.tbx and change the path in MultiRISK.py (in the MultiRISK folder) in line 18.
- Update the system registry:
  1. Browse \\ArcGIS\ArcToolbox\Scripts.
  2. Double-click the file RegisterAmlAsExecutable.reg.
  3. Click Yes to add this information to the registry.
     If the modeling of shallow landslides still does not work follow the indications in the box below or on this web-page: (http://resources.arcgis.com/content/kbase?fa=articleShow&d=29077)
- Setup the shallow landslide toolbox:
  1. Start ArcGIS.
  2. Right-click the ArcToolbox window and click Add Toolbox.
  3. Left-click to the “+” in front of the stability Toolbox.
  4. Right-click ArcStability – click “Properties…” and then on the “Source” tab
  5. Browse to the location of the ArcStability.aml in the MultiRISK folder and click OK.

START

a) Start the MultiRISK from Python by double-click on MultiRISK.py or

b) Start the program from ArcGIS by adding it as Toolbox: Right-click on ArcToolbox window and choose "New Toolbox". Right-click on the Toolbox you created, point to Add and choose "New Script". Choose Name and Label for the Script and click next/weiter. Upload the python script MultiRISK.py. Untick “Run Python script in process” and tick “Show command window when executing script”. In the last panel just Finish has to be clicked. Now the script is added and it can be started by double-click on the script-name and push OK in order to confirm.

ALTERNATIVE WAY TO ENABLE THE .aml FILE

If the modeling of shallow landslides still does not work after having updated the system registry, follow the indications in this box (they were copied from the web-page specified below) or on this web-page:

(http://resources.arcgis.com/content/kbase?fa=articleShow&d=29077

Alter the RegisterAMLasExecutable.reg file so that it works correctly with Windows XP SP2. To do this, insert the full path to the arc.exe file in the .reg file.

⚠ WARNING: The instructions below include making changes to essential parts of your operating system. It is recommended that you backup your operating system and files, including the registry, before proceeding. Consult with a qualified computer systems professional, if necessary.

ESRI cannot guarantee results from incorrect modifications while following these instructions; therefore, use caution and proceed at your own risk.

Follow the steps below.

1. Navigate to ...\\ArcGIS\ArcToolbox\Scripts.
2. Locate the file named RegisterAmlAsExecutable.reg. Right-click it and select 'Edit'.
3. At the line:
   ```
   @="arc.exe \"&run\" %0 %*"
   ```

   Replace arc.exe with the full path to arc.exe. For example, if the path to arc.exe is C:\arcgis\arcexe9x\bin\arc.exe, the new line appears as follows:

   ```
   @="\"C:\\arcgis\\arcexe9x\\bin\\arc.exe\" \"&run\" %0 %*"
   ```

   Notice that the \ is an escape character that must be inserted before all quotation marks and back-slashes.

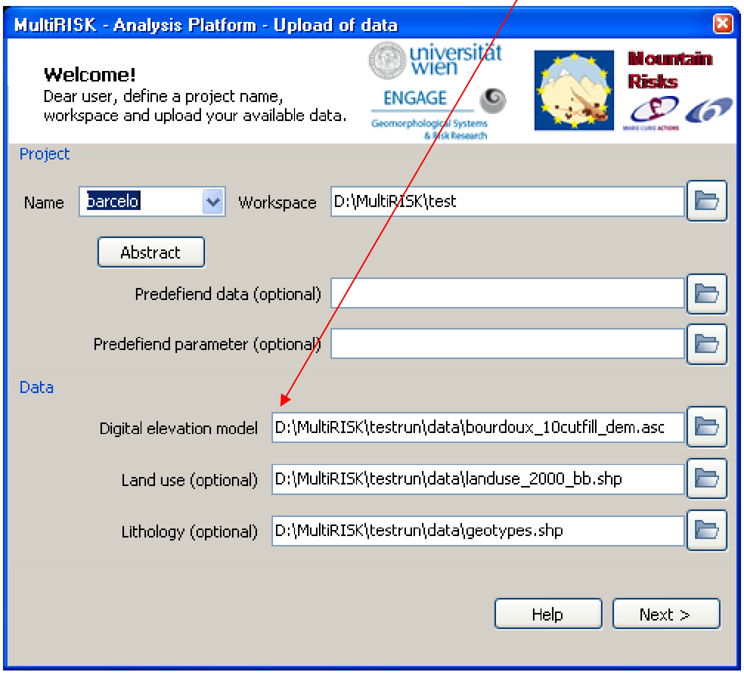
4. Save the file.
5. Double-click the file to run it. Click 'Yes' when prompted to add the information to the registry.

2.2. The Hazard Modeling

In the following the modeling procedure is explained and illustrated with screen-shots. The bold-written terms refer directly to terms in the screenshots.

2.2.1. Project naming and data upload

If you choose a **Digital elevation model** of the raster format “grid” it will not be shown as single file but as folder. Open the folder and choose any of the files inside (e.g. sta.adf, w001001.adf, w001001x.adf, hdr.adf etc.). When clicking “return” the right path and file name will be written in the edit line. This does not apply for e.g. .asc or .img DEMs – they are depicted as single files - browse them in the normal way.



MultiRISK - Analysis Platform - Upload of data

Welcome!
Dear user, define a project name,
workspace and upload your available data.

Project

Name: barcelo
Workspace: D:\MultiRISK\test

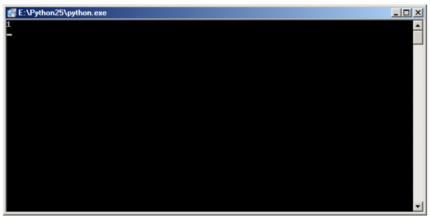
Predefiend data (optional):
Predefiend parameter (optional):

Data

Digital elevation model: D:\MultiRISK\testrun\data\bourdoux_10cutfill_dem.asc
Land use (optional): D:\MultiRISK\testrun\data\landuse_2000_bb.shp
Lithology (optional): D:\MultiRISK\testrun\data\geotypes.shp

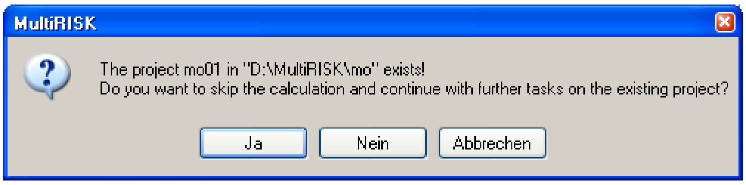
In case you want to start a new **Project** choose a **Workspace** (the folder in which all results will be saved) and enter a **Name** for the **Project** (this name will be given to all output files, complemented by abbreviations indicating the content of the file. For an overview of the abbreviations used to name the output files see section 3.5 **Terminology**.). Then browse and upload the input **Data** (**Digital elevation model**, **Land use** and **Lithology**).

General remark: during the whole computation a DOS window is open - please do not close it because this cancels the modeling procedure. Furthermore, in this window the progress of the modeling procedure is shown and possible errors are specified.



```
1
_
```

In case you want to continue a **Project** you already worked on in a previous session, select the **Workspace** in which you located it before and choose the Name of the project. Automatically the Data paths you chose when you started the project will be filled in below. When continuing with **Next >** you will get the following options:



The project mo01 in "D:\MultiRISK\mo" exists!
Do you want to skip the calculation and continue with further tasks on the existing project?

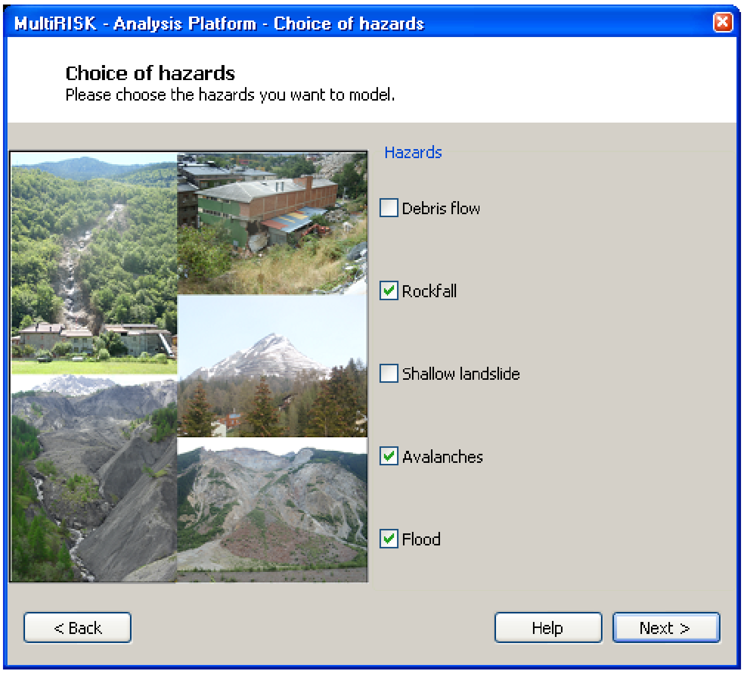
By selecting Yes/Ja you will skip the hazard modeling part and jump directly to the validation, exposure analysis and visualization. By selecting No/Nein, you can complement the hazard modeling by those processes you have not worked on last time or update (overwrite) the previous results. By selecting Cancel/Abbrechen you can choose a new Project Name to avoid overwriting of previous results or make any other type of changes.

By browsing **Predefined data** or **Predefined parameters** (see a more detailed description on these two files below) selections made previously can be uploaded. This means the data or the parameter selection is automatically input into the respective fields - but this does not impede to make changes.
With the button **Abstract** you will get the option to enter background information on the modeling you perform and this text will directly be saved in the metadata of the file (you can access the metadata information with ArcCatalog). This option is very helpful to remind the objective of the model run, reasons for certain parameter choices etc. afterwards. Together with the abstract also the model parameters are saved in the metadata file.

DATA SPECIFICATION:

Name:	Name of the Project you create (e.g. projna) or you upload.
Workspace:	Path of your working directory.
Predefined data:	You can upload the input data (Digital elevation model, Land use, Lithology) from a previously performed project. The predefined data file is automatically produced and located in the Workspace of the project for each run. (eg.:projna_data.xml).
Predefined parameters:	You can upload the parameter specification from a previous modeled project in order to use the same modeling parameters. This file is automatically produced and located in the Workspace of the project for each run. (eg.:projna_parameters.xml).
Digital elevation model:	Any ArcGIS compatible raster format (e.g. asc or grid).
Land use / cover:	Polygon shape file in which one column has to indicate the different land use / cover classes. The name of this column and the classes can be chosen freely by the user.
Lithology	Polygon shape file in which one column has to indicate the different land lithology classes. The name of this column and the classes can be chosen freely by the user.

2.2.2. Choice of hazards to be modeled



MultiRISK - Analysis Platform - Choice of hazards

Choice of hazards

Please choose the hazards you want to model.

Hazards

☐ Debris flow

☑ Rockfall

☐ Shallow landslide

☑ Avalanches

☑ Flood

Select the hazards you want to model - the processes you do not choose will be disabled in the following steps. If you already modeled a hazard within this project the former results will be overwritten. If you model a process you have not worked on before, only this hazard will be computed while the other processes and results are not overwritten or modified. However the .xml files will be overwritten (projna_data.xml and projna_parameters.xml) and especially in the case of the parameters only those chosen for the last modeling run will be available.

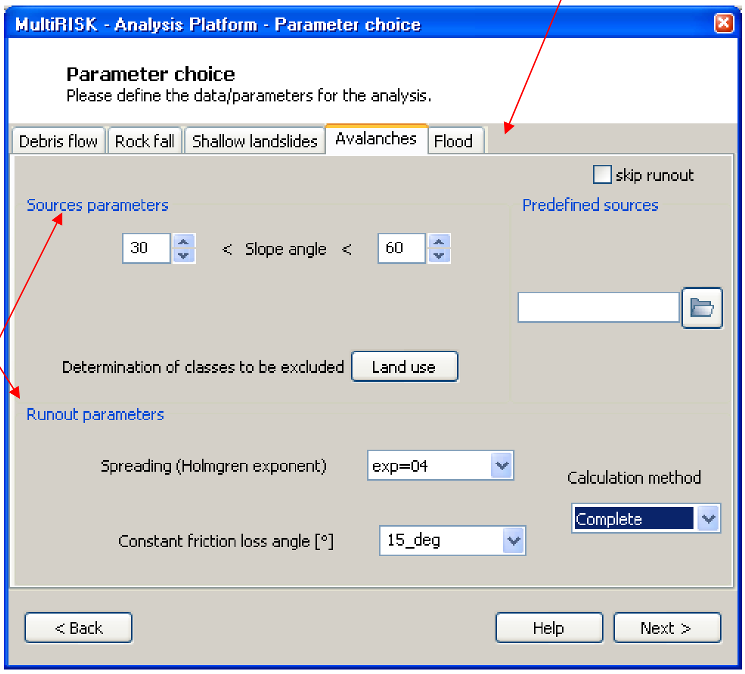
2.2.3. Parameterisation of the models

(For details about the models and parameters please have a look at the previous section)

General options occurring in the parameterization of several hazards:

General options used for several hazard refer to the run out modeling (a) and the exclusion of land use/cover and lithology classes as potential sources (b). After having presented these two procedures the hazard model parameterizations will be explained one by one

For each hazard one tab is available. By clicking on the tab the record card is opened and the parameters can be specified. Those hazards not chosen in the previous step are grey and not modifiable. By going back you can change your hazard choice without loosing the parameter choices you already made.



MultiRISK - Analysis Platform - Parameter choice

Parameter choice

Please define the data/parameters for the analysis.

☐ skip runout

Sources parameters

30 < Slope angle < 60

Runout parameters

Spreading (Holmgren exponent): exp=04

Constant friction loss angle [°]: 15_deg

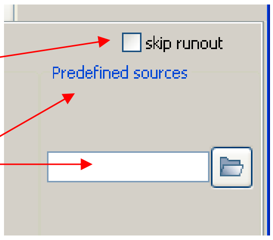
Calculation method: Complete

For the processes debris flows, rock falls, shallow landslides and avalanches the parameter choice is subdivided in two steps: the Source parameters and the Runout parameters.

Since the possible choices for the run out parameters are the same for all four processes, they will only be explained once.

a) Run out modeling of the processes debris flow, rock fall, shallow landslides and avalanches:

As already mentioned, these four processes are modeled in two steps, the source identification and the run out. Three options exist for the performance of these two steps: i) Both steps can be carried out in MultiRISK, ii) **Predefined sources** can be uploaded and their run out is computed or iii) only the sources are identified, the run out is not considered (**skip runout**). Within MultiRISK these options can be chosen as described below:



☐ skip runout

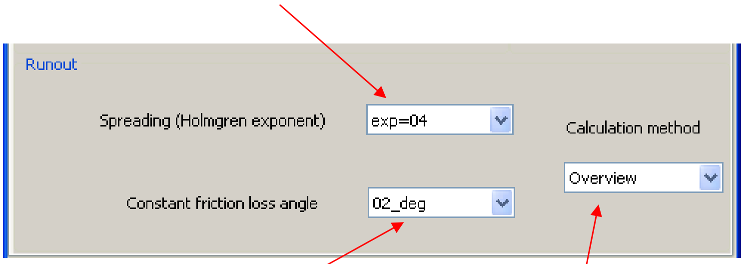
Predefined sources

Only sources are modeled if the run out is skipped

Only the run out is computed if predefined sources are uploaded

Exponent in the formula $f_i = \frac{(\tan\beta_i)^x}{\sum_{j=1}^{8}(\tan\beta_j)^x}$

For $x = 1$ it converts into the basic multiple flow direction after Quinn et al. 1991, i.e. a very wide spreading, and for $x \to \infty$ it turns into a single flow, i.e. no distribution of the flow to all lower-lying cells any more but only to the lowest only (see Equation 2).



Runout

Spreading (Holmgren exponent) exp=04

Constant friction loss angle 02_deg

Calculation method Overview

The mass is transferred from pixel to pixel and for each transition the constant friction loss angle is subtracted from the angle between the two pixels.
(Choose any value between 1 and 45)

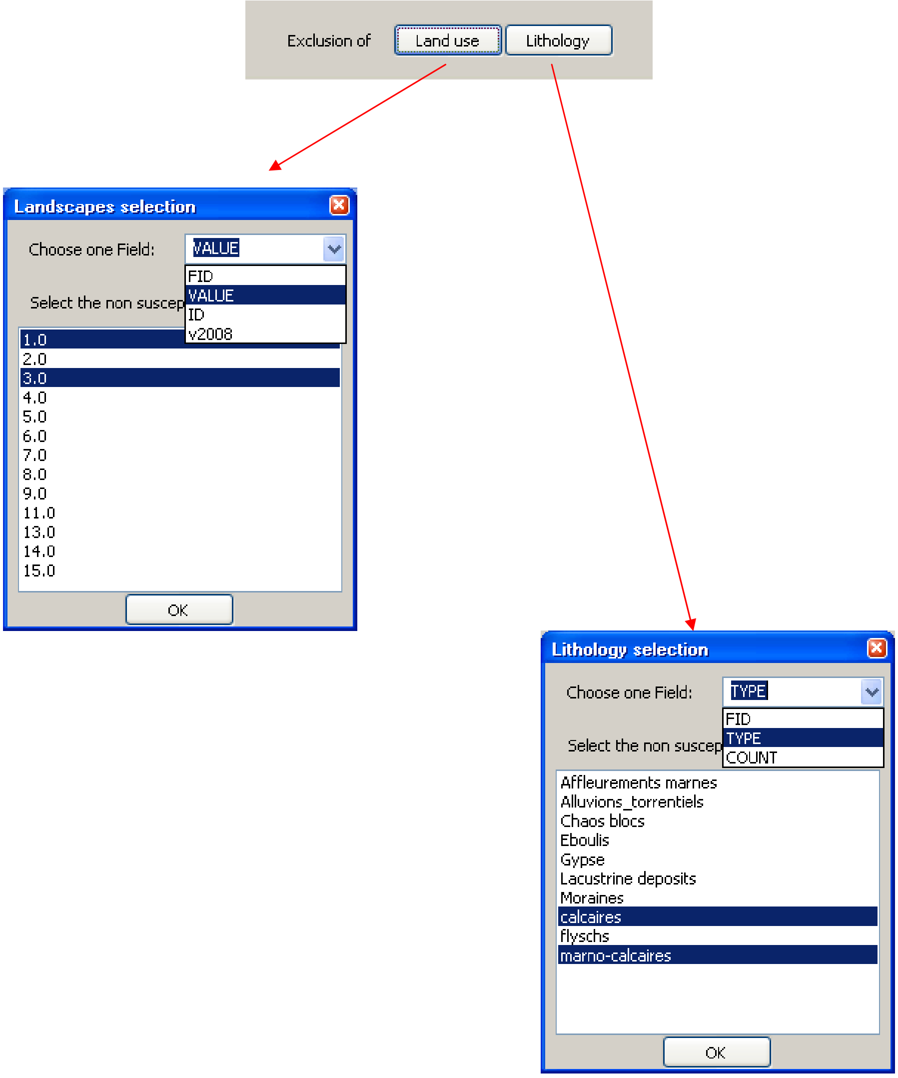
Modeling modi
Overview: only superior sources are modeled. Quick is the better option for a fast overview.
Quick: superior sources are modeled first and if lower once are likely to take a similar way with similar velocity they are not modeled.
Complete: each source pixel is simulated without any condition

DATA SPECIFICATION:

Predefined sources: .asc file with the pixel value 1 for the sources and NoData for the non-source areas. The resolution and alignment of the raster has to fit the characteristics of the recalculated DEM!

b) Exclusion of certain land use/cover and lithology classes

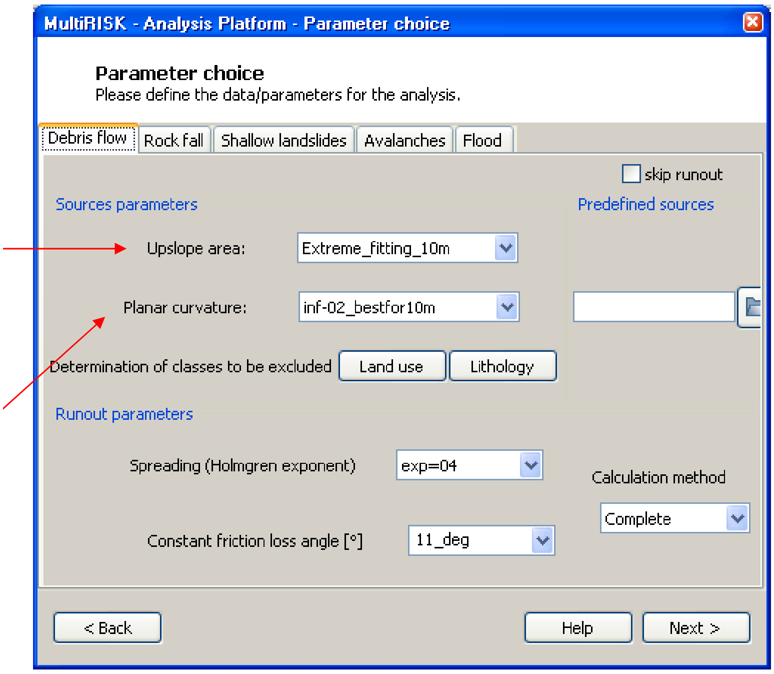
For the source identification of several processes the **Exclusion of** certain land use/cover or lithological classes is offered. Please find here the general description how to use this option:
Click the button **Land use/cover** or **Lithology** to exclude certain classes from being potential sources of instabilities. In the window which opens choose the column containing the **Land use/cover** or **Lithology** class names. Subsequently all classes of this column will be listed. Choose one or more of them to be excluded as possible source (e.g. outcropping limestone as source for debris flows).



Debris flows:

See Figure 2 for an explanation of the possible choices. 10m/ 20m indicates the raster resolution for which the curve shall be used. Currently MultiRISK is designed for a 10m resolution, thus select the _10m options.

Threshold of Planar curvature below which the existence of a gully / concave structure is assumed, e.g. inf-02 equals to -2/100m^{-1} equals to -0.02m^{-1}



MultiRISK - Analysis Platform - Parameter choice

Parameter choice

Please define the data/parameters for the analysis.

☐ skip runout

Upslope area: Extreme_fitting_10m

Planar curvature: inf-02_bestfor10m

Determination of classes to be excluded

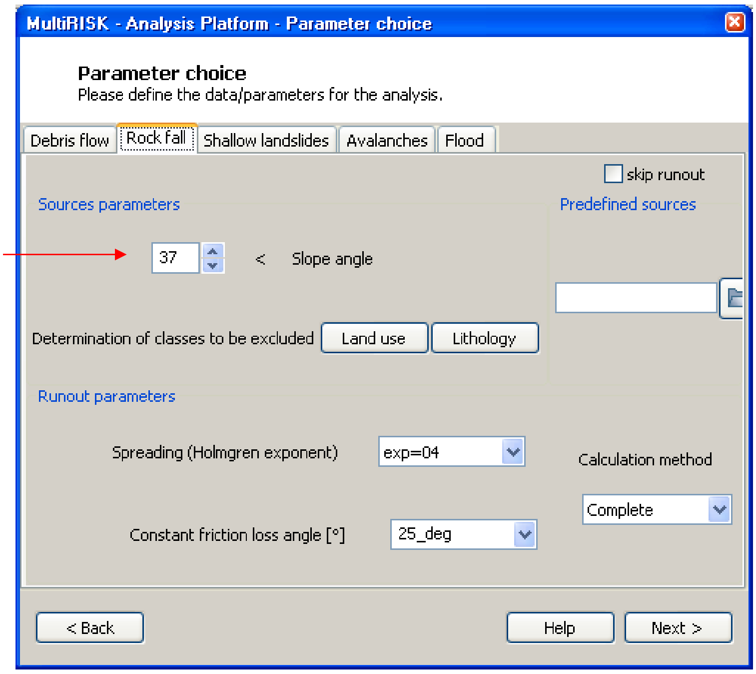
Spreading (Holmgren exponent) exp=04

Constant friction loss angle [°] 11_deg

Calculation method Complete

Rock fall:

Slope angle above which the existence of a rock wall (which is the possible source of rock fall) is assumed.



MultiRISK - Analysis Platform - Parameter choice

Parameter choice
Please define the data/parameters for the analysis.

Sources parameters

37 < Slope angle

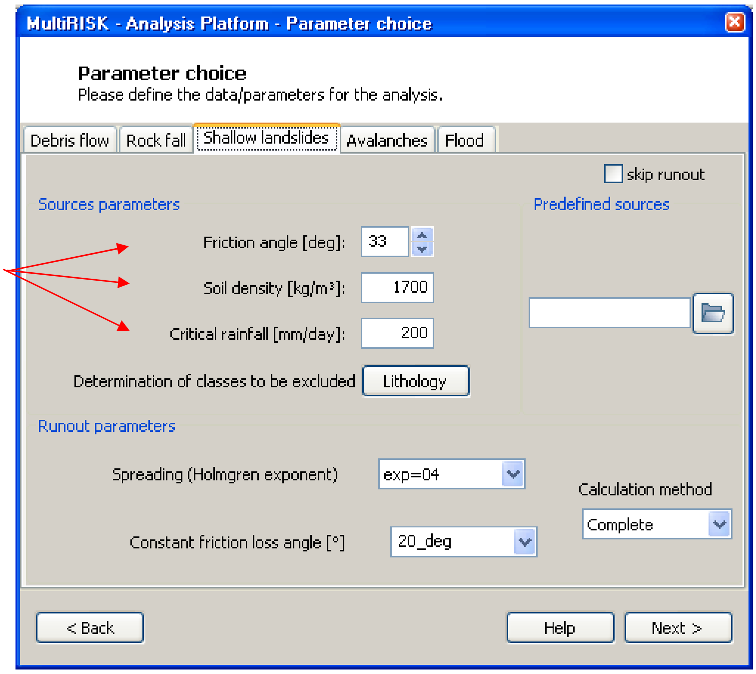
Runout parameters

Spreading (Holmgren exponent): exp=04

Constant friction loss angle [°]: 25_deg

Calculation method: Complete

Shallow landslides:



Parameters according to Equation 1

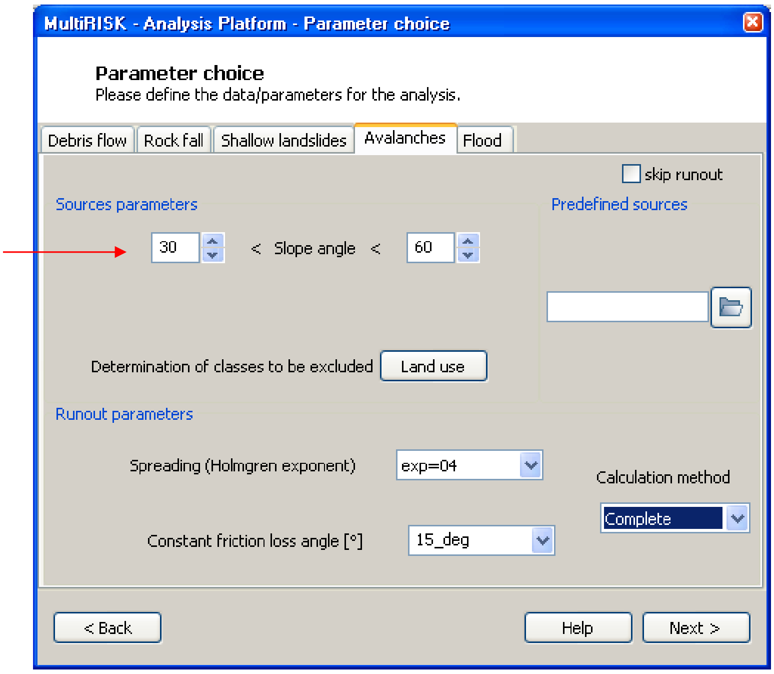
Parameter choice
Please define the data/parameters for the analysis.

☐ skip runout

Friction angle [deg]: 33
Soil density [kg/m³]: 1700
Critical rainfall [mm/day]: 200
Determination of classes to be excluded: Lithology

Spreading (Holmgren exponent): exp=04
Constant friction loss angle [°]: 20_deg
Calculation method: Complete

Snow avalanches:



Between the lower and upper slope angle threshold avalanche initiation is considered possible

MultiRISK - Analysis Platform - Parameter choice

Parameter choice

Please define the data/parameters for the analysis.

Sources parameters

30 < Slope angle < 60

Determination of classes to be excluded: Land use

☐ skip runout

Predefined sources

Runout parameters

Spreading (Holmgren exponent): exp=04

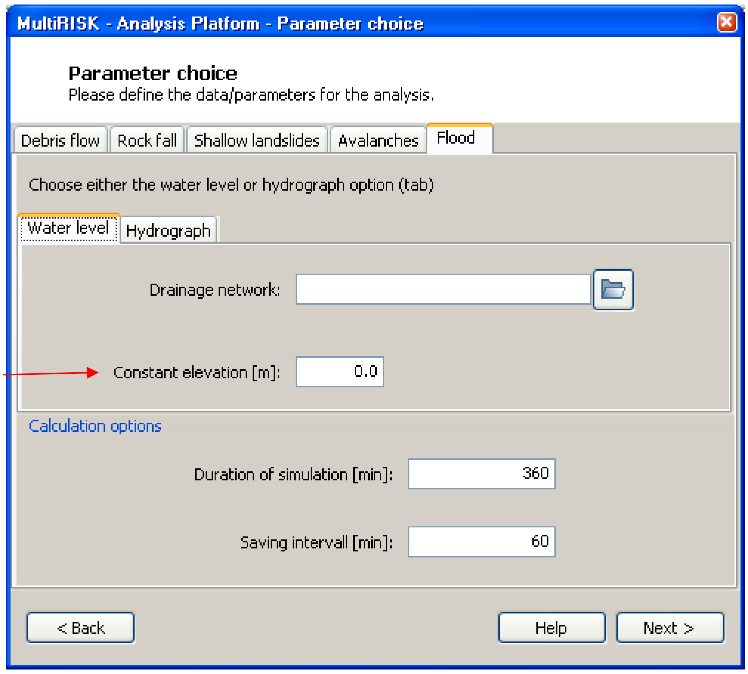
Constant friction loss angle [°]: 15_deg

Calculation method: Complete

River Floods:

For the modeling of river floods, two approaches are available, the definition of a **Water level** and the implementation of **Hydrograph** information.

a) Modeling of a defined **Water level**


MultiRISK - Analysis Platform - Parameter choice

Parameter choice

Please define the data/parameters for the analysis.

Choose either the water level or hydrograph option (tab)

Drainage network:

Constant elevation [m]: 0.0

Calculation options

Duration of simulation [min]: 360

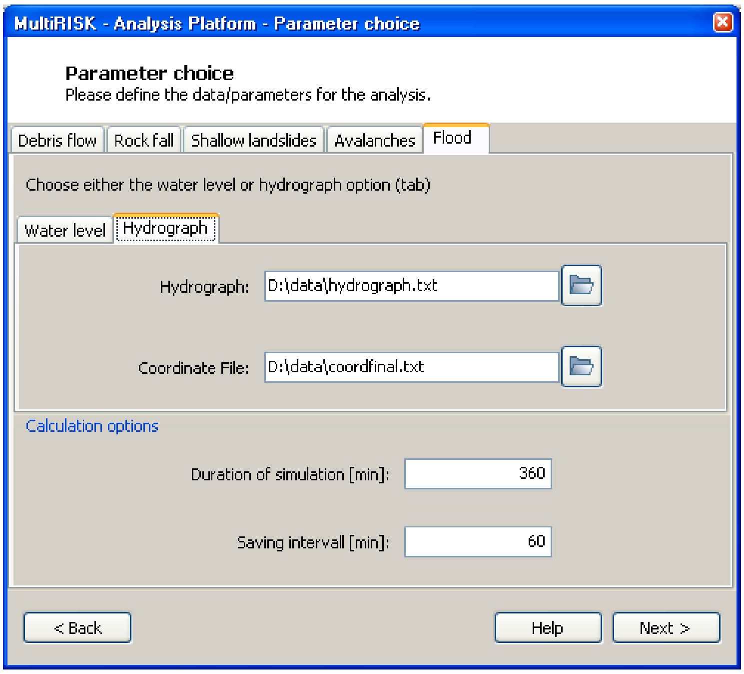
Saving intervall [min]: 60

Height of the water above the altitude of the indicated drainage network which is then extrapolated into the area.

DATA SPECIFICATION:

Drainage network: Raster file of the drainage network (river layer) with the altitudinal information for each pixel with the same pixel size and alignment as the original DEM which was uploaded.

b) Modeling by means of Hydrograph information:



Please define the data/parameters for the analysis.

Choose either the water level or hydrograph option (tab)

Hydrograph: D:\data\hydrograph.txt

Coordinate File: D:\data\coordfinal.txt

Duration of simulation [min]: 360

Saving intervall [min]: 60

The **Duration of simulation** refers to overall time (real time, not modeling time) which is modeled and **saving interval** to the time steps after which an output file is produced. For the case of e.g. 3600min of duration of simulation and a saving interval of 600min a total of 6 files is saved.

DATA SPECIFICATION:

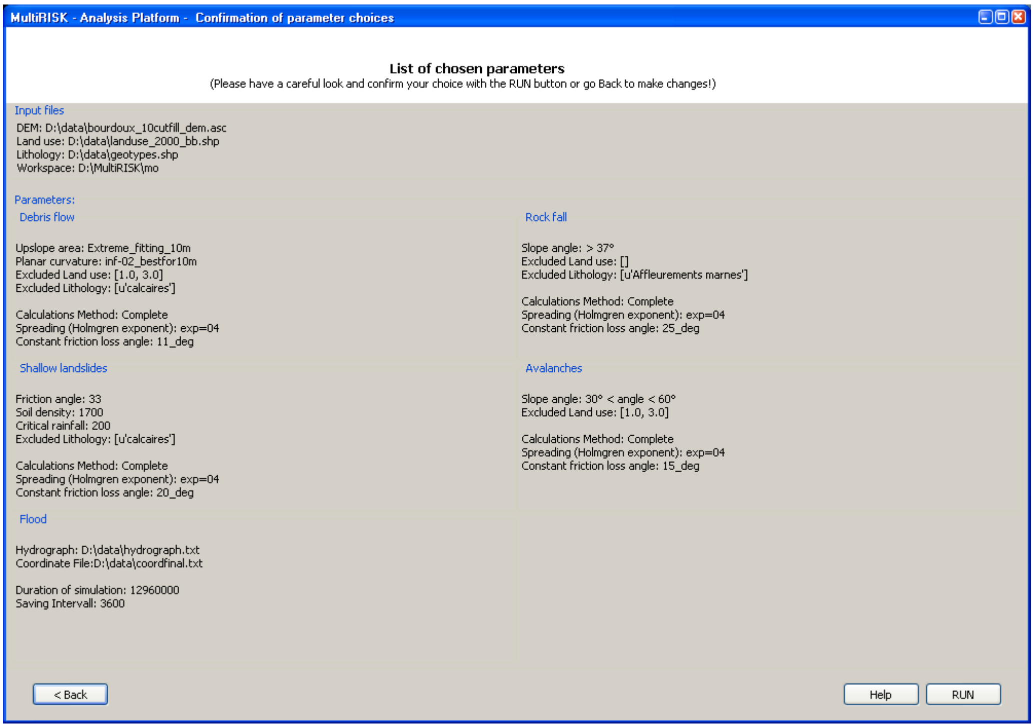
The **Hydrograph** file is a simple .txt file. The first column indicates the time step, the second column the discharge values [m^3/s] of the point with the first set of coordinates, the third column the discharge values of the second point etc. The columns are separated by tabs.

e.g.	0.00	50	5
	05.00	100	10
	10.00	480	15
	15.00	120	10
	20.00	50	5

Coordinate File: The coordinates are entered by means of a .txt file as well. Each line describes one coordinate with its x and y information separated by space-slash-space and complemented by the following sequence: / -1 / 0 / 0

e.g. 941024.5 / 244220.8 / -1 / 0 / 0
941060.3 / 244230.1 / -1 / 0 / 0

2.2.4. Confirmation of the parameter choice


MultiRISK - Analysis Platform - Confirmation of parameter choices

List of chosen parameters
(Please have a careful look and confirm your choice with the RUN button or go Back to make changes!)

Input files
DEM: D:\data\bourdoux_10cutfill_dem.asc
Land use: D:\data\landuse_2000_bb.shp
Lithology: D:\data\geotypes.shp
Workspace: D:\MultiRISK\mo

Parameters:

Debris flow

Upslope area: Extreme_fitting_10m
Planar curvature: inf-02_bestfor10m
Excluded Land use: [1.0, 3.0]
Excluded Lithology: [u'calcaires']

Calculations Method: Complete
Spreading (Holmgren exponent): exp=04
Constant friction loss angle: 11_deg

Shallow landslides

Friction angle: 33
Soil density: 1700
Critical rainfall: 200
Excluded Lithology: [u'calcaires']

Calculations Method: Complete
Spreading (Holmgren exponent): exp=04
Constant friction loss angle: 20_deg

Flood

Hydrograph: D:\data\hydrograph.txt
Coordinate File:D:\data\coordfinal.txt

Duration of simulation: 12960000
Saving Intervall: 3600

Rock fall

Slope angle: > 37°
Excluded Land use: []
Excluded Lithology: [u'Affleurements marnes']

Calculations Method: Complete
Spreading (Holmgren exponent): exp=04
Constant friction loss angle: 25_deg

Avalanches

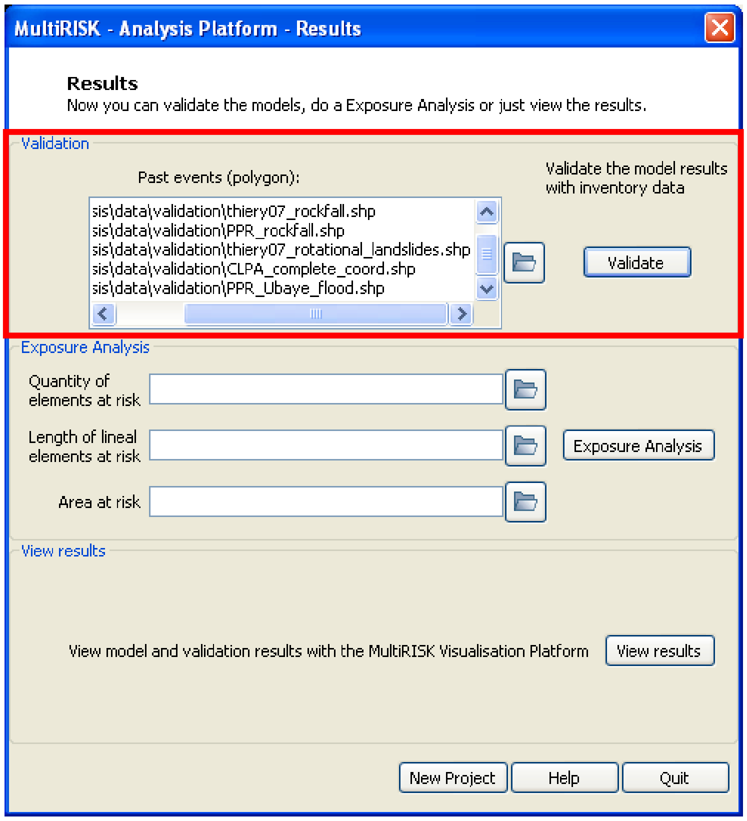
Slope angle: 30° < angle < 60°
Excluded Land use: [1.0, 3.0]

Calculations Method: Complete
Spreading (Holmgren exponent): exp=04
Constant friction loss angle: 15_deg

The parameters chosen previously are resumed. If errors are discovered or generally changes have to be made go back with the button < Back, the parameter choice will not be erased by this step. With RUN you start the modeling which can, according to the size of the study area, the quantity of sources identified for which subsequently the run out is computed or the time period the flood modeling is computed, take several days. However, you will see the advances of the modeling in the DOS window and the results are one after the other saved in the workspace folder.

2.3. Hazard model validation

The validation is done by an overlay of the modeling results with recorded events (alternatively field assessments of possibly unstable areas etc.). It is carried out within the following interface in which you upload the information on past/potentially threatened areas:



Results

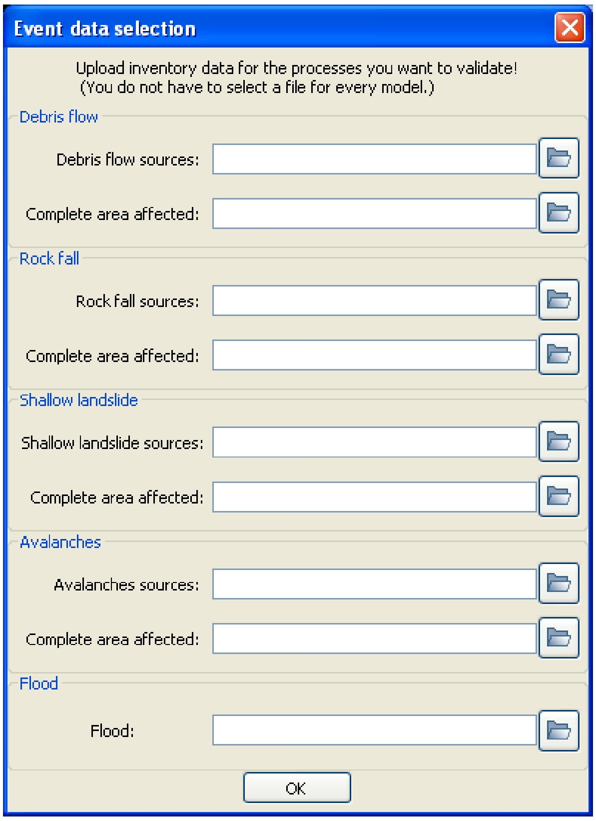
Now you can validate the models, do a Exposure Analysis or just view the results.

sis\data\validation\thiery07_rockfall.shp
sis\data\validation\PPR_rockfall.shp
sis\data\validation\thiery07_rotational_landslides.shp
sis\data\validation\CLPA_complete_coord.shp
sis\data\validation\PPR_Ubaye_flood.shp

View model and validation results with the MultiRISK Visualisation Platform

Browse and upload the event information (click on 🗁, see the explanation for the data upload below) and start the validation by clicking the button Validate after the uploading is finished.

When clicking 📂 the following window opens:



Event data selection

Upload inventory data for the processes you want to validate!
(You do not have to select a file for every model.)

Debris flow

Debris flow sources:

Complete area affected:

Rock fall

Rock fall sources:

Complete area affected:

Shallow landslide

Shallow landslide sources:

Complete area affected:

Avalanches

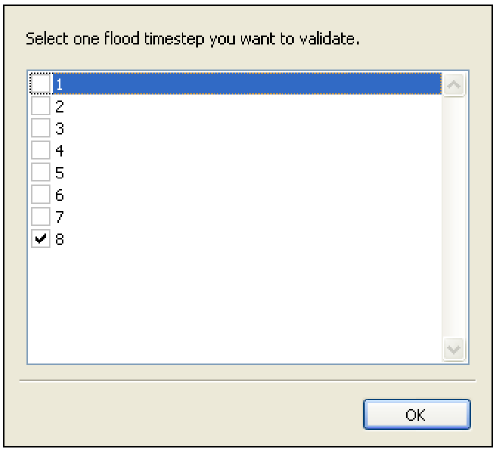
Avalanches sources:

Complete area affected:

Flood

Flood:

For the validation two options are offered: validation of the Sources (especially useful option if the validation is done on basis of expert assessment of possibly unstable areas in the field) and validation of the Complete area (sources and run out - especially useful for recorded events where source and run out cannot be distinguished anymore as e.g. the case for shallow landslides). However you can only upload files for hazards you modeled previously - in this interface the processes which were not computed are grey shaded, i.e. inactive.



Select one flood timestep you want to validate.

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ 7
☑ 8

If you modeled several flood time steps, you will get the choice which one you want to use for the validation.

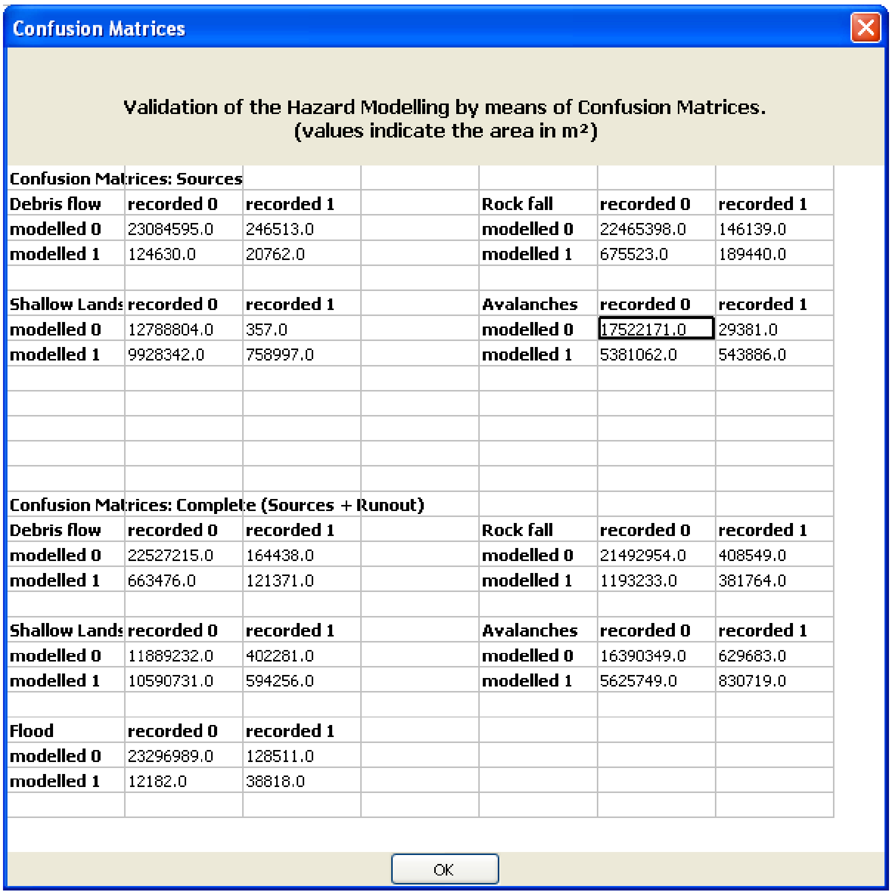
After pressing the OK button the previous interface reappears and by clicking on **Validate** the validation is initiated.

DATA SPECIFICATION:

Inventory data: Upload polygon shape files of either recorded events or expert assessment in the field, on basis of aerial photos or the like.

The confusion matrix - result of the validation:

The result of the validation is (additionally to the shape files of the overlay) a confusion matrix opposing the number of modeled and the recorded pixels. After the validation finished, the interface displayed below is automatically shown.



Validation of the Hazard Modelling by means of Confusion Matrices.
(values indicate the area in m²)

Confusion Matrices: Sources						
Debris flow	**recorded 0**	**recorded 1**		**Rock fall**	**recorded 0**	**recorded 1**
modelled 0	23084595.0	246513.0		**modelled 0**	22465398.0	146139.0
modelled 1	124630.0	20762.0		**modelled 1**	675523.0	189440.0
Shallow Lands	**recorded 0**	**recorded 1**		**Avalanches**	**recorded 0**	**recorded 1**
modelled 0	12788804.0	357.0		**modelled 0**	17522171.0	29381.0
modelled 1	9928342.0	758997.0		**modelled 1**	5381062.0	543886.0
Confusion Matrices: Complete (Sources + Runout)						
Debris flow	**recorded 0**	**recorded 1**		**Rock fall**	**recorded 0**	**recorded 1**
modelled 0	22527215.0	164438.0		**modelled 0**	21492954.0	408549.0
modelled 1	663476.0	121371.0		**modelled 1**	1193233.0	381764.0
Shallow Lands	**recorded 0**	**recorded 1**		**Avalanches**	**recorded 0**	**recorded 1**
modelled 0	11889232.0	402281.0		**modelled 0**	16390349.0	629683.0
modelled 1	10590731.0	594256.0		**modelled 1**	5625749.0	830719.0
Flood	**recorded 0**	**recorded 1**				
modelled 0	23296989.0	128511.0				
modelled 1	12182.0	38818.0				

In the resulting shape file the classes are termed in the following way (called confusion_matrix.txt and located in the workspace folder):

	Modeled	Not Modeled
Event	1	-1
No Event	2	0

2.4. Multi-hazard exposure analysis

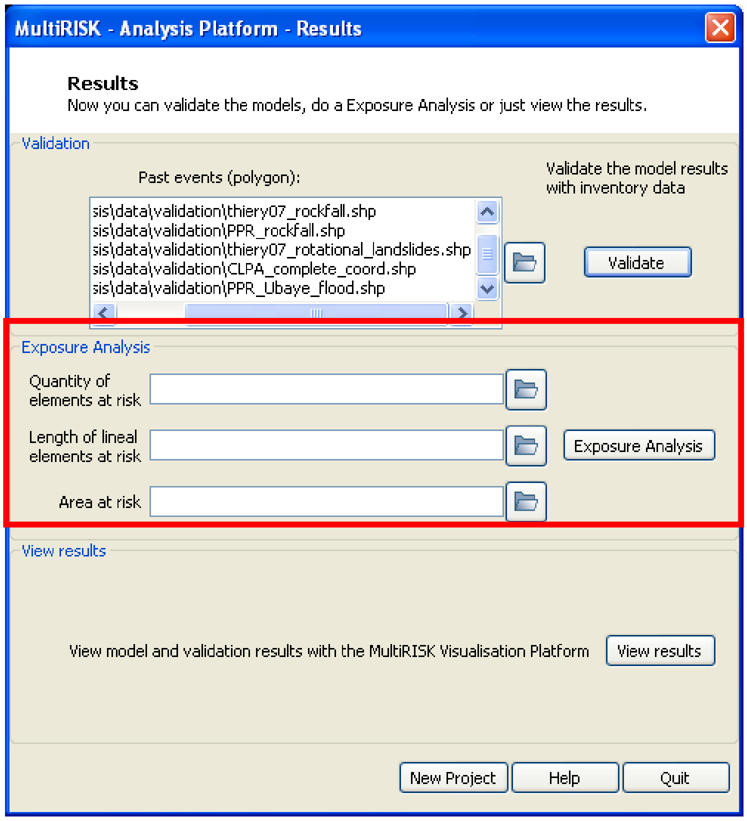
Please browse first the risk elements and start then the analysis by pushing **Exposure analysis**.

Three formats of elements at risk can be uploaded:

Quantity of elements at risk: Points, lines or polygons can be entered and are identified as exposed/affected if they lie at least partly inside the hazard zones - i.e. they are treated as units.

Length of lineal elements at risk: Linear features can be uploaded (e.g. roads, railway lines etc.) and the length lying inside of hazard zones is identified.

Area at risk: Polygons can be uploaded (e.g. settled area if information at single building level is not available) and the percentage of the area/the area [m^2] lying in hazard zones is computed



Results

Now you can validate the models, do a Exposure Analysis or just view the results.

Validate the model results with inventory data

```
sis\data\validation\thiery07_rockfall.shp
sis\data\validation\PPR_rockfall.shp
sis\data\validation\thiery07_rotational_landslides.shp
sis\data\validation\CLPA_complete_coord.shp
sis\data\validation\PPR_Ubaye_flood.shp
```

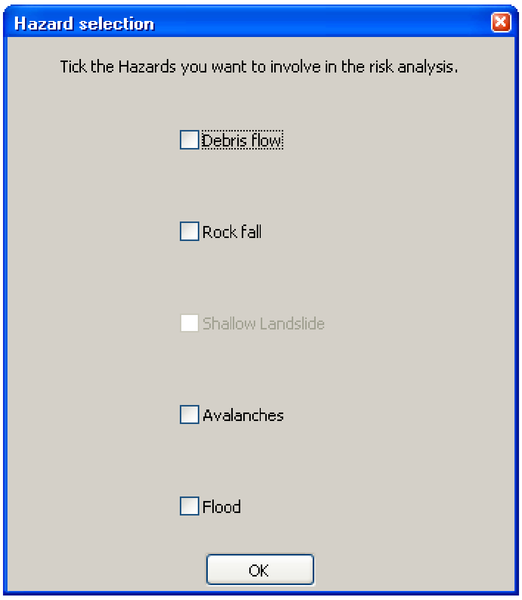
View model and validation results with the MultiRISK Visualisation Platform

At the current state, only an exposure, not a full risk analysis can be carried out since the vulnerability is assumed to be 1 and values of the elements are not directly considered.

DATA SPECIFICATION:

Quantity of elements at risk:	Point, line or polygon shape files
Length of lineal elements at risk:	Polyline shape files
Area at risk:	Polygon shape files

After having uploaded the elements and when clicking **Exposure Analysis** those hazards which have been modeled before can be chosen for the analysis. Those which have not been computed before are shaded grey and inactivated.



Tick the Hazards you want to involve in the risk analysis.

☐ Debris flow

☐ Rock fall

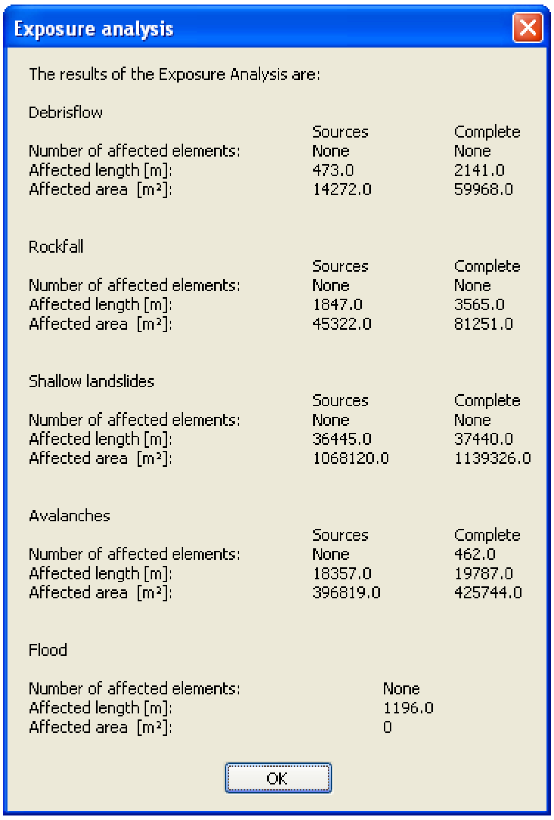
☐ Shallow Landslide

☐ Avalanches

☐ Flood

For the hazards you select the risks will be analyzed for the sources and the complete area.

The result is the following interface:



```
The results of the Exposure Analysis are:

Debrisflow
                                  Sources          Complete
Number of affected elements:      None             None
Affected length [m]:              473.0            2141.0
Affected area  [m²]:              14272.0          59968.0


Rockfall
                                  Sources          Complete
Number of affected elements:      None             None
Affected length [m]:              1847.0           3565.0
Affected area  [m²]:              45322.0          81251.0


Shallow landslides
                                  Sources          Complete
Number of affected elements:      None             None
Affected length [m]:              36445.0          37440.0
Affected area  [m²]:              1068120.0        1139326.0


Avalanches
                                  Sources          Complete
Number of affected elements:      None             462.0
Affected length [m]:              18357.0          19787.0
Affected area  [m²]:              396819.0         425744.0


Flood

Number of affected elements:              None
Affected length [m]:                      1196.0
Affected area  [m²]:                      0
```

This information is saved in a file called exposure_matrix.txt in the workspace.

2.5. Terminology of the output files

The files produced during the whole modeling procedure are saved in the folder which has been defined as **Workspace** in the first interface. The **Project Name** (max. 7 letters) forms the first part of each file. This name is complemented by the following abbreviations to clearly label each of the files and to avoid confusion and effort of the user when searching for / defining names.

FILE NAMING:

Hazard modeling

Rock falls	_rf	
Shallow landslides	_sl	
Avalanches	_av	
Debris flows	_df	
Floods	_fl or _f	
Sources	_s	
Run out	_r	
Complete (sources + run out)	_c	
Reclassified run out	_rc	(only used for the visualization)
Number of overlapping hazards	_nr	
Multi-hazard	_mh	
Past events	_pe	

Validation

Validation sources	_vl_s
Validation complete	_vl_c

Risk analysis

Risk (number of units)	_ru	
Risk (length)	_rl	
Risk (area)	_ra	
Elements (units)	_eu	
	_el	(the file el only produced for the visualization)
	_ea	

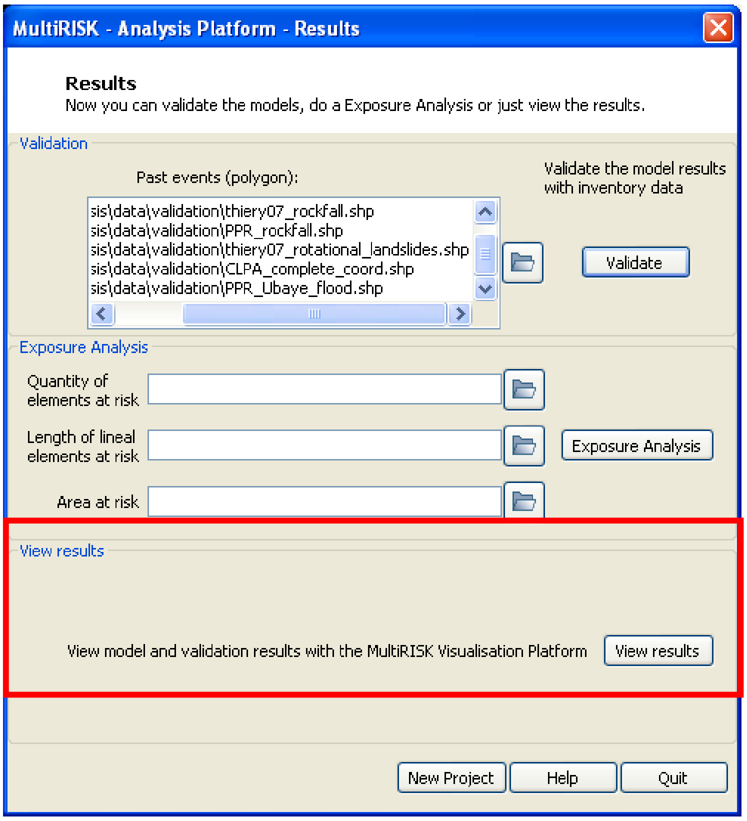
E.g. the results of full debris flow modeling, validation and exposure analysis for a project called "Barcelo" could be:

Barcelo_df_s	Modeled debris flow sources (raster file)
Barcelo_df_r	Modeled debris flow runout (raster file)
Barcelo_df_vl_s	Validation of modeled debris flow sources (shape file)
Barcelo_df_vl_c	Validation of the complete area affected by debris flows (shape file)
Barcelo_df_ru	Elements (units as e.g. buildings) which are according to the modeling results exposed to debris flows are marked
Barcelo_mh	Shape file containing the information of the distribution of all hazards
Barcelo_nr	Raster file with the information of the number of overlapping hazards

etc.

2.6. Connection to the MultiRISK Visualization Tool

The MultiRISK Modeling Tool is directly linked to the MultiRISK Visualization Tool:



MultiRISK - Analysis Platform - Results

Results

Now you can validate the models, do a Exposure Analysis or just view the results.

Past events (polygon):

sis\data\validation\thiery07_rockfall.shp
sis\data\validation\PPR_rockfall.shp
sis\data\validation\thiery07_rotational_landslides.shp
sis\data\validation\CLPA_complete_coord.shp
sis\data\validation\PPR_Ubaye_flood.shp

Validate the model results with inventory data

View model and validation results with the MultiRISK Visualisation Platform

By pushing the **View results** button:

- all produced results are copied in the folder C:\MutliRISK\rev_vis
- the MultiRisk Visualization Tool is updated
- After launching the internet browser and navigating to the MultiRisk Visualization Tool (http://localhost/cartoweb3/htdocs/MHRA.php) the just produced output of the MultiRISK Modeling Tool can be explored.

IMPORTANT: PLEASE CLOSE YOUR WEB-BROWSER BEFORE CLICKING VIEW RESULTS AND LAUNCHE IT ONLY AFTER THE SCRIPT RAN COMPLETELY THROUGH!!!

(This does only apply if you already installed the Visualization Tool - see the instructions below)

3. The implementation: MultiRISK - the Visualization Tool

3.1. Installation (read-me file)

- Installation of MapServer 4 Windows (MS4W 2.2.9.) with the default setting. Download at: http://dl.maptools.org/dl/ms4w/ms4w-2.2.9-setup.exe

  Although there are more recent versions available, this one is the currently last stable one in combination with CartoWeb. For all versions and manually access to MapServer versions look at: http://dl.maptools.org/dl/ms4w/

- Open your browser and browse localhost to check if the MapServer 4 Windows has been installed properly. If information on MS4W appears the installation has been successful.

- Installation of CartoWeb3 as well as the Third Party's Gettext (you are asked during the CartoWeb installation if you want to install Third Party's Gettext and after CatroWeb is installed the second installation will be launched automatically if you selected it before).

- Open your browser and browse "localhost" - now one application (CartoWeb) is installed (Check at the bottom of the page, in "Applications" paragraph).

- Copy the folder MHRA into the folder C:\ms4w\apps\cartoweb3\projects\

- Go to C\ms4w\apps\cartoweb3\htdocs, copy the file democw3.php and paste it in the same folder.

  Rename the copied file into "MHRA.php", open it and change "democw3.php" into "MHRA.php".

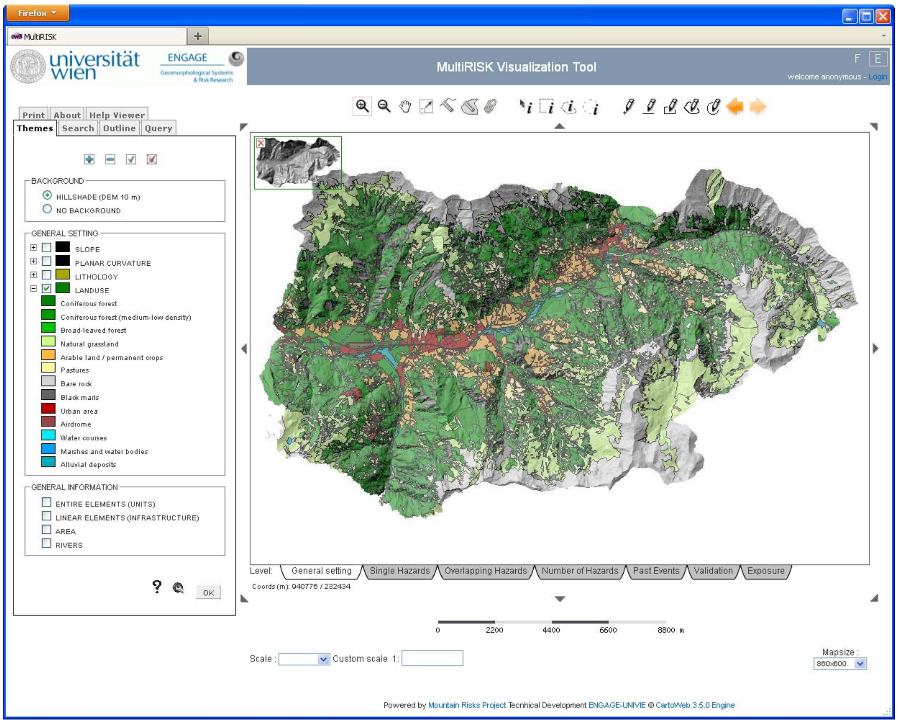
  "Publish" the data in the folder - This is done by lunching MHRA_WEB.py

- Enter the Visualization Tool with your browser under http://localhost/cartoweb3/htdocs/MHRA.php

3.2. The Visualization

The visualization (to be entered with your internet browser under http://localhost/cartoweb3/htdocs/MHRA.php) consists in total of seven tabs and maps, respectively, which show different contents to transmit the multi-dimensional information step by step.

3.2.1. General setting


BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

GENERAL SETTING
☐ SLOPE
☐ PLANAR CURVATURE
☐ LITHOLOGY
☑ LANDUSE

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☐ RIVERS

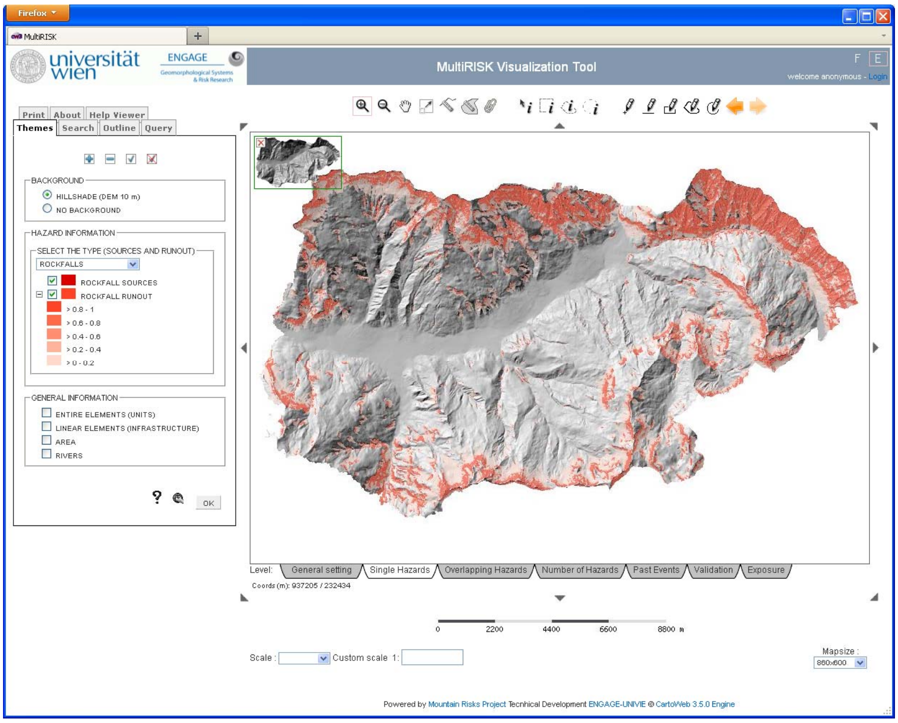
Level: General setting

Coords (m): 940776 / 232434

Mapsize : 860x600

This first map is dedicated to give general information about the area under consideration. For now, slope, planar curvature, lithology and land use/cover information is shown since they are the basis for the modeling procedure. Further information as orthophotos from different periods or the like could be integrated in the future and according to the needs of the user.

3.2.2. Single hazards



BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

HAZARD INFORMATION
SELECT THE TYPE (SOURCES AND RUNOUT): ROCKFALLS
☑ 🟥 ROCKFALL SOURCES
☑ 🟥 ROCKFALL RUNOUT

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☐ RIVERS

Level: Single Hazards

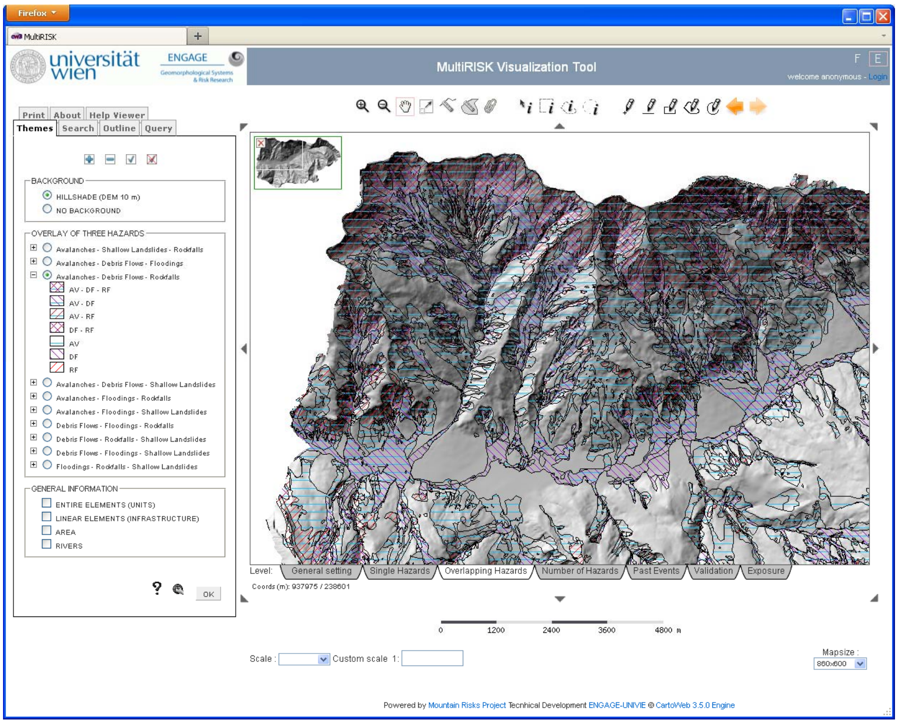
Coords (m): 937205 / 232434

Mapsize : 860x600

Powered by Mountain Risks Project Tecnhical Development ENGAGE-UNIVIE © CartoWeb 3.5.0 Engine

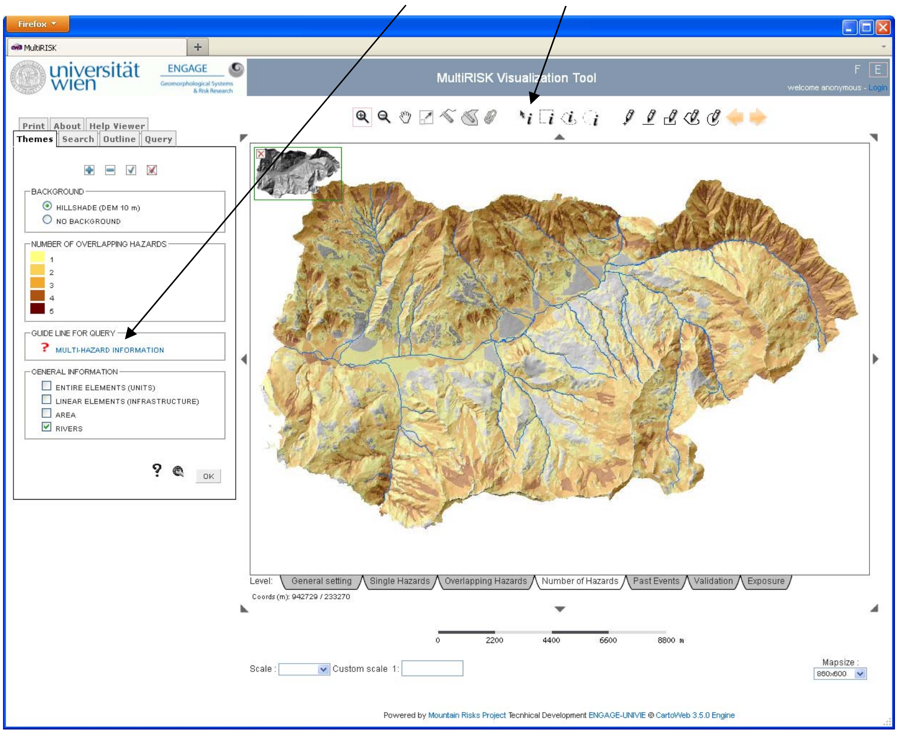
In this map the details on each process are given. To not overload the map only one hazard can be visualized at a time, subdivided into source and run out area for the three landslide types and the avalanches. This map shall enable the user to identify single-hazard patterns without getting confused by e.g. overlapping of hazards.

3.2.3. Overlapping hazards



In the third tab, the focus lies on the areas where two or three hazards overlap. To not confuse the map reader, no details are given on the single hazards, but the footprint of the hazards are overlain to reveal the areas of overlapping hazards. The overlay is restricted to three processes since already for four hazards the distinction of the different combinations would get very difficult.

3.2.4. Number of hazards



BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

NUMBER OF OVERLAPPING HAZARDS
1
2
3
4
5

GUIDE LINE FOR QUERY
? MULTI-HAZARD INFORMATION

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☑ RIVERS

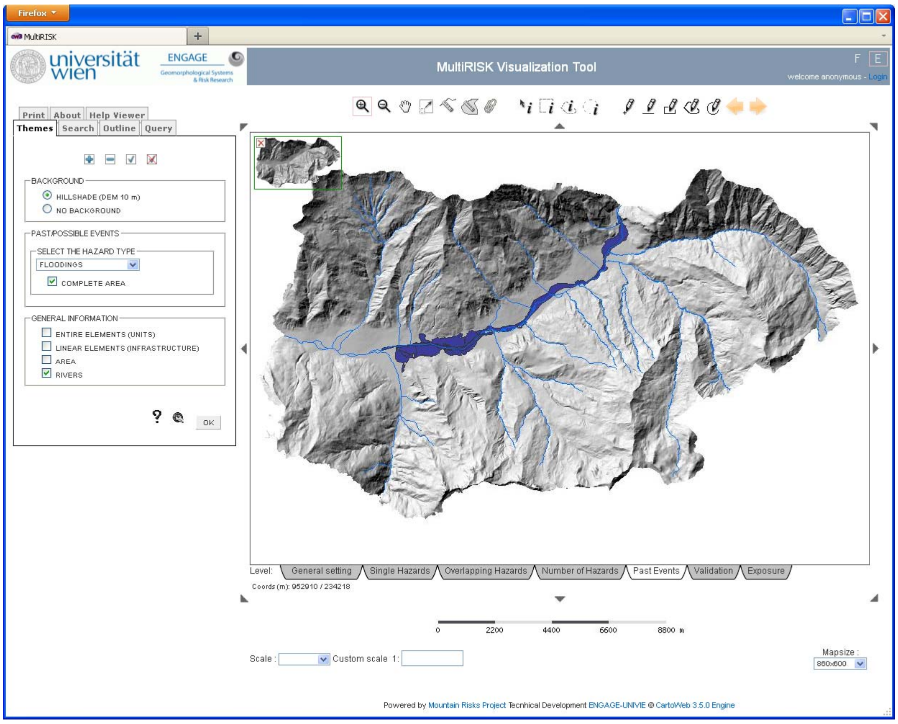
Coords (m): 942729 / 233270

Mapsize: 860x600

Spatial query to identify which processes contribute to the number of hazards.
Further information is available when clicking on the hyperlink

Since more than three processes can hardly be visualized at a time without overloading the map, by visualizing the simple presence of hazards and summing them up those areas affected by only one, two, three, four or event five hazards are depicted. However, to offer the possibility to identify which processes sum up to this number the user can use the spatial query button ↖i and get the information which hazards overlap at a certain point by clicking on the point of interest.

3.2.5. Past events



BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

PAST/POSSIBLE EVENTS
SELECT THE HAZARD TYPE: FLOODINGS
☑ COMPLETE AREA

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☑ RIVERS

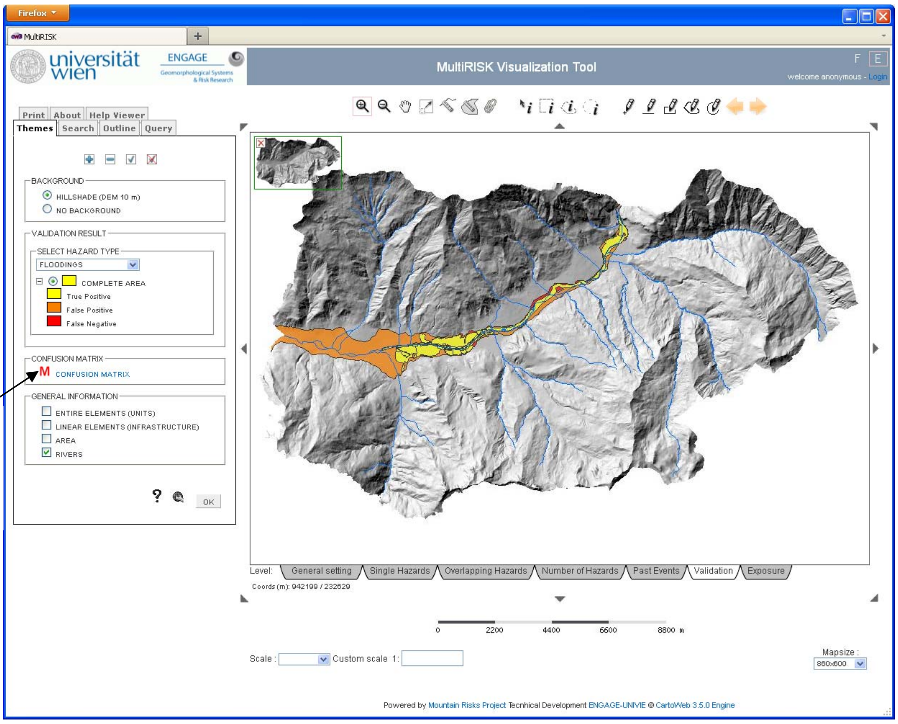
Coords (m): 952910 / 234218

Scale : Custom scale 1:

Mapsize : 860x600

The past events are the basis for the validation step and are thus shown before the result of the validation is depicted in the next tab. If the user uploaded potentially hazardous zones (e.g. potential sources for shallow landslides) those areas are shown.

3.2.6. Validation



BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

VALIDATION RESULT
SELECT HAZARD TYPE: FLOODINGS
● 🟨 COMPLETE AREA
🟨 True Positive
🟧 False Positive
🟥 False Negative

CONFUSION MATRIX
M CONFUSION MATRIX

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☑ RIVERS

Coords (m): 942199 / 232629

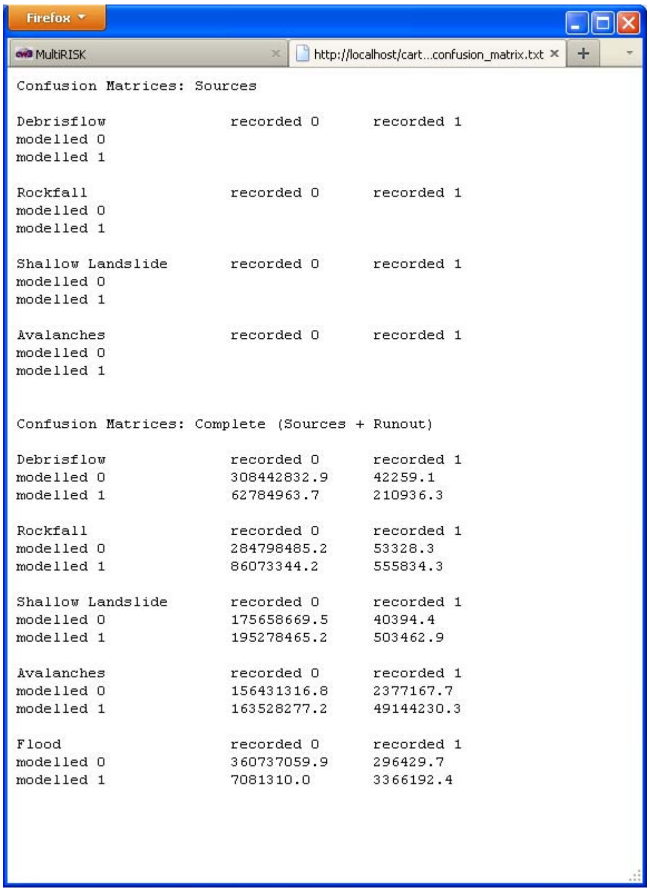
Mapsize : 860x600

Hyperlink to the confusion matrix

In this tab the result of the validation by means of overlaying modeled and recorded/potential events resulting in a confusion matrix is given. The "True Negatives" are not visualized since normally no records of "no Event" exist and the simple fact that no event has been recorded does not mean that no event has happened till now or will happen in the future.

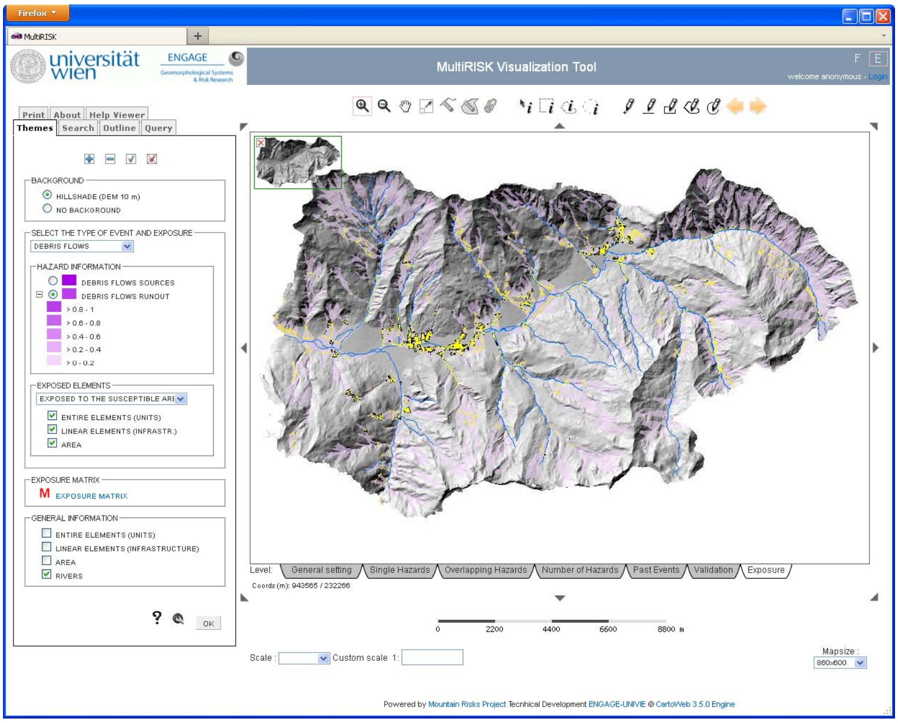
	Modeled	Not Modeled
Event	True Positives	False Negatives
No Event	False Positives	True Negatives

By clicking on the red M – Confusion matrix (hyperlink) another tab opens which contains the information on the confusion matrices, e.g. the surface in m³ which is falls in each of the classes.



```
Confusion Matrices: Sources

Debrisflow              recorded 0      recorded 1
modelled 0
modelled 1

Rockfall                recorded 0      recorded 1
modelled 0
modelled 1

Shallow Landslide       recorded 0      recorded 1
modelled 0
modelled 1

Avalanches              recorded 0      recorded 1
modelled 0
modelled 1


Confusion Matrices: Complete (Sources + Runout)

Debrisflow              recorded 0      recorded 1
modelled 0              308442832.9     42259.1
modelled 1              62784963.7      210936.3

Rockfall                recorded 0      recorded 1
modelled 0              284798485.2     53328.3
modelled 1              86073344.2      555834.3

Shallow Landslide       recorded 0      recorded 1
modelled 0              175658669.5     40394.4
modelled 1              195278465.2     503462.9

Avalanches              recorded 0      recorded 1
modelled 0              156431316.8     2377167.7
modelled 1              163528277.2     49144230.3

Flood                   recorded 0      recorded 1
modelled 0              360737059.9     296429.7
modelled 1              7081310.0       3366192.4
```

3.2.7. Exposure



BACKGROUND
● HILLSHADE (DEM 10 m)
○ NO BACKGROUND

SELECT THE TYPE OF EVENT AND EXPOSURE
DEBRIS FLOWS

HAZARD INFORMATION
○ DEBRIS FLOWS SOURCES
● DEBRIS FLOWS RUNOUT
> 0.8 - 1
> 0.6 - 0.8
> 0.4 - 0.6
> 0.2 - 0.4
> 0 - 0.2

EXPOSED ELEMENTS
EXPOSED TO THE SUSCEPTIBLE ARE
☑ ENTIRE ELEMENTS (UNITS)
☑ LINEAR ELEMENTS (INFRASTR.)
☑ AREA

EXPOSURE MATRIX
M EXPOSURE MATRIX

GENERAL INFORMATION
☐ ENTIRE ELEMENTS (UNITS)
☐ LINEAR ELEMENTS (INFRASTRUCTURE)
☐ AREA
☑ RIVERS

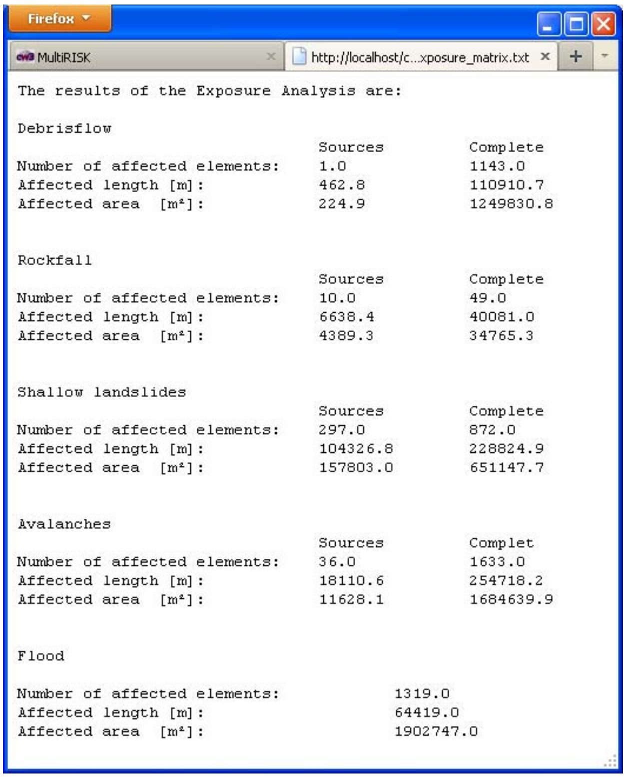
Coords (m): 943565 / 232266

Scale :
Custom scale 1:
Mapsize : 860x600

Finally the exposed elements are depicted in yellow:

1. entire units (points, lines or polygons treated as units),
2. linear elements of which the segment actually threatened is identified and
3. polygons of which the area possibly affected is determined.

By clicking on the red M – **Exposure matrix** (hyperlink) another tab opens which contains the information on the number of exposed elements, the length of exposed infrastructure and the area exposed.



```
The results of the Exposure Analysis are:

Debrisflow
                                Sources         Complete
Number of affected elements:    1.0             1143.0
Affected length [m]:            462.8           110910.7
Affected area  [m²]:            224.9           1249830.8


Rockfall
                                Sources         Complete
Number of affected elements:    10.0            49.0
Affected length [m]:            6638.4          40081.0
Affected area  [m²]:            4389.3          34765.3


Shallow landslides
                                Sources         Complete
Number of affected elements:    297.0           872.0
Affected length [m]:            104326.8        228824.9
Affected area  [m²]:            157803.0        651147.7


Avalanches
                                Sources         Complet
Number of affected elements:    36.0            1633.0
Affected length [m]:            18110.6         254718.2
Affected area  [m²]:            11628.1         1684639.9


Flood

Number of affected elements:            1319.0
Affected length [m]:                    64419.0
Affected area  [m²]:                    1902747.0
```

Conclusions and Outlook

The platform consists of two tools, the Modeling and the Visualization Tool which offer together standardized, fast and repeatable modeling and the clear visualization of the results. Until now the MultiRISK Modeling Tool offers only the performance of a regional susceptibility and exposure analysis. Several further developments are planned for the future:

- An expansion of MultiRISK towards a local, full-hazard and risk analysis including a more sophisticated vulnerability concept.
- Complementation of the current set of hazards by further processes as e.g. flash floods, storms and others.
- The automated consideration of hazard interactions. This would for example include feedback loops (e.g. the destruction of forest by avalanches and the loss of the protective effect towards rock fall and further avalanches) or the triggering of one hazard by another (e.g. river or torrent damming due to landslides) etc. Conceptually several ideas exist already (refer to (Kappes et al.2010) but the automation is still difficult.
- The full transferability of the two Tools. Up to now several adjustments have to be done manually which shall be automated in the future.

Bibliography:

Ayala-Carcedo, F., Cubillo-Nielsen, S., Alvarez, A., Domínguez, M., Laín, L., Laín, R., and Ortiz, G. (2003). Large scale rockfall reach susceptibility maps in La Cabrera Sierra (Madrid) performed with GIS and dynamic analysis at 1:5,000. *Natural Hazards*, 30:325–340.

Barbolini, M., Pagliardi, M., Ferro, F., and Corradeghini, P. (2009). Avalanche hazard mapping over large undocumented areas. *Natural Hazards*.

Beguería, S. (2006). Validation and evaluation of predictive models in hazard assessment and risk management. *Natural Hazards*, 37:315–329.

Blahut, J., Horton, P., Sterlacchini, S., and Jaboyedoff, M. (2010). Debris flow hazard modelling on medium scale: Valtellina di Tirano, Italy. *Natural Hazards and Earth System Sciences*. online.

Corominas, J., Copons, R., Vilaplana, J., Altimir, J., and Amigó, J. (2003). Integrated landslide susceptibility analysis and hazard assessment in the Principality of Andorra. *Natural Hazards*, 30:421–435.

Delmonaco, G., Leoni, G., Margottini, C., Puglisi, C., and Spizzichino, D. (2003). Large scale debris-flow hazard assessment: a geotechnical approach and GIS modelling. *Natural Hazards and Earth System Sciences*, 3:443–455.

Dietrich, W. and Montgomery, D. (1998). Shalstab: a digital terrain model for mapping shallow landslide potential. Technical report, NCASI. access 15 November 2009.

European Comission (2011). Risk assessment and mapping guidelines for disaster management. Commission staff working paper, European Union.

Frattini, P., Crosta, G., Carrara, A., and Agliardi, F. (2008). Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. *Geomorphology*, 94(3-4):419 – 437. GIS technology and models for assessing landslide hazard and risk.

Geomer (2008). *FloodArea - ArcGIS extension for calculating flooded areas: user manual*. Geomer GmbH and Ingenieurgemeinschaft Ruiz Rodriguez + Zeisler + Blank.

Guzzetti, F., Reichenbach, P., and Wieczorek, G. F. (2003). Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. *Natural Hazards and Earth System Science*, 3(6):491–503.

Holmgren, P. (1994). Multiple flow direction algorithms for runoff modelling in grid based elevation models: an empirical evaluation. *Hydrological Processes*, 8:327–334.

Horton, P., Jaboyedoff, M., and Bardou, E. (2008). Debris flow susceptibility mapping at a regional scale. In *4th Canadian Conference on Geohazards*, Québec, Canada. Université Laval.

Jaboyedoff, M. and Labiouse, V. (2003). Preliminary assessment of rockfall hazard based on GIS data. In of Mining, S. A. I. and Metallurgy, editors, *ISRM - Technology roadmap for rock mechanics*, Johannesburg, South Africa.

Kappes, M., Gruber, K., S., F., Bell, R., Keiler, M., and Glade, T. (in prep.). A medium/regional-scale multi-hazard risk analysis tool: the multirisk platform.

Kappes, M., Keiler, M., and Glade, T. (2010). *Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence*, chapter From single- to multi-hazard risk analyses: a concept addressing emerging challenges, pages 351–356. CERG Editions, Strasbourg.

Kappes, M., Malet, J.-P., Remaître, A., Horton, P., Jaboyedoff, M., and Bell, R. (2011). Assessment of debris flow susceptibility at medium-scale in the Barcelonnette Basin, France. *Natural Hazards and Earth System Science*. online.

Kappes, M., von Elverfeldt, K., Glade, T., and Keiler, M. (subm.). Challenges of dealing with multi-hazard risk: a review. *Natural Hazards*.

Kienholz, H. and Krummenacher, B. (1995). Symbolbaukasten zur Kartierung der Phänomene. Technical report, Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bundesamt für Wasser und Geologie (BWG).

Maggioni, M. (2004). *Avalanche release areas and their influence on uncertainty in avalanche hazard mapping*. PhD thesis, Universität Zürich.

Maggioni, M. and Gruber, U. (2003). The influence of topographic parameters on avalanche release dimension and frequency. *Cold Regions Science and Technology*, 37:407–419.

Marzocchi, W., Mastellone, M., and Di Ruocco, A. (2009). *Principles of multi-risk assessment: interactions amongst natural and man-induced risks*. European Commission.

Montgomery, D. and Dietrich, W. (1994). A physically based model for the topographic control on shallow landsliding. *Water Resources Research*, 30:1153–1171.

Montgomery, D. and Greenberg, H. (2009). Dave and Harvey's slope stability package.

Montgomery, D. R., Sullivan, K., and Greenberg, H. M. (1998). Regional test of a model for shallow landsliding. *Hydrological Processes*, 12:943–955.

Quinn, P., Beven, K., Chevallier, P., and Planchon, O. (1991). The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes*, 5:95–79.

Tarvainen, T., Jarva, J., and Greiving, S. (2006). Spatial pattern of hazards and hazard interactions in Europe. In Schmidt-Thomé, P., editor, *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions*, volume 42, pages 83–91. Geological Survey of Finland.

UN-ISDR (2009). UNISDR terminology on disaster risk reduction. Technical report, United Nations International Strategy of Disaster Reduction.

Wichmann, V. and Becht, M. (2006). Rockfall modelling: methods and model application in an alpine basin (reintal, germany). *Göttinger Geographische Abhandlungen*, 115:105–116.

WMO (1999). Comprehensive risk assessment for natural hazards. Technical document 955, World Meteorological Organisation.

B. English and German Summary

B.1. Zusammenfassung

Viele Gebiete der Erde sind von multiplen Naturgefahren betroffen wie beispielsweise Bergregionen und Küstenzonen. Um jedoch das Gesamtrisikos in diesen Gebieten zu verringern, können Maßnahmen nicht auf einzelne Prozesse beschränkt bleiben sondern müssen alle relevanten Gefahren einbeziehen. Hierbei liefern Risikoanalysen die notwendige Information, um in Multi-Gefahrensituation Risiken beurteilen und Maßnahmen planen zu können. Noch ist die getrennte Analyse der Einzel-Gefahren und das Zusammenführen der Analyseergebnisse erst für die Risikobeurteilung und Entscheidungsprozesse übliche Praxis. Sich jedoch Multi-Gefahren Risikoanalysen wirklich nur die Summe von Einzel-Gefahren Risikoanalysen? Und können die Ergebnisse von getrennt voneinander untersuchte Einzel-Gefahren am Ende problemlos zusammengeführt werden? Ziel dieser Arbeit ist es, diese Fragen auf Basis eines Literaturreviews und der Entwicklung eines Multi-Gefahren Risikoanalyseschemas im Detail zu untersuchen.
Auf Basis einer umfangreichen Literaturanalyse von Multi-Gefahren Studien werden sieben wesentliche Multi-Gefahrenaspekte zusammengestellt: (1) hoher Datenbedarf von Multi-Gefahren Risikoanalysen, (2) Skalenunterschiede zwischen Prozessen, (3) unterschiedliche, prozess-spezifische Modellierungsansätze, (4) Beziehungen zwischen Prozessen, (5) unterschiedliche Einheiten für die Gefahrenquantifizierung, (6) Vielzahl der Einzelschritte einer Multi-Gefahren Risikoanalyse und (7) Schwierigkeiten bei der übersichtlichen Darstellung der Analyseergebnisse. Unter Berücksichtigung dieser Multi-Gefahrenaspekte wird ein top-down Ansatz bestehend aus einer regionalen und einer lokalen Skala entworfen. Dabei werden auf der regionalen Skala, auf Basis eine Expositionsanalyse mit geringen Datenanforderungen, Gebiete sich überlagernder Prozesse und möglichen Risikos identifiziert, welche daraufhin auf lokaler Skala im Detail untersucht werden können. Mit dem Analysekonzept verbunden ist ein Visualisierungskonzept, welches der übersichtlichen Darstellung der vielschichtigen Analyseresultate dient. Zusätzlich wurde für eine eher lokale Skala ein indikatorenbasierter Ansatz für die Abschätzung der physikalischen Vulnerabilität gegenüber multiplen Gefahren entwickelt.
Die konzeptionellen Ansätze wurden in als Modellierungs- und Visualisierungstool in die MultiRISK Software Plattform umgesetzt, welche schnelle und wiederholbare Analysen multipler Gefahren, sowie eine klare und übersichtliche Darstellung der Ergebnisse ermöglicht. Um die Plattform wie auch die zugrundeliegenden Konzepte zu überprüfen

wurde eine Fallstudie in Barcelonnette, Frankreich, durchgeführt.
Vor dem Hintergrund der gewonnenen Erfahrungen werden die identifizierten Multi-Gefahrenaspekte erörtert und die Anfangsfrage diskutiert. Dabei wird deutlich, dass durch die Kombination unterschiedlicher Prozesse im Rahmen von Multi-Gefahren Risikoanalysen Herausforderungen und Phänomene entstehen, welche über die Summe getrennt durchgeführter Einzelgefahrenanalysen hinausgehen. Darunter zählen Prozessinteraktionen, ein eventuell höherer Bedarf an Information und die Notwendigkeit die unterschiedlichen Skalen verschiedener Prozesse einander anzupassen, aber auch Vorteile wie eine erhöhte Effektivität durch die gemeinsame Analyse multipler Gefahren.
Im Zusammenhang mit Maßnahmen zur Risikoreduzierung soll die vorgestellte Plattform eine Diskussionsgrundlage mit Akteuren in diesem Feld bieten. Auf Basis dieses ersten Vorschlages können der praktische Nutzen solcher Programme und Ansätze wie auch notwendige Anpassungen besprochen und geplant werden.

B.2. Summary

Despite the increasingly recognised need for joint multi-hazard risk analyses, current practice is still the separate analysis of each natural hazard and the risk it poses. In the final stage for decision-making for risk reduction purposes the single-hazard results are combined. However, is a multi-hazard risk analysis really just the sum of multiple single-hazard risk analyses? Can single hazards be studied separately and can the final results be combined that easily? The objective of this study is to investigate these questions in detail by means of the examination of the work currently done in this field and the development of a multi-hazard risk analysis approach.

Based on an extensive review of current studies in the multi-hazard context seven *major multi-hazard issues* are compiled: (1) high data requirements of multi-hazard risk analyses, (2) scale differences between hazards, (3) differing hazard-specific model principles, assumptions and uncertainties, (4) relations between hazards, (5) differing metrics for hazard quantification, (6) multitude of steps multi-hazard risk analyses consist of and (7) difficulties to visualise the multi-dimensional analysis outcome.

These issues receive specific attention during the development of an analysis and visualisation scheme according to a top-down approach consisting of two scales, a regional and a local scale. At the regional level, an exposure analysis based on low data requirements is proposed to indicate zones of possible hazard relations and potential risk for the detailed investigation at a local level. The related visualisation concept aims to communicate the multi-dimensional content of the analysis output in a structured way. Additionally, in a step towards a more local and detailed analysis, an indicator-based approach for the assessment of physical multi-hazard vulnerability has been developed.

The completed conceptual approach was implemented as a Modelling and Visualisation Tool into the software platform MultiRISK which offers fast and repeatable analysis of multiple hazards and clear and structured visualisation of the results. To test the applicability of the MultiRISK Platform and the underlying conceptual approach, a case study has been carried out in the Barcelonnette basin, France.

In the light of the experiences gained, the identified *multi-hazard issues* are recapitulated and the initial questions are discussed. Thereby, it becomes apparent that in multi-hazard risk analyses several challenges and phenomena emerge due to the combination of multiple hazards that lie beyond the sum of separate analyses. This refers to difficulties such as additional information requirements or differing hazard scales but also to advantages such as the efficient analysis of multiple hazards.

The elaborated software platform is supposed form a suitable base for discussions with stakeholders about the practical utility of such tools and required adjustments to meet their needs.

Eidesstattliche Erklärung

Hiermit erkläre ich, Melanie Simone Kappes, geboren am 27.01.1981 in Karlsruhe die vorliegende Diplomarbeit selbstständig angefertigt zu haben. Aus fremden Quellen direkt oder indirekt übernommene Informationen und Gedanken sind als solche kenntlich gemacht.
Die Arbeit wurde bisher weder in gleicher noch in ähnlicher Form einer anderen Prüfungsbehörde vorgelegt oder veröffentlicht.

Wien, Juli 2011 ....

C. Curriculum Vitae

Dipl. Geoökol. Melanie S. Kappes

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Professional Career:

01/2011 - 09/2011	Beneficiary of the University of Vienna research grant (Forschungsstipendium).
04/2008 - 12/2010	Early stage researcher in the EU funded Marie Curie Research Training Network “Mountain Risks: from prediction to management and governance” and employee at the University of Vienna. In the EU project tasks comprised the development of a multi-hazard analysis scheme for risk governance strategies and the presentation and publication of the research results. Further activities included the organization of conferences and workshops, the elaboration of financial audits and the elaboration of project reports. University duties included teaching, co-supervision of diploma students and organisatory tasks at the institute.

03/2007 - 03/2008	Trainee of the German Development Service ded (Deutscher Entwicklungsdienst) in Carazo, Nicaragua. Tasks comprised the development of a Geographic Information System (in ArcGIS 9.2) for land use planning in municipalities, the collection, quality check and integration of data, capacity building of technical teams in the software ArcView 3.2, management and presentation of the Geographic Information System, assistance in planning processes and the training of my successor.

Education:

07/2010	Research stay at the Isle of Wight Centre for the Coastal Environment, Ventnor, Isle of Wight, UK.
09/ - 11/2009	Research stay at CEMAGREF (L'institut de recherch en sciences et technologies pour l'environnement), Grenoble, France.
10/2008 - 09/2011	PhD studies at the University of Vienna with the topic: multi-hazard risk analyses - a concept and its implementation. Main objective was the development of an analysis concept for the hazards rock falls, debris flows, shallow landslides, snow avalanches and river floods. Herein, the consideration of hazard relations was a key aspect. The analysis concept was implemented in a user-friendly modeling software, MultiRISK, and linked to a Visualisation Tool (a web-GIS platform) to present the modeling results in a structured and clear way. A further focus was the analysis of physical vulnerability in a hazard-specific way. An indicator-based approach was developed to assess vulnerabilities in a multi-hazard context.
14/12/2006	Diploma degree in Geoecology. Title of diploma thesis: "Character and magnitude of correlations between vegetation patterns and grazing on the summer pastures in the Fergana Range, Tian Shan (Kyrgyzstan)". Under integration of ASTER satellite images predictive mapping was used for the statistical modeling of the vegetation patterns.
07/ - 09/2005	Data acquisition in Kyrgyzstan, Central Asia, for the diploma thesis.
10/2003 - 02/2004	Studies of Environmental Sciences with ERASMUS in León, Spain.
10/2000 - 12/2006	Studies of Geoecology at the University of Bayreuth.
06/2000	High school graduation.

Further educational courses:

02/ - 13/08/2010	Participation in the "Summer Institute for Advanced Study of Disaster and Risk: Disaster, Risk, and Climate Change", Beijing Normal University, China.
19/ - 25/06/2010	Participation and teaching in the Intensive Course "Mountain Disasters - Risk Management", Barcelonnette & Avignonet, France, organized by the Mountain Risks project.
07/ - 08/06/2010	Participation in the course "Motivation and Team-Building", University of Vienna, Austria. 26/07 - 02/08/2009 Participation in the 9th Edition of the international Summer School "Environmental hazards and sustainable development in mountain regions", Partalagele, Rumania, organized by the Institute of Geography of the Romanian Academy.
21/06 - 26/06/2009	Participation in the Intensive Course "Multi-technique landslide investigation for hazard assessment", Les Diablerets, Switzerland, organized by the Mountain Risks project.
01/09 - 04/09/2008	Participation in the Intensive Course "Quantitative Landslide Risk Assessment and Risk Management" in Barcelona, Spain, organized by the Mountain Risks project.
30/06 - 18/07/2008	Participation in the "Multi-hazard Risk Assessment" Course at ITC, Netherlands.
15/06 - 18/06/2008	Organisation of and participation in the Intensive Course "Mountain Risks and Risk Governance" in Kempten, Germany, organized by the Mountain Risks project.

Teaching:

2009 - 2010	Co-supervision of diploma students.
03/2009 - 09/2009	Physio-geographic project seminar: Natural hazards and risks in mountain areas - part II. Introductory seminar course: Geomorphology in high mountains, Barcelonnette, France. Excursion: Natural hazards and risks in mountain areas, Barcelonnette, France.
10/2008 - 02/2009	Physio-geographic project seminar: Natural hazards and risks in mountain areas - part II.

Languages:

German	Mother tongue
English	Excellent
Spanish	Fluent
French	Good knowledge

Other activities:

01 - 04/2010	Member of the PhD Curricular Commission at the University of Vienna.
Since 2008	Member of the European Geoscience Union.
11/2005 - 1/2007	President of oikos Bayreuth (oikos: international student organization dealing with sustainable economics and management).
2004 - 2007	Cooperation in oikos Bayreuth.
04/ - 09/2003	Cooperation in IAESTE (international student exchange).

Publications:

Kappes M.S., Gruber K., Frigerio S., Bell R., Keiler M. & Glade T. (subm.) A multi-hazard exposure analysis tool: the MultiRISK Platform. Geomorphology.

Kappes M.S., Papathoma-Köhle M. & Keiler M. (acc.) Assessing physical vulnerability for multi-hazards using an indicator-based methodology, Applied Geography.

Kappes M.S., von Elverfeldt K., Glade T. & Keiler M. (subm.) Challenges of dealing with multi-hazard risk: a review. Natural Hazards.

Kappes M.S., Malet J.-P., Rematre A., Horton P., Jaboyedoff M. & Bell R. (2011) Assessment of debris flow susceptibility at medium-scale in the Barcelonnette Basin, France, Natural Hazards and Earth System Sciences, 11: 627-641.

Kappes M., Keiler M. & Glade T. (2010) From single- to multi-hazard risk analyses: a concept addressing emerging challenges. In Malet, J.-P., Glade, T. & Casagli, N. (Eds.), Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence. CERG Editions, Strasbourg, 351-356.

van Westen C.J., Quan Luna B., Vargas Franco R., Malet J., Jaboyedoff M. & Kappes M.S. (2010) Development of training materials on the use of Geo-information for Multi-Hazard Risk Assessment in a Mountainous Environment. In Malet, J.-P., Glade, T. & Casagli, N. (Eds.), Mountain Risks: Bringing Science to Society. Proceedings of the International Conference, Florence. CERG Editions, Strasbourg, 469-475.

Papathoma-Köhle M., Kappes M.S., Keiler M. & Glade T. (2010) Physical Vulnerability Assessment for Alpine Hazards - State of the art and future needs, Natural Hazards, 58: 645-680.

Kappes, M.S. (2006) Character and magnitude of correlations between vegetation patterns and grazing on the summer pastures in the Fergana Range, Tian Shan (Kyrgyzstan), University of Bayreuth, diploma thesis.

Abstracts:

Kappes M.S., Frigerio S., Gruber K. & Glade T. (accepted) Multi-hazard risk analyses with MultiRISK - Tools for a user-friendly performance. 12th Congress INTERPRAEVENT, Grenoble, France.

Keiler M. & Kappes M. (accepted) Multi-hazard risk analyses - challenges of interaction and connectivity. 12th Congress INTERPRAEVENT, Grenoble, France.

Kappes M. & Glade T. (accepted) Landslides considered in a multi-hazard context. Proceedings of the Second World Landslide Forum, Rome, Italy.

Kappes M., Gruber K., Frigerio S. & Glade, T. (2011) MultiRISK - a tool for coherent multi-hazard risk analyses. Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, Vol 13, available at: http://meetingorganizer.copernicus.org/EGU2011/EGU2011-9306.pdf

Papathoma-Köhle M., Kappes M. & Keiler, M. (2011) An indicator-based methodology for vulnerability assessment in alpine areas. Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, Vol 13 available at: http://meetingorganizer.copernicus.org/EGU2011/EGU2011-4942.pdf

Garcia C., Frigerio S., Kappes M.S. & Peters Guarin G. (2010) Social survey and GIS mapping tools: integrating people's perception, preparedness and trust for vulnerability assessment, AGIT 2010, Salzburg, Austria.

Kappes M.S., Frigerio S., Quan Luna B., Traveletti J., Spickermann A., Krzeminska D., & Angignard M. (2010) Dealing with natural hazards in the Barcelonnette region - a multi-disciplinary collaboration from understanding to management, Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, vol 12., available at: `http://meetingorganizer.copernicus.org/EGU2010/EGU2010-15413-1.pdf`

Kappes M.S., Keiler M., & Glade T. (2010) Consideration of Hazard Interactions in Medium-Scale Multi-Hazard Risk Analyses, Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, vol 12, available at: `http://meetingorganizer.copernicus.org/EGU2010/EGU2010-3331.pdf`

Frigerio S., Grzegorz S., Kappes M.S., Malet J.-P., & Puissant A. (2010) A WebGIS service for managing, sharing and communicating information on mountain risks: a pilot study at the Barcelonnette Basin (South French Alps), Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, vol 12, available at: `http://meetingorganizer.copernicus.org/EGU2010/EGU2010-12555-1.pdf`

Ramesh A., Glade T., Kappes M.S., & Malet J.-P. (2010) Delineation of Flood Inundated Areas using Aerial photo Interpretation and GIS-based Hydrological Modeling - an application in Barcelonnette, France), Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, vol 12, available at: `http://meetingorganizer.copernicus.org/EGU2010/EGU2010-3519-1.pdf`

Kappes, M.S., Keiler, M., Bell, R. & Glade, T. (2009) Multi-hazard risk analysis for management strategies, Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, vol 11, available at : `http://meetingorganizer.copernicus.org/EGU2009/EGU2009-7391-1.pdf`

Kappes, M.S., Malet, J.-P., Rematre, A., Horton, P., Jaboyedoff, M. & Bordonnŕ, M. (2009) Regional assessment of debris-flow hazards: a method to characterize temporal changes in debris flow exposure, Geophysical Research Abstracts, EGU General Assembly, Vienna, Austria, vol 11, available at: `http://meetingorganizer.copernicus.org/EGU2009/EGU2009-7953.pdf`

Presentations:

Glade T. & **Kappes M.S.** (03/05/2011) Geographische Katastrophenforschung: Stand und zukünftige Herausforderungen. Workshop “Umgang mit Naturgefahren”. Organisation Österreichisches Roten Kreuz & Boku, Wien, Österreich. Invited talk.

Kappes M.S., Malet J.-P., Remaître A., Horton P., Jaboyedoff M. & Bell R. (04/02/2011) Assessment of debris flow susceptibility at medium-scale in the Barcelonnette Basin, France. Journes des Jeunes Gomorphologues, Avignon, France. Invited talk.

Frigerio S., Malet J.-P., Kappes M.S., van Westen C.J., Glade T. & Gruber K. (21/12/2010) A web solution to support, educate and train on Multi-Risk, Workshop: Multi-Hazard Risks - status quo and future challenges, Vienna, Austria.

Kappes M.S., Gruber K., Keiler M., Bell R. & Glade T. (20/12/2010) MultiRISK - A Platform for coherent Multi-Hazard Risk Modelling, Workshop: Multi-Hazard Risks - status quo and future challenges, Vienna, Austria.

Papathoma-Köhle M., Kappes, M.S. & Keiler M. (20/12/2010) Physical Vulnerability to Alpine Hazards (debris flow, snow avalanches, floods, landslides), Workshop: Multi-Hazard Risks - status quo and future challenges, Vienna, Austria.

Kappes M.S., Keiler M., Gruber, K. & Glade, T. (25/11/2010) From Single- to Multi-Hazard Analyses: A Concept addressing Emerging Challenges, International Conference: Mountain Risks - Bringing Science to Society, Florence, Italy.

Frigerio S., Malet J.-P., Kappes M.S., van Westen, C.J. & Glade T. (11/2010) CartoWeb Experience - Open source frame for sharing and communicating information on hazards and risks, International Conference: Mountain Risks - Bringing Science to Society, Florence, Italy.

Garcia C., Frigerio S., Kappes M.S. & **Peters Guarin G.** (07/2010) Social survey and GIS mapping tools: integrating people's perception, preparedness and trust for vulnerability assessment, AGIT 2010, Salzburg, Austria.

Kappes M.S., Keiler M. & Glade, T. (06/2010) From Single- to Multi-Hazard Risk. Intensive Course "Mountain Disasters - Risk Management", Barcelonnette & Avignonet, France.

Kappes M.S., Ramesh A. & Bhattacharya (06/2010) Modlisation de l'ala 'crue' dans le Bassin de Barcelonnette, Restitution de travaux scientifiques sur l'aléa et le risque hydro-gravitaire (mouvement de terrain, laves torrentielles, crues) issus des projets europens Mountain-Risks et SafeLand et changes avec les gestionnaires, Barcelonnette, France.

Kappes M.S., Keiler M., & Glade T. (05/2010) Consideration of Hazard Interactions in Medium-Scale Multi-Hazard Risk Analyses, EGU General Assembly, Vienna, Austria.

Kappes M.S., Keiler M. & Glade T. (09/2009) Multi-Gefahren Risikoanalysen für integrales Risikomanagement: Notwendigkeit im Wandel. Deutscher Geographentag - AK Naturgefahren, Vienna, Austria.