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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.

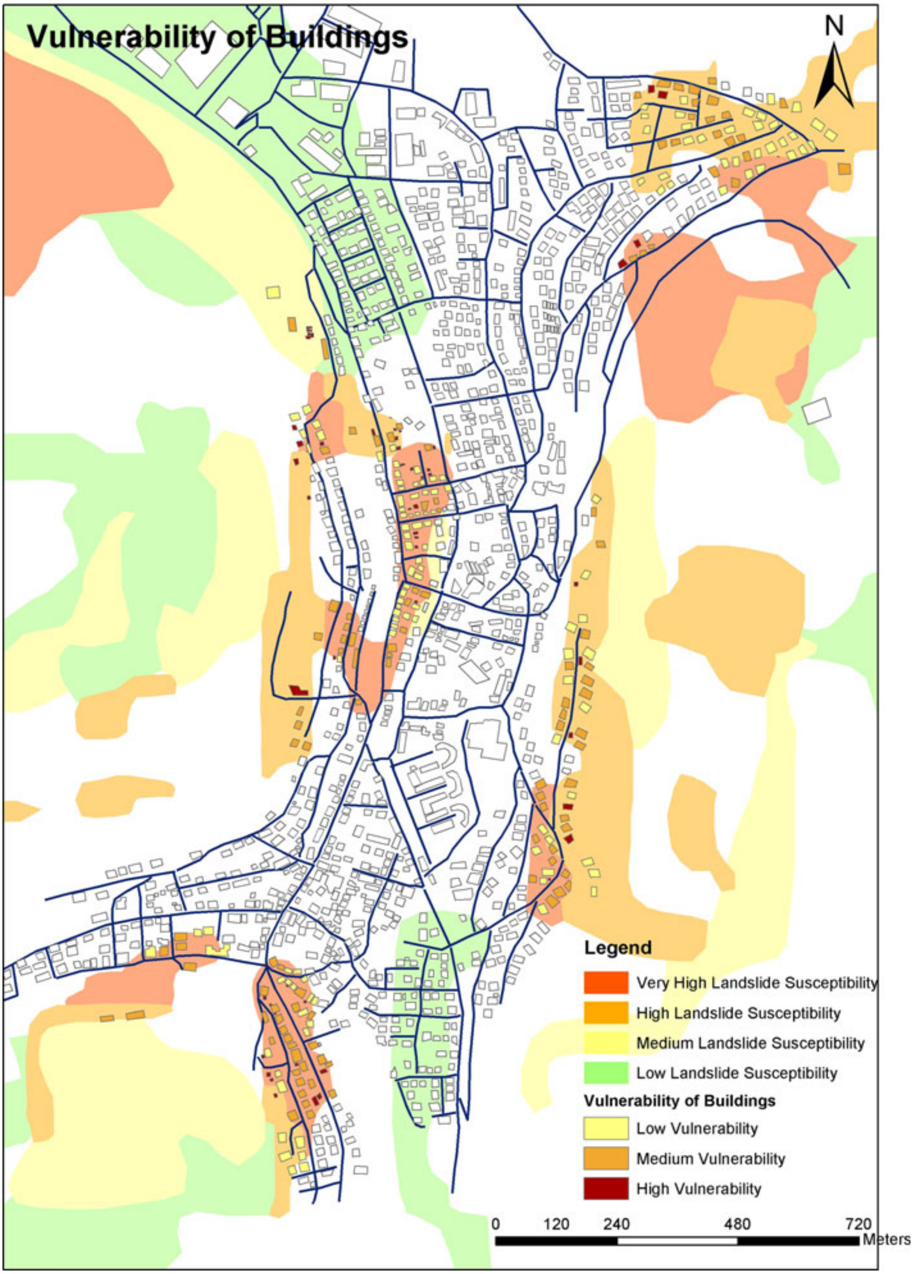

Fig. 1 Map showing the landslide susceptible areas of Lichtenstein (Germany) and the vulnerability of the buildings that are found within them (Papathoma-Köhle et al. 2007)

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).

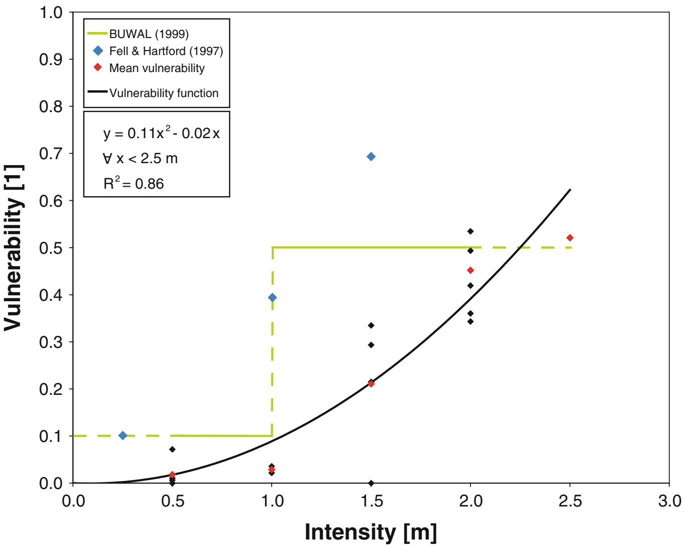

Fig. 2 The generalised relationship between debris flow intensity and vulnerability is represented by the black curve (refer to Fuchs et al. 2007). Mean vulnerability values published by BUWAL (1999b) and Fell and Hartford (1997) (refer to *green line* and *blue dots*, respectively)

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;

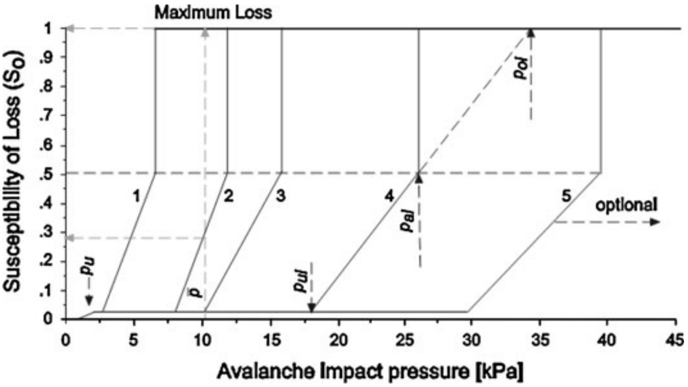

Fig. 3 The relationship between the avalanche impact pressure and the vulnerability of the buildings (expressed here as the susceptibility of loss) is determined for 5 building types: (1): lightweight construction, (2): mixed construction, (3): massive construction, (4): concrete reinforced construction, (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.

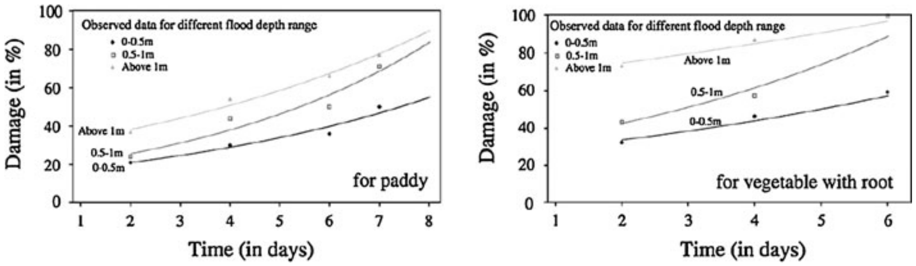

Fig. 4 Stage-damage curves for agriculture product damage estimation (Dutta et al. 2003)

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

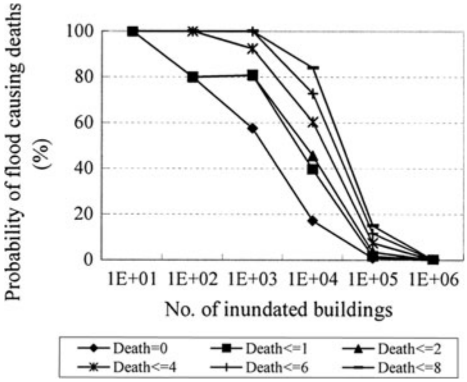

Fig. 5 Probability of a flood causing a certain number of deaths versus the number of inundated buildings (Zhai et al. 2006)

- 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

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