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The Application of the Risk Concept to Debris Flow Hazards

Debris flows present a serious hazard in alpine regions, where natural environment meets the space of human interest such as settlements and infrastructure. In the past various measures have been developed to protect human life and property. However, a complete protection from damage is not possible, also due to limited financial resources of public fund providers. Therefore, the concept of risk management was adopted from technical sciences as an alternative and sustainable protection strategy, and was increasingly implemented in Alpine countries within the last decades. This paper provides an introduction to the state of the art in risk analysis for debris flow hazards, including an overview of different but complementary methods for debris flow risk analysis at different scales.

Die Anwendung des Risikokonzepts auf Murgang-Gefahren
Murgänge stellen eine wesentliche Gefährdung im Überschneidungsbereich des Natur- und Kulturraums der Bergregionen dar. In der Vergangenheit wurde eine Vielzahl von Maßnahmen ergriffen, um den Lebensraum oder Sachwerte vor den Auswirkungen dieser Gefährdung zu schützen. Ein vollständiger Schutz vor Schäden ist aber nicht möglich, auch aufgrund einer zunehmenden Finanzknappheit im Öffentlichen Sektor. Deshalb wurde in den vergangenen Jahrzehnten das Risikokonzept als eine alternative und nachhaltige Schutzstrategie adaptiert und in einigen Alpenländern implementiert. Der Beitrag gibt, in Abhängigkeit der Datenverfügbarkeit für verschiedene Bearbeitungstiefen und Maßstäbe, einen aktuellen Überblick zur Methodik der Risikoanalyse für Murgang-Gefahren.

1 Introduction

Periodic and episodic erosion processes in torrents are common in alpine environments. It is the exposure of people and property, i.e. settlements, road networks and tourism facilities that creates a hazard from such events; in particular if a certain threshold in magnitude or frequency is exceeded. Thus, natural hazards such as debris flows are phenomena at the intersection between the natural environment and the environment formed and controlled by human activities. Situated amongst landslides, rockfall, and floods [1], debris flows are mixtures of water and sediment, ranging from clay sized particles to boulders of several metres of diameter. The destructive nature of debris flows is mainly due to high possible values of density, velocity and discharge (Figure 1). Front velocities exceeding 20 m/s have been observed [2] [3] and peak discharges one or two orders of magnitude larger than normal floods in the same catchment have been estimated.

Dealing with natural hazards has a long tradition in the Alps, above all since areas suitable for settlement and economic activity are relatively scarce due to a high relief energy. During the last centuries, areas potentially endangered were predominantly used for extensive agricultural purpose to avoid danger. Since the outgoing 19th century, a change of these patterns of utilization is traceable due to the socio-economic development of European mountain regions. At the same time, the first authorities for the protection of natural hazards were founded, e.g. in Switzerland in the late 1870s [4] and in Austria in 1884 [5]. For more than half a century technical mitigation measures had been developed and implemented. These active measures, representing the human reaction to hazard processes, appeared to be the appropriate way to cope with this challenge. Since the 1960s, these technical mitigation measures were supplemented by passive protection concepts, and hazard maps were introduced aiming to reduce an exposure to hazards. The need for hazard mapping was regulated in the Austrian law related to forests in 1975 [6] and an associated decree in 1976 [7].

Though considerable amounts of public money were spent for conventional mitigation and hazard mapping, a comprehensive protection of settlements and infrastructure against any loss resulting from hazard processes is not possible. Particularly in the 1990s, considerable damage occurred all over the Alps due to avalanches (winter 1998/99),

Fig. 1. Debris flow at Tullbach, Austria
Bild 1. Murgang im Tullbach, Österreich

torrent processes (1999, 2002, 2005) and inundation (2002, 2005, 2006). As a result society increasingly realised – also on the political level – that a complete protection against natural hazards is not affordable and economically justifiable [8] [9]. People and political decision makers are more and more aware of the impacts resulting from hazards, and thus in some Alpine countries a paradigm shift took place from hazard reduction to a risk culture [10], a shift that is not yet fully realised in Austria due to current legal regulations [11] [12]. However, principles of sustainability have necessarily to be considered when dealing with natural hazards, as laid down in the Alpine Convention [13] [14] and in the Agenda 21 [15]. One possibility to meet these goals is the extension of the current approach of dealing with natural hazards in Austria by the concept of risk.

1.1 Concept of risk

The analysis of natural hazard risk is embedded in the circle of integral risk management, including a risk assessment from the point of view of social sciences and economics, and strategies to cope with (adverse) effects of hazards. The underlying objective for risk management is the planning and implementation of protective measures in an economically efficient and societal agreeable manner. Thus, risk assessment includes both, risk analysis and risk valuation within a defined system at the intersection between different disciplines. For this reason, the scales of valuation (temporal, spatial, degree of detail) have to be well defined for a sustainable risk minimization.

To be able to compare different types of hazards and their related risks, and to design and implement adequate risk reduction measures, a consistent and systematic approach has to be established. While a hazard analysis focuses on natural processes such as debris flows, the method of risk analysis additionally includes the qualitative or quantitative valuation of elements exposed to these hazards, i.e. their individual values and the associated vulnerability. Originating from technical risk analyses [16] [17], the concept of risk with respect to natural hazards is defined as a quantifying function of the probability of occurrence of a process and the related extent of damage, the latter specified by the damage potential and the vulnerability:

$$R_{i,j} = f\left(p_{Si}, A_{Oj}, v_{Oj,Si}, p_{Oj,Si}\right) \qquad (1)$$

Hence, specifications for the probability of the defined scenario (p_{Si}), the value at risk affected by this scenario (A_{Oj}), the vulnerability of object j in dependence on scenario i ($v_{Oj,\,Si}$), and the probability of exposure of object j to scenario i ($p_{Oj,\,Si}$) are required for the ex-ante quantification of risk ($R_{i,\,j}$). The procedure of hazard assessment is methodologically reliable in determining the hazard potential and the related probability of occurrence (p_{Si}) by studying, modelling, and assessing individual processes and defined design events [18] [19]. Until now, little attention has been given to the damage potential (A_{Oj}) affected by hazard processes, even if theoretic concepts and guidelines exist in some Alpine countries [9] [20] [21]. Though in Austria risk analyses are not legally prescribed, there is

Table 1. Elements to be considered within the framework of risk analysis
Tabelle 1. Bei der Risikoanalyse zu berücksichtigende Arbeitsschritte

Definition of scale (e.g., time, space,…) and system boundaries		
Hazard analysis	Vulnerability analysis	Analysis of values at risk
Analysis of terrain and environment	Analysis of direct and indirect consequences	Analysis of number and categories of persons
Definition of scenarios/ design events	Analysis of (structural) resistance	Analysis of number and value of tangible assets
Modelling and simulation	Analysis of resilience and coping capacity	Analysis of intangibles (monetarily?)

an implicit need for the consideration of damage potential because of the data needed for the standardised cost-benefit analysis during the measurement planning [22].

As shown in Table 1, risk analysis includes
– Hazard analysis,
– Vulnerability analysis, and
– Analysis of values at risk.

All three steps of risk analysis should be carried out within a GIS-environment for a spatially explicit calculation.

After defining the scale and system boundary for the analysis, all necessary steps for the risk analysis will be conducted. The hazard analysis includes an event and impact analysis and results in a specific process scenario, e.g. the extent of a 150-year design event. Identifying elements at risk harmed by the defined scenario, a vulnerability analysis and an analysis of values at risk will be carried out. A vulnerability analysis includes the assessment of resistance, resilience and coping capacity; with respect to Alpine natural hazards and from an engineering point of view, only the analysis of structural resistance is regularly carried out. The analysis of values at risk includes number and value of tangible assets, and an analysis of number and categories of people being present in endangered areas. A facultative analysis of intangibles can be undertaken, while the valuation procedure of intangibles is neither always satisfyingly nor definitely possible. All steps of the risk assessment have to be undertaken by a well-defined objective procedure to guarantee for transparent and reproducible results.

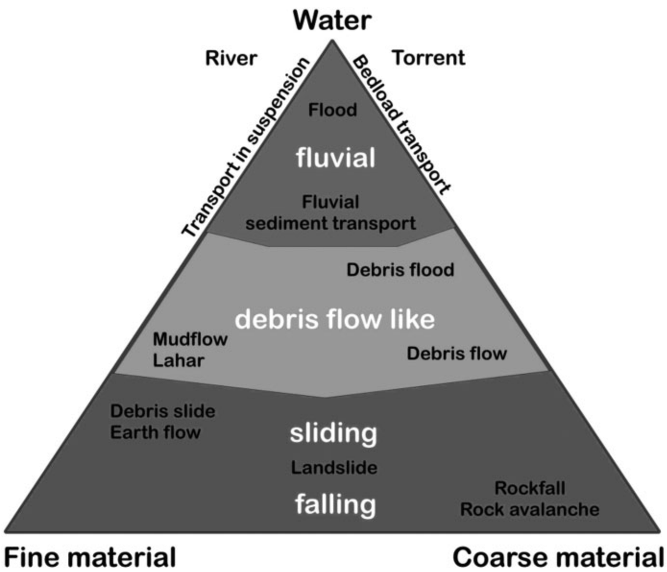

Fig. 2. Phase diagram of torrential processes [23]
Bild 2. Phasendiagramm für Wildbachprozesse [23]

1.2 Torrent processes

The transport mechanism in torrent catchments can be classified into fluvial, debris flow like, sliding, and falling dislocation [23]. A general classification can be made depending on the relative concentration of water, fine and coarse sediment, as first suggested by *Phillips* and *Davies* [24] (Figure 2).

As suggested by *Bergmeister* et al. [25] and defined in the Austrian standard ONR 24800 [23], debris flows are highly-concentrated mixtures of water, fine and coarse sediment, and frequently woody debris. The coarse sediment is usually concentrated in the upper layers and at the front of the flow. The sediment concentration reaches values up to the plastic limit, but is often between 40 and 70 % by volume. The specific bulk density of the mixture amounts to 1.7 to 2.4 g/cm^3. The flow is characterised as unsteady and non-uniform, and typically debris flows occur in one to five surges [26] [27]. The flow behaviour is generally termed "non-Newtonian", indicating that standard hydraulic models are not capable to describe the flow satisfyingly. The event volumes of debris flows vary considerable between several thousand to some hundred thousand cubic metres.

Debris flows can be roughly classified due to the relative concentration of fine and coarse sediment by the prefix "viscous/muddy" or "granular/stony" to describe the main flow behaviour [28] [29] [30]. *Coussot* and *Ancey* [31] developed a simplified classification scheme for particle-fluid mixtures in motion to identify the prevailing sources of energy dissipation using dimensionless numbers. Above a critical solid concentration, direct interactions (friction or collision) and lubricated contacts between the particles are dominating processes. Models from soil mechanics like the Mohr-Coulomb model and ideas based on the work of *Bagnold* [32] are used to describe the flow behaviour of these mixtures. Beyond a critical solid concentration a viscoplastic flow behaviour can be expected [33]. Phenomenological laws like the Bingham law or the generalised Herschel Bulkley law are often used to describe the rheological behaviour [33].

2 Hazard analysis

The main objective of a hazard analysis is the evaluation of debris flow hazards in a particular torrent catchment, including the spatial identification of the debris flow

Table 2. Recommended methods for landslide risk analysis on different scales (including debris flows) [42]
Tabelle 2. Überblick skalenabhängiger Methoden zur Risikoanalyse für Rutschprozesse (inklusive Murgänge) [42]

Scale	Qualitative methods		Quantitative methods		
	Event documentations	Heuristic analysis	Statistical analysis	Probabilistic prediction analysis	Process-based and numerical analysis
< 1:10,000	Yes	Yes	Yes	Yes	Yes
1:15,000-1:100,000	Yes	Yes	Yes	Yes	Probable
1:125,000-1:500,000	Yes	Yes	Probable	Probable	No
> 1:175,000	Yes	Yes	No	No	No

process and the estimation of magnitude and frequency. *Rickenmann* [34] proposed a two-staged method for a debris flow hazard analysis:

- Determination of the occurrence probability of a debris flow event in the studied torrent catchment, i.e. the recurrence interval and the frequency of an event.
- Quantitative estimation of the principal debris flow parameters needed for hazard assessment, such as event magnitude, runout length, and deposition area.

The frequency of a debris flow event for hazard analysis can be described by several probability concepts and in different ways, such as the probability of the main triggering mechanism (e.g., recurrence interval of meteorological phenomena), or the probability to reach a defined point during run-out in the deposition area. Therefore, it is necessary to explicitly define which probability value is used in the set of calculations. Several methods have been proposed to estimate the likelihood of debris flow occurrence in a particular torrent catchment [35] [36] [37] [38] [39] [40]. However, there are no rigorous methods that allow a strict assessment to determine an exact probability of debris flow occurrence so far, neither based on physically measured characteristics of a catchment nor based on statistical analyses. The information available on past debris flow events is often the most reliable indication [3].

For hazard assessment the determination of frequency must be accompanied by an estimation of magnitude for the potential debris flow event, which is a matter of scale. Based on the scale classification for engineering geology maps [41], *Glade* and *Crozier* [42] recommend a method of analysis to be assigned to individual scales of investigation based on the distinction between qualitative and quantitative approaches (Table 2).

2.1 Qualitative methods

The management of natural hazard risks in mountain environments require a broad and accessible information basis to prevent disasters. A considerable amount of information is needed, above all data about former events, which must be available to develop and verify analysis methods. Event documentations are thus an important tool as information source for hazard and risk analysis as well as for regional and sectoral development concepts. A standardised inventory concept for data collection in terms of natural hazard processes, including debris flows, was developed by DIS-ALP [43]. The basic structure of the event documentation is highly dependent on the quality of available data. As shown in Figure 3, different scales of investigation require different levels of information.

Heuristic approaches are mainly based on a priori knowledge, local experiences as well as expert judgements and spatial information related to debris flow occurrence. Commonly, such information includes topographical, hydrological, geological, geotechnical or geomorphical factors, as well as information on vegetation coverage and land use patterns [42].

Qualitative methods provide preliminary estimations of debris flow susceptibility and hazard. This information is used at different scales within qualitative risk analyses and is based on descriptive or numeric rating scales to describe the magnitude of potential consequences (see Table 2) [44].

2.2 Quantitative methods

Quantitative methods can be divided into two different approaches: On the one hand statistical and probabilistic prediction analysis, and on the other hand process-based analysis. In contrast to qualitative methods, quantitative approaches draw comparisons or classifications of different debris flow events in a more comprehensible style.

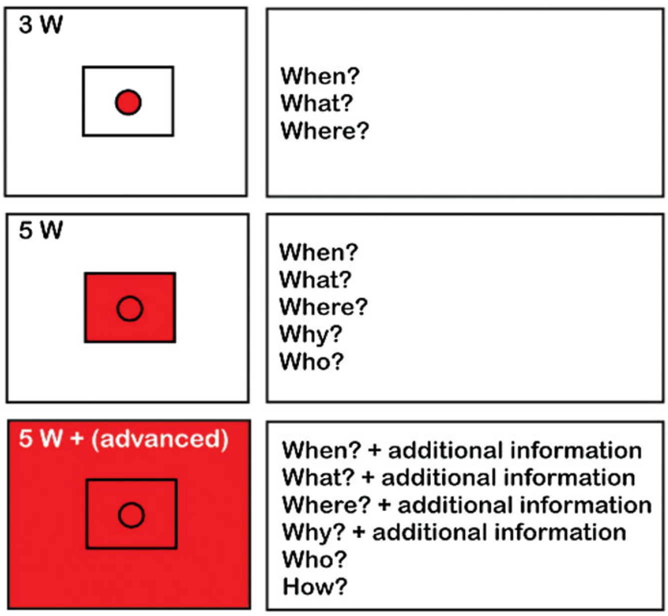

Fig. 3. Standards for data collection [43]
Bild 3. Standards zur Datenbeschaffung [43]

Thus, quantitative methods are widely applied for hazard analyses on a regional scale.

2.2.1 Statistical and probabilistic prediction analysis

The statistical methods have been extensively developed in connection to landslide hazard assessment, and have been also adopted for debris flows [45] [46]. Factor maps describing geology, soil, and topography (e.g., slope angle, horizontal and vertical curvature, aspect, distance to divide) are compared with debris flow distribution from inventory maps, and a spatial debris flow density is calculated.

Various statistical analyses are used to compare each individual factor with the hazard locations. As a result, weighting factors are computed for every factor [42]. Further statistical methods providing probabilistic prediction models (e.g., Bayesian probability, fuzzy logic) can also be used to calculate these susceptibility maps [47] [48].

At this level of detail, rough quantitative assessment of susceptibility is possible, but no detailed information about event parameters such as volume, flow velocity, or runout length is available. A useful approach to designate different debris flow hazard classes to torrent catchments has been proposed by *Rickenmann* [34].

2.2.2 Process-based and numerical analysis

At the watershed scale, the magnitude of channel-based hazard processes is often expressed by the measured geomorphic features, such as potential debris volume, mean flow velocity, peak discharge, and runout distance. For this purpose, empirical and semi-empirical equations may be used. As an alternative dynamic (often numerical) simulation models might be considered to assess the flow properties and the depositional behaviour [e.g., 49]. *Rickenmann* [3] proposed a flow chart for estimating debris flow parameters with the help of empirical formulae (Figure 4).

With respect to hazard evaluation, the potential debris flow volume is the most important parameter. Many attempts had been made to estimate a maximum debris flow volume for a given torrent catchment using empirical relations [40] [50] [51] [52] [53] [54]. *Rickenmann* [3] showed that that these attempts may overestimate the actual debris flow volume up to a factor of 100. It is therefore

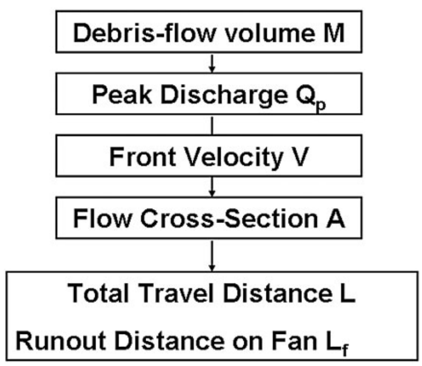

Fig. 4. Flow chart for estimating debris flow parameters by means of empirical formulae [3]
Bild 4. Schema zur Abschätzung von Murgang-Parametern mittels empirischer Formeln [3]

recommended to conduct a geomorphologic assessment of the catchment to estimate the possible volume of material to be susceptible to mobilization. Subsequently, the debris flow volume can be used to derive an estimate of the associated peak discharge, the total travel distance, and the runout distance on the fan [55] [56] [57]. A compendium on such empirical relationships for debris flows can be found in *Rickenmann* [3].

However, some limitations occur by applying these empirical approaches. Often calculated for specific regions and originating from individual case studies, empirical relations are not necessarily applicable to other regions. Furthermore, complex flow mechanisms which are important for a quantitative (small-scale) risk analysis cannot be mirrored or modelled. Therefore, dynamic simulation models are an alternative tool to estimate debris flow parameters relevant for hazard analysis.

Dynamic simulation models are used to calculate the spatial distribution of debris flow susceptibility within user-defined boundary conditions based on a mathematical formulation defining the material (flow) behaviour (e.g., rheological or friction models, single or multiphase flow models). A variety of flow resistance laws describing the flow behaviour of debris flows have been proposed and are still subject of research [35] [58] [59].

Analytical solutions are applied to predict the runout of a debris flow using simplified approaches. *Hungr* et al. [60] and *Takahashi* [28] described theoretical equations to estimate the runout length for debris flows on the fan assuming constant width and slope along the entire flow path. Due to inherent simplifications analytical models can only be applied when the main surge of the debris flow is expected to travel in the channel to the lowest point of deposition with essentially no change in flow width.

Numerical simulation models are based on one- and two-dimensional continuum mechanical equations (e.g., depth averaged "shallow water" equations). In particular for modelling the spatial deposition pattern on the fan, which is important for delineation of hazard zones, a 2D simulation is preferable. In practice a widely-used code is the commercially available software Flo-2D based on the quadratic rheologic model [61] [62]. It has been criticised that single phase models – such as the Flo-2D model – are based on strong simplifications and do not reflect mechanics and characteristics of debris flows accordingly. Detailed comparisons of different single phase-approaches can be found in *Naef* et al. [63] and *Rickenmann* et al. [64].

Physically based models – where the solid and the fluid components are modelled separately – have been recently proposed [65] [66] [67]. In practical application these models are not yet used due to the complexity of the approaches. Furthermore, necessary parameters such as the matrix permeability or the pore-water pressure are not easily assessable [68].

In general, numerical simulation based on basic rheologic models is a helpful tool in hazard assessment as long as necessary coefficients can be measured or back-calculated from past events in the same channel [69] [70]. However, the main disadvantage is the high demand for precise data, which is often not available in view of the costs involved, the complexity of the natural terrain as well as the properties of the flowing material.

3 Analysis of values at risk

Currently, only few conceptual suggestions and operational methods are available for the comprehensive assessment of values at risk endangered by natural hazards. Accordingly, the evaluation of damage potential is often based on subjective estimations rather than on widely-accepted standardised approaches. Hence, results of such assessments are rarely comparable, and do not necessarily mirror the actual situation satisfyingly. With respect to integral risk management, the assessment of values at risk has to be based on a spatially explicit valuation using GIS techniques. Thus, the following procedures outlined in *Borter* [21] and further developed by *Keiler* et al. [71] are recommended for an area-wide application in European mountain regions with respect to persons, infrastructure lines and buildings at risk.

The basis for this procedure is a digitised layer of the values at risk, e.g. a building shapefile originating from orthophotos and information extracted from the land register plan. The surface area of buildings provides the source for any further economic valuation. This valuation is carried out by means of average reconstruction values for different building categories, multiplied by further characteristics of these buildings such as building height and technical equipment (Table 3). The number of persons at risk is derived from the number of households per building and multiplied by the average number of persons per household, e.g. by using information from the respective national statistical offices. If a considerable amount of values at risk is comprised by tourist infrastructure, the number of tourists being present in endangered buildings could be derived from the number of beds in the hotel and restaurant industry, multiplied by the respective rate of occupation.

Table 3. Average reconstruction values for buildings in Austria applied in the GIS-based assessment of values at risk [71]
Tabelle 3. Durchschnittliche Wiederherstellungswerte für Gebäude in Österreich, wie sie in einer GIS-basierten Bewertung des Schadenpotentials Verwendung finden [71]

Type of building	Floor height [m]	Number of floors [N]	Value/m³ [€]
Detached house	2.8	3.5	350
Apartment building	2.8	4.0	385
Hotel	3.0	5.0	528
B&B	3.0	3.5	435
Restaurant	3.0	3.0	399
Public building	3.5	3.5	406
Office	3.5	1.0	342
Shop	4.0	1.0	330
Garage	4.0	1.0	212
Barn	2.8	1.0	200
Haystack	6.8	1.0	94
Indoor swimming pool	6.0	1.0	601
Gym	6.0	1.0	160
Carpark	2.8	1.0	235

As a result, a relational database is developed within the GIS environment, containing spatially precise information on the economic value of buildings at risk, and the number of inhabitants and tourists. If necessary, people at risk can be further evaluated using economic techniques such as the human capital approach [8], a well established method derived from the insurance industry [72] [73]. A similar approach is recommended for infrastructure lines in *Zischg* et al. [74] based on earlier works by *Wilhelm* [9]. Hence, the damage potential is monetised and can be further processed with respect to the risk equation (Equation 1). Therefore, information on the vulnerability of values at risk is necessary.

4 Vulnerability analysis

The term vulnerability is closely related to the consequences of natural hazards, and is used in hazard and disaster management in a large number of ways. These consequences are generally measured in terms of damage or losses, either on an ordinal scale based on social values or perceptions and evaluations, or on a metric scale (e.g., as monetary unit). Consequently, two diverse perspectives on the concept of vulnerability exist:
– The perspective from social sciences and
– The perspective from natural sciences.

Focussing on the latter, and thus neglecting any social implications arising from hazards, vulnerability is usually considered as a function of a given process intensity towards physical structures. Therefore, vulnerability is related to the susceptibility of elements at risk, and is defined as the expected degree of loss for an element at risk as a consequence of a certain event [75]. Consequently, vulnerability values range from 0 (no damage) to 1 (complete destruction). Its assessment involves usually the evaluation of several different parameters and factors such as building materials and techniques, state of maintenance, presence of protection structures, presence of warning systems and so on. On the impact side, empirical process parameters such as the intensity have to be analysed based on theories of probability, which is usually undertaken by mapping the geomorphologic disposition and the extent of previous events, and by modelling (defined design) events.

Even if the latter perspective on vulnerability had been subject to extensive research and practical application for the last decades, considerable gaps still exist with respect to standardised equations allowing for a wider application of technical vulnerability assessments [76]. This has to be attributed to the overall lack of data, in particular concerning losses caused by alpine natural hazards, which is often a result of missing empirical quantification. Recently, promising approaches for a quantification of vulnerability have been made with respect to avalanches and rock fall processes, respectively [9] [21] [77]. However, sound suggestions for landslides and torrent processes are still outstanding, even if these processes caused major losses worldwide as well as in European mountain regions in recent years. An overview concerning the current state of the art in vulnerability assessment for landslide risk focussing on torrent processes is

Table 4. Compilation of suggestions related to the assessment of vulnerability of buildings with respect to torrent processes (modified from [78])
Tabelle 4. Zusammenstellung qualitativer und (semi-)quantitativer Vorschläge zur Bewertung der Verletzlichkeit von Gebäuden gegenüber Wildbachprozessen (verändert nach [78])

			Intensity							
			qualitative				(semi-)quantitative			
			Low	medium	high	very high	low	medium	high	very high
			not specified	not specified	not specified	not specified	not specified	h < 1 m or v < 1 m/s	h > 1 m and v > 1 m/s	not specified
Vulnerability	qualitative	[79, 80]	not linked to process intensity							
		[81]	superficial	functional	structural	structural				
	quantitative	[82]	0.1	0.4	0.7	1.0				
		[83]	0.1 (distal)		1.0 (proximal)					
		[84]	0.1	0.2	0.5	not specified				
		[85]	not specified	0.1 – 0.2	0.5	not specified				
		[21]					not specified	0.1	0.5	not specified

provided by *Fuchs* et al. [78]. As a consequence of research design, individual approaches vary significantly in scale and resulting numerical values (Table 4). Although vulnerability analysis is part of the consequence evaluation during a risk assessment procedure, many approaches do neither specify the type of process they are applicable to (e.g., "landslides", debris flows, hyperconcentrated flows), nor the physical mechanisms (e.g., travel distance) or the structural resistance of elements at risk. In particular, information on process intensities is often missing and therefore a valuation is only carried out semi-quantitatively. Thus, neither a unique method nor an overall applicable vulnerability function is currently available for the assessment of landslide risk, and in particular with respect to torrent processes or debris flows.

Recently, case studies aiming to obtain a vulnerability function for debris flows were carried out [78] [85]. The relationship between debris flow intensity and vulnerability of buildings was found to fit best to the data by a second order polynomial function for all intensities $0.33 \leq x \leq 3.06$ m:

$$f_{(x)} = \begin{cases} 0 \text{ if } x < 0.\overline{3} \\ 0.12x^2 - 0.04x \text{ if } 0.\overline{3} \leq x \leq 3.06 \\ 1 \text{ if } x > 3.06 \end{cases} \qquad (2)$$

However, for a wider application of this function more data is needed for validation. By definition, vulnerability ranges from 0 and 1. Consequently, for process intensities higher than approximately 3 m, vulnerability cannot be satisfyingly mirrored by such a polynomial. On the other hand, such high process intensities generally result in a total loss of the building since the arising efforts to repair the damage will exceed the expenditures necessary for a completely new construction.

5 Conclusion

Risk analysis is a method to estimate and assess the impact of a hazard to a given environmental setting. Having analysed the relevant hazard scenarios, the elements at risk exposed and the associated vulnerability, risk analyses can be carried out by means of Equation 1 using GIS. Risk analyses for debris flows are usually carried out on a regional or a local scale. Results from the former will provide an efficient overview on the situation in the study area. If necessary, a detailed analysis on the local scale can be carried out based on individually analysed object values.

Depending on the scale, risk is either obtained by applying average values per area during the sets of calculation, or calculated in a spatially more explicit manner only for endangered objects. Since average values per area are based on empirical assumptions, field studies are not necessarily required. The result will provide an overview on the risk situation for a larger region, e.g., a valley. If risk analysis will be carried out spatially explicit, there is a need for precise and accurate data acquisition and analysis. The quantification will result in quantitative risk for individual objects, and is therefore suitable for larger scales, e.g. individual torrent fans.

In doing so, either the cumulative risk or the individual risk can be analysed both, from a comprehensive point of view related to the studied scenario and in terms of annual risk. The analysis of cumulative risk includes all elements at risk exposed to the hazard scenario, and is obtained by summing up all values achieved for every element located in the endangered area. The results will usually be given in monetary terms or in number of persons at risk. The individual risk is usually based on the number of individual persons being present in endangered areas, and is obtained by dividing the cumulative risk by the number of persons.

It had been shown in recent studies that temporal changes of risk levels in European mountain regions are considerable both, on a long-term and on a short-term scale [86]. These changes result from the dynamics in every individual factor to be considered during the risk assessment procedure, i.e., the probability of occurrence of the hazardous process, the values at risk and the vulnerability. Apart from the question of what level of loss to expect, vulnerability tends to be a dynamic concept in relation to the perpetual duality between efforts to reduce or mitigate risks and human actions that create risks or increase their levels [87]. Viewed in terms of risk management, vulnerability of socio-economic systems to torrent events is a function of the costs and benefits of inhabiting mountain regions mediated by decisions taken on the basis of risk perception. As torrent risk is fundamentally a product of hazard, vulnerability and elements at risk, risk management issues from the point of view of social sciences and natural sciences should be combined for an efficient risk reduction. Hence, mechanisms of (intuitive or institutional) decision-making processes and functional relationships between individual factors have to be jointly combined for a sustainable risk management.

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