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Mountain torrents: Quantifying vulnerability and assessing uncertainties

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ABSTRACT

Vulnerability assessment for elements at risk is an important component in the framework of risk assessment. The vulnerability of buildings affected by torrent processes can be quantified by vulnerability functions that express a mathematical relationship between the degree of loss of individual elements at risk and the intensity of the impacting process. Based on data from the Austrian Alps, we extended a vulnerability curve for residential buildings affected by fluvial sediment transport processes to other torrent processes and other building types. With respect to this goal to merge different data based on different processes and building types, several statistical tests were conducted. The calculation of vulnerability functions was based on a nonlinear regression approach applying cumulative distribution functions. The results suggest that there is no need to distinguish between different sediment-laden torrent processes when assessing vulnerability of residential buildings towards torrent processes. The final vulnerability functions were further validated with data from the Italian Alps and different vulnerability functions presented in the literature. This comparison showed the wider applicability of the derived vulnerability functions. The uncertainty inherent to regression functions was quantified by the calculation of confidence bands. The derived vulnerability functions may be applied within the framework of risk management for mountain hazards within the European Alps. The method is transferable to other mountain regions if the input data needed are available.

1. Introduction

Natural hazards, such as snow avalanches, landslides and torrent processes, pose a threat to the urban development and infrastructure in mountain areas. The adverse effects associated with these hazards may increase due to the continued socio-economic development in some mountain regions and the possible influence of climate change on the frequency and magnitude of the hydro-geomorphic processes (Cendrero et al., 2006; Jakob and Lambert, 2009; Keiler et al., 2010). For decades, geohazard assessments focused on the hazard potential of mass movements and corresponding mitigation strategies (Merz, 2006; Holub and Fuchs, 2009). This evolved into a risk-based approach (e.g., Kienholz et al., 2004). The concept of risk represents a possibility to address mountain hazards and their potential consequences based on a common framework, normally referred to as risk or disaster management (Carter, 1992; Alexander, 2000; Kienholz et al., 2004). Vulnerability assessment for elements at risk (e.g., buildings located on torrent fans) is an important component in this risk-based approach (Uzielli et al., 2008; Fuchs, 2009; Fuchs et al., 2012). Vulnerability is thereby defined as the degree of loss of a given element at risk as a result from the occurrence of a natural phenomenon of a given intensity, ranging between 0 (no damage) and 1 (total loss) (UNDRO, 1979; Fell et al., 2008). Several methods to assess vulnerability have been proposed, and these assessment methods can be qualitative, semi-quantitative, or quantitative (Fuchs et al., 2011). With respect to mountain hazards, the quantification of vulnerability through the development and application of respective functional relationships has emerged within the previous two decades. These functions express a mathematical relationship between the intensity of the process and the degree of loss of the elements at risk. They are referred to either as vulnerability function (e.g., Fuchs et al., 2007a), vulnerability curve (e.g., Barbolini et al., 2004), damage function (e.g., FEMA, 2007) or fragility curve (e.g., Tsao et al., 2010). Fragility curves, however, generally relate the intensity of the process to the probability of exceeding certain damage states or, in the case of protection measures, states of failure (Merz, 2006; Schultz et al., 2010).

In this section, we summarise the different approaches dealing with vulnerability functions for torrent processes in chronological order.

Borter (1999a) reported a comprehensive approach for risk analyses focussing mainly on gravitational mass movements in the European Alps. Vulnerability functions were presented in this study for snow avalanches and rock fall processes (Borter, 1999b). With respect to floods and debris flows, however, vulnerability values were only given in tabular form for three classes (low, medium, high process intensity).

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The intensity parameters were quantified according to BWW (1997): the flood intensity was given as a combination between flow depth and flow velocity times flow depth and the debris flow intensity was given as a combination between deposition depth and flow velocity (Table 1).

Romang (2004) compiled a study on the effectiveness and costs of torrent mitigation measures in Switzerland. Flooding with an undefined amount of transported sediment was the considered process. Vulnerability data were based on the ratio between losses incurred and the reinstatement values of buildings at risk in order to calculate the degree of loss of buildings exposed to torrent processes. The respective data were provided by the building insurer.[1] Due to the considerable range in the vulnerability data, Romang (2004) concluded that a vulnerability function was not deducible and therefore, only mean vulnerability values for certain process intensity classes were presented. These intensity classes were defined according to the Swiss guidelines (Table 1).

Fuchs et al. (2007a) presented a vulnerability function for debris flows based on the analyses of an event in the Austrian Alps. Due to missing information on flow velocities, the deposition depth was taken as a proxy for the process intensity. Deposition depth directly adjacent to the damaged buildings was assessed during a field campaign following the incident and classified in steps of 0.5 m. The degree of loss was calculated as the ratio between monetary damage and reconstruction value for each building which included brick masonry and concrete residential buildings. The losses were collected using information from the federal authorities. Since in Austria an obligatory building insurance against losses from natural hazards is not available so far, property losses are partly covered by a governmental fund.[2] Consequently, these losses were collected on an object level immediately after an event by professional judges. The reconstruction values were calculated using the volume of the buildings and averaged prices (€/m^3) according to the type of building. The resulting vulnerability curve was expressed by a second order polynomial function. Although based on a limited number of data points, Fuchs et al. (2007a) demonstrated the general applicability of such an approach to torrent processes.

Akbas et al. (2009) applied the approach outlined by Fuchs et al. (2007a) to a debris flow event in the Italian Alps. Deposition depth as the intensity parameter and the degree of loss were derived similarly, and information regarding eleven damaged and two destroyed buildings was used to develop a vulnerability function as a second order polynomial function. Compared to the vulnerability function of Fuchs et al. (2007a), the vulnerability function obtained in Akbas et al. (2009) showed a similar shape but a higher degree of loss. Overall, the vulnerability values derived by Fuchs et al. (2007a) were approximately 35% smaller than the ones derived by Akbas et al. (2009). The limited number of data points, however, precludes a robust statement regarding the uncertainties. Possible explanations could be differences in process characteristics and construction techniques or the inherent range of the applied method (Akbas et al., 2009).

Table 1
Classification of intensity parameters according to BWW (1997) based on flow depth d_f (m), deposition depth d_d (m) and flow velocity v_f (m/s).

Intensity class	Flood	Debris flow
low	$d_f<0.5$ or $v_f \cdot d_f<0.5$	Not assessed
medium	$2>d_f>0.5$ or $2>v_f \cdot d_f>0.5$	$d_d<1$ or $v_f<1$
high	$d_f>2$ or $v_f \cdot d_f>2$	$d_d>1$ and $v_f>1$

Calvo and Savi (2009) applied vulnerability functions within a debris flow risk assessment. Three different vulnerability functions were tested in this study: a) a vulnerability function for flood waves using flow depth as intensity parameter, b) a vulnerability function for avalanches based on impact pressure, and c) a vulnerability relationship developed by Faella and Nigro (2001a,b) for debris flows, taking into account both hydrostatic and hydrodynamic forces. The latter is based on a combination of flow depth and flow velocity as intensity parameter. The debris flow hazard was computed using a Monte Carlo procedure. Calvo and Savi (2009) concluded that the vulnerability function developed for debris flows yielded the most reliable results. However, the main source of uncertainty in their debris flow risk assessment approach was the vulnerability assessment (Calvo and Savi, 2009).

Tsao et al. (2010) presented a debris flow risk estimation approach for Taiwan (Republic of China). For brick masonry and concrete buildings they used the vulnerability function presented in Fuchs et al. (2007a). A second vulnerability function was derived for wooden and sheet-metal buildings which represent a common construction type in Taiwan. As debris flows may damage the interior of a building, Tsao et al. (2010) recommended the use of an individual vulnerability curve for home interiors.

As outlined by Fuchs et al. (2007a), the second order polynomial functions used in these approaches have to be limited to an upper and lower threshold as they yield economic gains for very small process intensities and a degree of loss > 1 for high process intensities. To overcome these shortcomings, Totschnig et al. (2011) modified the approach by taking three torrent events characterised by fluvial sediment transport processes as an example. Instead of a second order polynomial function, cumulative distribution functions were used which define the degree of loss as a dependent variable in a confined interval between 0 and 1. In a first step, deposition depth was used as the intensity parameter to characterise the hazard process. A so-called relative intensity was further introduced to consider the influence of different building heights (different number of storeys) on the degree of loss. This relative intensity was defined as a normalised parameter composed from a ratio between the deposition depth and the height of the affected building. The individual analysis of both intensity parameters had shown that the application of a relative intensity parameter improves the calculation.

Quan Luna et al. (2011) applied a numerical debris flow model to derive vulnerability functions. The vulnerability values derived by Akbas et al. (2009) were related to different intensity parameters using the software FLO-2D. Accumulation height, impact pressure, and kinematic viscosity were back-calculated as intensity parameters for each individual building on the torrent fan. The proposed vulnerability

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[1] In Switzerland, 19 of 26 cantons conduct a mandatory insurance system for buildings, underwriting natural hazards damage unlimited until the legally certified reinstatement values of the buildings (Fuchs et al., 2007b). Those insurers are organised as independent public corporations based on cantonal law, and cover approximately 80% of all Swiss buildings with an insured value of around € 1.2 billion. Within the individual canton, each insurer operates as a monopolist regulated by public law. Apart from the insurance policies, the business segments include loss prevention and risk management. In this context, cantonal insurers perform a sovereign function, consulting municipalities in all concerns on building permits and spatial planning activities.

[2] In Austria, natural hazards are not subject to compulsory insurance. Apart from the inclusion of losses resulting from hail, pressure due to snow load, rock fall and sliding processes in an optional storm damage insurance, no standardised product is currently available on the national insurance market. Moreover, the terms of business of this storm damage insurance explicitly exclude coverage of damage due to avalanches, floods and inundation, debris flows, earthquakes and similar extraordinary natural events (Holub et al., 2011). Furthermore, according to the constitution of the Republic of Austria, catastrophes resulting from natural hazards do not fall under the national jurisdiction. Thus, the responsibility for an aid to repair damage resulting from natural hazards generally rests with the Federal States. However, the Austrian government enacted a law for financial support of the Federal States in case of extraordinary losses due to natural hazards in the aftermath of the avalanche winter in 1951. The so-called 'law related to the catastrophe fund' (Katastrophenfondsgesetz) is the legal basis for the provision of national resources for (a) preventive actions to construct and maintain torrent and avalanche control measures, and (b) financial aids for the Federal States to enable them to compensate individuals and private enterprises for losses due to natural hazards in Austria. The budget of the catastrophe fund originates from a defined percentage (since 1996: 1.1%) of the federal share on the income taxes, capital gains taxes, and corporation taxes. The annually prescribed maximum reserves amount to € 29 million (Republik Österreich, 1996).