ORIGINAL PAPER

Improvement of vulnerability curves using data from extreme events: debris flow event in South Tyrol

M. Papathoma-Köhle · M. Keiler · R. Totschnig · T. Glade

Abstract   Alpine hazards such as debris flow, floods, snow avalanches, rock falls, and landslides pose a significant threat to local communities. The assessment of the vulnerability of the built environment to these hazards in the context of risk analysis is a topic that is growing in importance due to global environmental change impacts as well as socio-economic changes. Hence, the vulnerability is essential for the development of efficient risk reduction strategies. In this contribution, a methodology for the development of a vulnerability curve as a function of the intensity of the process and the degree of loss is presented. After some modifications, this methodology can also be used for other types of hazards in the future. The curve can be a valuable tool in the hands of local authorities, emergency and disaster planners since it can assist decision making and cost–benefit analysis of structural protection measures by assessing the potential cost of future events. The developed methodology is applied in two villages (Gand and Ennewasser) located in Martell valley, South Tyrol, Italy. In the case study area, buildings and infrastructure suffered significant damages following a debris flow event in August 1987. The event caused extensive damage and was very well documented. The documented data were used to create a vulnerability curve that shows the degree of loss corresponding to different process intensities. The resulting curve can be later used in order to assess the potential economic loss of future events. Although the validation process demonstrated the reliability of the results, a new damage assessment documentation is being recommended and presented. This documentation might improve the quality of the data and the reliability of the curve. The presented research has been developed in the European FP7 project MOVE (Methods for the Improvement of Vulnerability Assessment in Europe).

M. Papathoma-Köhle (✉) · T. Glade
Department of Geography and Regional Research, University of Vienna, Universitätsstr. 7,
1010 Vienna, Austria
e-mail: maria.papathoma@gmail.com

M. Keiler
Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland

R. Totschnig
Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences,
Peter Jordan Str. 82, 1190 Vienna, Austria

1 Introduction

Alpine hazards such as floods, shallow and deep-seated landslides, debris flows, rock falls, and snow avalanches can cause significant damage to alpine communities. This includes loss of life, damage of buildings and infrastructure, loss of agricultural land and economic disruption as well as disruption of communication and transport lines that can additionally cause high indirect costs. Risk reduction strategies can focus on hazard reduction whenever possible or on the reduction of vulnerability of the elements at risk. The assessment of the vulnerability of the built environment is a topic which is growing in importance due to climate and global change. On one hand, according to the Intergovernmental Panel on Climate Change (IPCC) Working Group I (2007), the frequency and magnitude of some hazards such as heat waves, droughts, floods, etc. are expected to increase due to climate change. Furthermore, the highlighted changes of frequency/magnitude of extreme events are superimposed on long-term changes of processes conditions and resulting effects from interactions between different hazard processes (Keiler et al. 2010). On the other hand, it is understood that development, socio-economic setting, and land cover in mountain areas are also constantly changing (e.g., Fuchs et al. 2005; Hufschmidt et al. 2005; Keiler 2004; Keiler et al. 2005). Consequently, the vulnerability of the elements at risk is a dynamic factor (Keiler et al. 2006a; Hufschmidt and Glade 2010) that has to be considered for the risk reduction strategies especially at local scale to minimize the consequences of natural hazards in the affected communities. Decision makers are in need of tools that will enable them to assess the vulnerability of the elements at risk, to develop an overview of possible consequences and monetary losses and to conduct cost–benefit analysis for optimizing structural protection measures against the respective hazardous processes. However, cost–benefit analysis would require a quantification of all impacts of an event that is not always possible. In this case, decision makers would need tools in order to conduct cost-effectiveness analysis (Ganderton 2005).

The aim of the present study is to create a vulnerability curve for debris flow events using data from the impact of previous events in order to be able to assess more precisely the costs of future events. The vulnerability curve contributes to the highlighted challenges by improved information and estimation management, and finally to the reduction of risk. The presented methodology for developing vulnerability curves can be used for a number of alpine hazards such as snow avalanches, floods, and landslides; however, in the present contribution, the methodology is being tested for debris flows and related processes only. Hereby, debris flows are defined as rapid gravity-induced landslides 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 landslides do, but they also enter often the building through doors or windows and damage its interior (Holub and Fuchs 2009). The presented vulnerability curve has been developed using only photographic documentation of previous events; therefore, the methodology for its development is transferable to other places in the world where information regarding the consequences of past events are limited.

The following section provides a brief overview on vulnerability and vulnerability curves, specifically. This is followed by the description of the general concept of the multi-step procedure and the deduction of the required information. Furthermore, the uncertainties involved in the methodological steps to deduce a vulnerability curve are recognized and discussed. The section describing the application of the developed approach in South Tyrol presents the resulting vulnerability curve and its validation. Additionally, a comparison of the resulting curve with existing vulnerability curves developed for debris flow is presented. Within the discussion section, possible applications of the methodology and limitations are discussed followed by the outlook section where further improvements are suggested such as a new documentation form for damage assessment which would improve the vulnerability curve. Finally, the main results and conclusion drawn from this study are pointed out.

2 Vulnerability and vulnerability curves

There is an ongoing debate regarding the definition of vulnerability. Scientists with various scientific backgrounds have a different understanding of what vulnerability is (Hufschmidt 2011). For natural scientists and engineers, vulnerability is often described as the degree of loss to an element at risk (UNDRO 1984). In contrast, social scientists focus more on the characteristics of the society rather than the built environment. Hereby, vulnerability is "… the characteristics of a person or a group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard." (Wisner et al. 2004). In a review of existing vulnerability assessment methodologies for alpine hazards (landslides, rock falls, debris flows, and snow avalanches), Papathoma Köhle et al. (2011) suggest that there is neither a common definition for vulnerability nor a standard methodology for vulnerability assessment (refer also to Hufschmidt and Glade 2010). However, the different dimensions of vulnerability such as physical (structural), social, economic, or institutional vulnerability, although maybe differently defined, are connected to each other. Structural or physical vulnerability is hereby seen as a prerequisite or starting point, resulting in physical loss and may influence the other dimensions of vulnerability (Fuchs 2009). Natural scientists define vulnerability mainly 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). Nevertheless, the authors of the present paper believe that vulnerability should not be reduced to the degree of damage but it should also be considered a pre-existing condition of an element that is related to its characteristics and properties that increase its susceptibility to the impact of hazards (Papathoma Köhle et al. 2011). Vulnerability actually expresses the propensity of exposed elements (people and their livelihoods) to suffer damage and loss when impacted by hazardous events (Birkmann 2006; Wisner et al. 2004; Thywissen 2006; IPCC 2007). Consequently, vulnerability assessment should focus on the identification of these characteristics that contribute to the vulnerability of the elements at risk, the vulnerability indicators (Birkmann 2006). However, this is barely the case with physical vulnerability assessment. The reason why physical vulnerability is not adequately modeled is the lack of data regarding the hazard and its consequences on the elements at risk, the complexity of the structural damage mechanisms and the difficulties that are posed due to different temporal and geographical scales (Douglas 2007). Additionally, according to Douglas (2007), the fact that efforts and data collection are focused often on the human casualties due to the event itself and not the damaged buildings might also play a significant role. Finally, the possibility to modify the

hazard level in order to reduce risk (e.g., with structural protection measures) might also be one of the reasons for the poor modeling of the physical vulnerability (Douglas 2007).

Papathoma Köhle et al. (2011) recorded a range of methodologies by reviewing 41 vulnerability assessment methodologies for alpine hazards. Most of them took into consideration only one vulnerability indicator which was mostly the building type (for a further discussion cf. Kappes et al. 2012). Scientists often develop vulnerability curves, in other words, functions that express the relationship between the degree of loss and the intensity of the process. In some cases, the degree of loss is expressed as monetary loss as relation to reconstruction costs (e.g., Keylock and Barbolini 2001; Barbolini et al. 2004; Romang 2004; Fuchs et al. 2007; Cappabianca et al. 2008; Totschnig et al. 2011) and in others as damages (esthetic, functional, structural, etc.; refer to e.g., Corominas et al. 2005; Sterlacchini et al. 2007; Mavrouli and Corominas 2008). In the literature, there are more studies developing vulnerability curves for debris flows than for landslides and avalanches; however, their number is limited in comparison with studies developing vulnerability curves for other hazard types such as earthquakes or floods (Douglas 2007; Fuchs et al. 2007). However, there are some studies that focus on the development of vulnerability curves for debris flow such as BUWAL (1999), Romang (2004), Fuchs et al. (2007), Akbas et al. (2009), Tsao et al. (2010) and Quan Luna et al. (2011) in case studies in Switzerland, Austria, Italy, and Taiwan, respectively. In the majority of the studies, debris flow intensity was expressed as deposition height. As far as information regarding the degree of loss is concerned, in most of these studies, the development of the curve was based on data provided by local authorities or insurance companies.

Different approaches are based on general assumptions and concentrate on some essential parameters. Therefore, each approach exhibits advantages and disadvantages. The vulnerability curves are usually developed for a specific construction type that is common in the study area. The disadvantage of the vulnerability curves is that they do not consider different characteristics of the buildings such as number of floors, material, condition, or size. The building height, a similar parameter as the number of floors, was only recently included in a study (Totschnig et al. 2011). However, even if we consider vulnerability to be influenced by a range of indicators (characteristics of the element at risk), vulnerability curves provide valuable information (1) concerning the economic loss related to different intensity scenarios and (2) for the cost–benefit analysis of structural protection measures (Fuchs and McAlpin 2005). A second disadvantage can be considered the diverse expression used to describe the intensity parameter, which makes vulnerability curves difficult to compare. Consequently, this also means that only one characteristic of the process is taking into account, whereas other properties are ignored. In the case of debris flows, on the one hand, Fuchs et al. (2007) stress that the intensity of the debris flow is often expressed as deposition height whereas properties such as the flow velocity are not considered. On the other hand, Quan Luna et al. (2011) developed multiple vulnerability curves for debris flows expressing the intensity not only as deposit height but also as impact pressure and kinematic viscosity. Information regarding the intensity of the event was obtained through the back-modeling of an event.

Nevertheless, vulnerability curves provide an approximation regarding the way an element may react under different process intensities (no matter how these are defined). Also, information regarding the thresholds in process intensity may be deduced from vulnerability curves indicating where measures could most efficiently be implemented. Therefore, vulnerability curves remain a valuable tool in the hands of decision makers and planners that should be further developed, improved, and used.

In order to develop approved vulnerability curves for buildings, information regarding a significant amount of buildings is needed. Consequently, vulnerability curves for hazards that affect a small amount of buildings (e.g., rock fall) are difficult to develop, whereas for other hazards, such as floods and earthquakes, the required information is available since a larger number of buildings is involved which also increases the reliability of the resulting curve (Douglas 2007; Kappes et al. 2012). In the case of debris flows, a significant amount of buildings can be affected but often the post-event damage assessment does not provide detailed information regarding the condition of a building following an event or the cost of its reconstruction. Limited information is also available regarding the intensity of the process on individual buildings due to inadequate damage assessment documentation. However, information regarding the intensity of the process can be acquired later by modeling the event.

3 Methodology

The methodological steps followed in the presented study are shown in Fig. 1. The methodology is transferable to other types of hazards and elements at risk. However, the applicability of this method is tested for debris flows and buildings in the present paper. For this reason, the following paragraphs are focused on debris flow as far as the intensity of the process and its consequences are concerned.
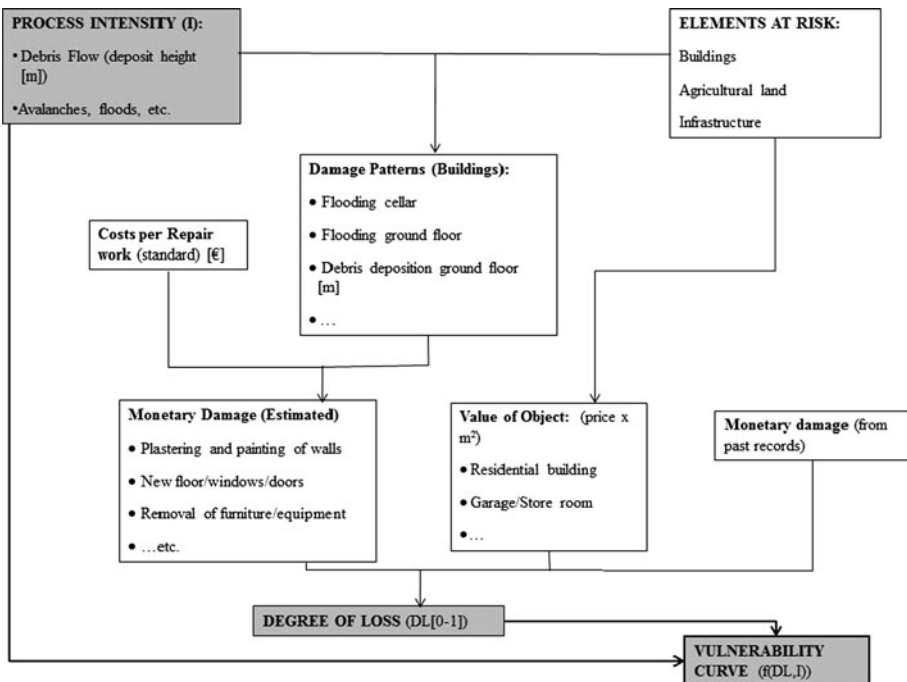
Fig. 1 Methodological steps for deriving a vulnerability curve including the main interacting parameters: process intensity and degree of loss. To deduce these parameters several sub-procedures are necessary for evaluation considering different aspects such as elements at risk and their value, damage pattern, cost of repair work and monetary damage

The vulnerability curve is a function of the intensity of the process and the degree of loss. Information regarding the intensity of the process can be acquired from detailed damage and process documentation of past events, interviews, or modeling of the process. In case of lack of other sources of information, photographic documentation of the consequences of the event can provide valuable information. In more detail, using photographic documentation, it is possible:

- to assess the intensity of the debris flow on each building by estimating the height of the deposits and
- to assess the degree of loss by analyzing the process impact to the building.

3.1 Intensity assessment

The assessment of the intensity of the debris flow has been done on the basis of the deposition height. However, more parameters, such as velocity or pressure, play also a very important role and are commonly assessed by modeling analysis because real measurements of these parameters are mostly not available from the event records. Nevertheless, due to lack of other field data, the intensity is assessed on the basis of the debris height in the present study. The height of the maximum debris and water flow can be assessed from the indicated marks on the building walls in relation to the building height and average height of the floors (e.g., according to Kaswalder 2009, the average height of a room in South Tyrol is 2.60 m). In some cases, the debris has entered the building or even destroyed parts of it. The intensity of the process on the specific building is deduced by analyzing the deposit height from different perspective on the damaged buildings.

3.2 Degree of loss assessment

The degree of loss is expressed as the percentage of the value of the building that was lost due to the impact of the process. Thus, this requires evaluating the impact on the building in form of damaging costs, which are often not recorded after an event, as well as the building values. The value of the building is estimated by the reconstruction value (= "standard prices"/m^2) after the event for different building types and functions as they are also used for insurances purposes (cf. e.g., Keiler 2004). In the presented case study, the "standard price" refers to compensation information that was provided by the municipality of Martell, South Tyrol. During the reconstruction phase, local authorities use standard prices per m^2 in order to compensate owners of completely destroyed buildings which have to be rebuilt. For this study, data for the elements at risk (building use, size and photos) and reconstruction values were provided by local authorities (Province of South Tyrol and Municipality of Martell). The values were combined and adapted for the basement and the attic of each building from the Austrian prices transferred from Keiler (2004) and Keiler et al. (2006a, b) (Table 1). The "reconstruction values" refer to the building itself and not to any furniture, special features or other content of the building prior to the damage.

However, evaluating the damage costs resulting from the impact of debris flows on the buildings is a challenging process consisting of several sub-steps, which will be discussed in the following paragraphs in detail.

After an event, the initial aim of the building owners and the local authorities is commonly to restore the buildings to their initial state. Following the outlined method in Fig. 1, a first step is to assess the damage pattern per building, in other words, the impact of

Table 1 Unit values of different building sections per m² building area for the calculation of the building value

Building section	Value (€/m²)	Source
Living area	1,153	DDC
Attic (not used as living area)	294	Modified from Keiler (2004) and Keiler et al. (2006a, b)
Attic (used as living area)	1,153/2 + 294/2	DDC, modified after Keiler (2004) and Keiler et al. (2006a, b)
Basement/garage	576	Modified from Keiler (2004) and Keiler et al. (2006a, b)

The value of the attic used as a living area is divided by 2 because the habitable area is reduced due to inclination of the ceilings

DDC Department of Domestic Construction of the Autonomous Province of Bozen/Bolzano—South Tyrol

the process on the individual structures needs to be described in detail using standardized characteristics. The impact may include flooding of the basement, flooding of the first floor, destruction of walls, material deposition in the basement or/and ground floor, breaking of doors and windows, material deposition in the garden, etc. Subsequently, the resulting damage of the impact has to be translated into repair works and their costs. For example, the "deposit of material and water in the basement" refers to removal of the material, removal of furniture or equipment, drying, cleaning, re-plastering the inner walls and painting of the inside walls, and possibly the installation of new doors or floors. In some cases, it is necessary to test or even reinstall the electricity, heating and sewage network. In our case, testing and reinstallation costs were considered for buildings where the ground floor was severely damaged (water and debris in the ground floor). As far as the outside of the building is concerned, apart from the outer wall that might need to be re-plastered and painted, auxiliary buildings such as garages or storerooms might have been affected, as well as the garden surrounding the building. In the literature, there are different reports listing these costs per square meter or per hours of work, each one taking into consideration different aspects of the reconstruction process (Stoll 2004; Kaswalder 2009; Autonome Provinz Bozen 2010).

In the present study on South Tyrol, the local report from Kaswalder (2009) was used. He assessed the potential economic loss following a flood event in the area between Bruneck and St. Lorenzen in South Tyrol. The report distinguishes the following categories of buildings: residential buildings, public buildings and sport facilities, industrial buildings and buildings related to religion (e.g., churches and cemeteries). For all these building categories, Kaswalder (2009) lists the reparation works for three scenarios according to the water height of the flood (<0.5, 0.5–2.5 and >2.5 m) and suggests that for intensities more than 2.5 m, the building will have to be entirely rebuilt (degree of loss = 1) (Table 2). For lower water heights, the costs will vary according to the intensity and the consequences of the processes on the building. The intensities proposed by Kaswalder (2009) refer to the three flood scenarios of 30, 100, and 200 return periods. As far as residential buildings are concerned, Kaswalder (2009) based the report on his personal experience with reconstructing buildings damaged by flood. He used as an example a typical South Tyrolean residential building of 100 m² building area and a 40 m² basement in order to provide a "standard list" of the required reconstruction costs for damaged buildings. However, the impact of debris flows on a structure is not always identical to the impact of a river or a flash flood. In some cases, the debris may destroy walls that would need to be rebuilt. For

this reason, the study of Kaswalder (2009) was modified to include also the rebuilding of walls using prices from an official catalogue of fixed base prices for civil engineering operations (Autonome Provinz Bozen 2010) (cf. Table 2).

3.3 Development of a vulnerability curve

After the intensity and the degree of loss have been assessed for every building that has been affected by the process, each building can be represented as a point in a XY coordinate system (x: intensity, y: degree of loss).

Nonlinear regression approaches can be applied to obtain functions, which fit best to the data. The coefficient of determination (R^2) was hereby used as the deciding parameter. Totschnig et al. (2011) recommend cumulative distribution functions, as these distributions fulfill the following important mathematical requirements:

- They define the depending variable (degree of loss) in a both-sided confined interval [0;1].
- They are steady and monotonic increasing within the interval of its explaining variable (intensity).

These requirements are essential for vulnerability functions that should be applicable without any mathematical limitation. A Weibull, Frechet, and Log-Logistic distribution were also tested in this study (refer to Totschnig et al. (2011) for further details). Additionally, a logistic distribution was applied (results are presented in Fig. 4).

Table 2 The prices of repair works following a flood event based on South Tyrol buildings

Repair works	Max. water depth = 0.5 m	Max. water depth 0.5–2.5 m
Disposal and transportation of equipment and furniture	28 €/m³	28 €/m³
Cleaning of rooms and surfaces	65 €/m³ (Removal of material) 6.3 €/m² (cleaning with high-pressure water)	65 €/m³ (Removal of material) 6.3 €/m² (Cleaning with high-pressure water)
Restoration of internal and external doors and windows	Internal door: 480 € Basement door: 150 € Garage door: 320 €	Internal door: 480 € Window: 670 € Entrance door: 670 € Garage door: 320 €
Checking and reinstallation of electrical network	51 €/h (8 h)	51 €/h (16 h)
Checking and reinstallation of heating	Flat rate: 7,250 €	Flat rate: 8,400 €
Checking and reinstallation of sewage system		33 €/h (8 h)
Restoration of floor	82 €/m²	82 €/m²
Internal and external plastering	44 €/m²	44 €/m²
Internal painting and coating	5.7 €/m² (Basement) 11 €/m² (Living area)	5.7 €/m² (Basement) 11 €/m² (Living area)
External painting and coating	5.7 €/m²	5.7 €/m²
Garden	3.5 €/m²	3.5 €/m²
Total (for a South Tyrol standard house)	280.7 €/m²	450.4 €/m²

The total refers to a standard dwelling house in South Tyrol, in case all of the mentioned repair works have to be carried out (Kaswalder 2009). If the water depth exceeds 2.5 m, the building has to be totally rebuilt

3.4 Validation

In order to confirm the reliability and validity of the resulting vulnerability curve, real compensation data were acquired and the 'real' degree of loss could be assessed for some of the buildings. Compensation data of past events have to be indexed to today's values and the currency has to be converted to the currency that is used to calculate the value of the building. As a consequence, the vulnerability curve can be continuously further refined with each additional information on process intensity and related damage, for example, collected during a new damaging event. This will allow the visual comparison between the vulnerability curve based on recent compensation data and the vulnerability curve developed in the earlier stages of the research.

3.5 Methodological steps and uncertainties

The study was carried out in the absence of all necessary data to derive directly vulnerability curves because of a lack of detailed damage documentation. This is a common problem as also expressed in similar studies considering vulnerability related to debris flows (cf. e.g., Douglas 2007; Fuchs et al. 2007; Tsao et al. 2010; Totschnig et al. 2011). Therefore, general assumptions had to be made and a multi-step procedure was developed, which consequently also increases the inherent uncertainty of the results. Uncertainty can be classified into three main types (Zimmermann 1993): First, uncertainty that is based on the lack of knowledge of the future state of a system (e.g., frequency and magnitude of debris flows or changes of build environment). This type of uncertainty is subject to randomness (stochastic uncertainty). In the case of vulnerability assessment, these uncertainties can correspond to, for example, characteristics of buildings (e.g., height) or people living in the area under investigation (e.g., income per capita) (Vinchon et al. 2011). This type of uncertainty cannot be reduced. Second, uncertainty that arises due to lack of information about the system behavior (epistemic uncertainty), for example, consequences of impact by debris flows on a structure (vagueness, ambiguity, fuzziness) and it can be reduced (Zimmermann 1993). Third, uncertainty maybe based on inexactness of measurements (impreciseness, fuzziness). Concerning the development of vulnerability curves from past events, the focus has to be on uncertainties regarding vagueness, ambiguity, fuzziness, and impreciseness.

Although not quantified in this study, possible sources of uncertainty according to the proposed method are highlighted:

- Intensity of the event: The intensity of the event was expressed as the deposition height; however, other characteristics of the process such as velocity, or duration of the water and debris staying inside the building, etc. were not considered. Moreover, the intensity of the process was assessed through photographs that were taken after the event. The marks of the water and debris on the building as well as the extent of the damage may give information regarding the deposit height; however, the quality, the aspect, and the number of photos per building influence the credibility and preciseness of the intensity assessment.
- Damage: The damage pattern was also assessed by using photos. Since the photos often do not show the interior of the building and they are rather limited to external damages, the evaluation of the interior damage pattern was based on defined criteria and assumptions to derive comparable results.

- Costs of reconstruction: This assessment was based on the list of repair costs that was developed for floods rather than debris flows. Modifications were made (wall reconstruction costs) but still there were further assumptions necessary regarding, for example, the costs of testing and reinstallation of electricity, heating and sewage network or the costs of other interior damages which were based to insurance and engineering approaches (Kaswalder 2009) and transferred to the context of this study.
- Value of the building: Uncertainties regarding the value of the building derive from the fact that often the basement size of the building or the use of the attic is unknown. If the attic is used as a living area, then the consequent value of the building is higher.
- Credibility of the existing data: in some cases, buildings that were not severely damaged in the photos received a compensation for total rebuilt. There was no explanation for that in the available data. Either the photos did not show the real extent of the damage or the building should be rebuilt in another location to avoid future damages or provide space for retention areas.

In the following, the proposed methodology is applied to a study region in South Tyrol. This area is described in the following chapter.

4 Case study: the valley of Martell

The case study area is located in the Autonomous Province of Bolzano-South Tyrol, Italy. South Tyrol has been impacted by a range of natural hazards such as snow avalanches, floods, forest fires, and various types of mass movements. The "Office for Geology and Construction Material Testing" and the "Office for Water Protection, Torrent and Avalanche Control" (Department 30) have started the detailed documentation of past and contemporary landslide events (Röhrs and Glade 2010) in the course of the project IFFI (Inventario dei fenomeni franosi in Italia) "Inventory of mass movements in Italy". The event database in this form is a unique product worldwide and it supports the implementation of current and future risk plans (Röhrs and Glade 2010). The Department 30 of the Autonomus Province of Bolzano-South Tyrol maintains a documentation database for floods, debris flows, and erosion processes called ED30 (personal communication with Department 30). Although the landslide events are thoroughly documented, the damages on individual buildings are only generally recorded as "heavy", "average" or "light" damages without any information regarding the initial state and condition of the building, the detailed damages suffered (broken windows, flooded basement, destroyed wall, material in the ground floor etc.) or the costs of its reconstruction. Nevertheless, there is often photographic documentation accompanying the recorded events depicting buildings that have suffered significant damage following an event, hence, without detailed description regarding the damages for each building.

The required data for testing the methodology were allocated by the municipality of Martell. Detailed photos of more than 50 buildings, that have suffered serious damages following an event in Martell valley in August 1987, were provided. The data from Martell valley were used in order to test the methodology and to develop a vulnerability curve for debris flows. Unfortunately, the municipality of Martell did not hold information regarding the exact damages that each building suffered from the 1987 event. The Department of Domestic Construction of the Autonomous Province of Bozen/Bolzano—South Tyrol provided us with information on the compensation that the damaged buildings received in

order to be repaired, or, in cases of very extensive damages, to be rebuilt. Thus, having acquired the compensation data, a validation of the estimated damage was possible. Although there was no description of the damage on each building, the compensation data were sufficient in order to calculate the degree of loss.

4.1 The case study area and the event of 1987

The valley of Martell, a 24-km-long tributary valley to the Vinschgau valley, is one of the numerous alpine valleys of South Tyrol. The main villages comprising the municipality of Martell are Gand (in Italian: Ganda), Ennewasser (Transacqua), Ennetal (Val d'Enne), Meiern and Sonnenberg (Montesole). According to the municipality (Gemeinde Martell 2012), there are approximately 900 inhabitants living in the valley which occupies 143 km^2 in an elevation ranging between 957 and 3,757 m. Although the municipality of Martell stretches through the whole valley, only 2% of the total area is permanent settlement located in the valley floors. The forest area occupies 29.7 km^2 (see Fig. 2). The river Plima drains the valley and changes often into a raging torrent by the confluence of high water and sediment discharge from the tributary streams. In the rear part of the valley, an artificial lake was planned and completed after the Second World War (1957) damming the river and allowing hydro-power production (Regensburger 2006).

The valley of Martell and its inhabitants have often suffered due to the occurrence of catastrophic events such as snow avalanches, floods, and debris flows. There is information on disastrous events, mainly floods from as early as the end of eighteenth century (Pfitscher 1996). Flood events in the valley were often associated with very intense precipitation (e.g., 1772, 1777, 1789) but also with the outburst of glacier lakes such as the event of June 1889 (Pfitscher 1996; Regensburger 2006).

However, one of the most severe debris flow events, that the municipality of Martell has experienced with catastrophic consequences, had a man-made and a natural cause. In August 1987, very intense precipitation raised the water level of the reservoir located in the rear Martell valley. In order to avoid an overflow, the managers of the reservoir opened the water gates and released water in the valley. However, due to a power cut and to limited personnel available that day, the water gates were closed too late after having already allowed a significant amount of water (300–500 m^3) to be released in the valley in the direction of the downstream located settlements (Pfitscher 1996). The high discharge entrained the river bed and caused erosion. The eroded material (rocks, debris, trees, etc.) was transported by the water allowing a range of process types from debris flow to hyper-concentrated flow during the long-lasting event. These processes resulted in massive destruction to the built environment and infrastructure of the valley settlements and villages but also in the loss of the lives of many animals. Fortunately, 220 inhabitants and 80 tourists were evacuated at the last minute. The villages of Gand, Ennewasser, and Latsch suffered most of the damages as far as built environment and infrastructure is concerned. In the village of Gand, many houses suffered great damage and were declared uninhabitable. A few buildings were even completely demolished and swept away. Agricultural and small industrial buildings suffered serious damages and loss of equipment. The critical lifelines such as electricity, telephone, and water network were significantly damaged. Roads were removed or covered with debris. Gardens were filled with mud. Animals, such as goats, chicken, and pigs were swept away. In Ennewasser, the damages were similar to the ones in Gand. In Ennewasser, at least 12 houses suffered heavy damages and others serious damage (Fig. 3). The costs of the natural-man-made event for the municipality of Martell totaled to 7,762,000,000 Italian Lire (Pfitscher 1996), what corresponds approximately to 8.5 million € in indexed 2011 values.
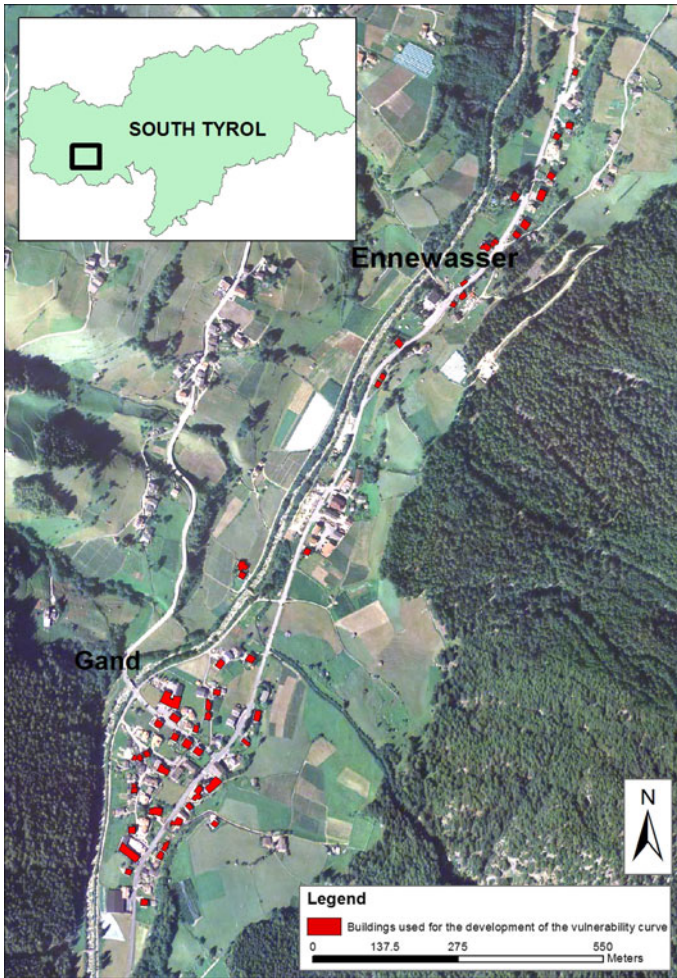
Fig. 2 The case study area: the villages of Gand and Ennewasser in the valley of Martell (*Source*: Autonomous Province of Bozen/Bolzano—South Tyrol)

## 4.2 Application of the methodology: results and validation

The photographic documentation material provided by the municipality of Martell was used in order to assess the damage that the debris flow caused on each of the buildings. First of all, through the impact of the process on each building the intensity was assessed. Following the intensity assessment, the recorded damages of each building were analyzed. For each object, the reconstruction cost was calculated by adding the costs of all the works that were required in order to restore the building to its initial state. The costs of the repair works (Kaswalder 2009) are summarized in Table 2. Finally, by knowing the area that each building occupied and the number of floors, the value of each building was calculated (as costs of the entire rebuilt of the building). The relation between the intensity of the process and the degree of loss for each building is represented as points in a two-

Fig. 3 Photographs of damaged buildings following the event of August 1987 (*Source*: Municipality of Martell) with assessed intensity as deposit height and the corresponding degree of loss
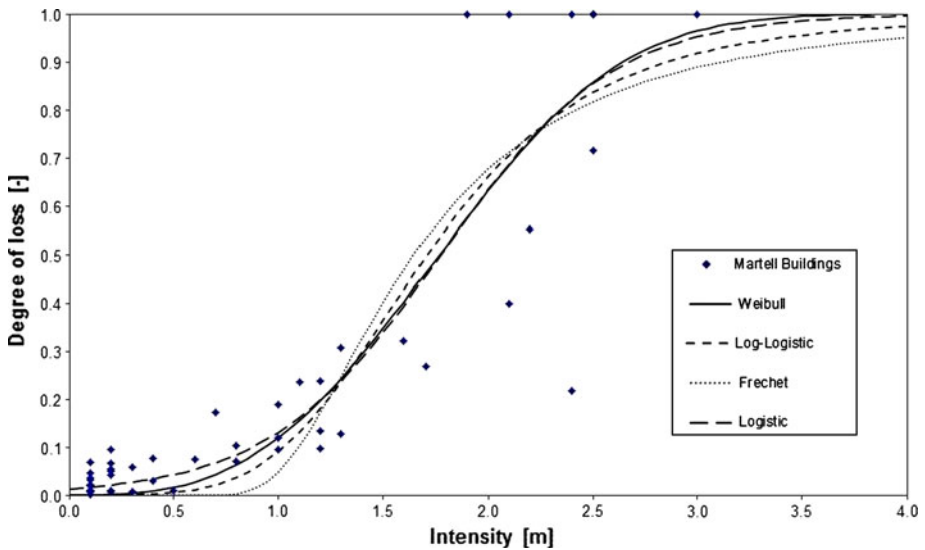
Fig. 4 The development of four different best-fitting functions based on the information of debris flow intensity expressed as deposition height and degree of loss for buildings in the Martell valley, South Tyrol

$$y = 1 - e^{-0.270\left(\frac{x+1.287}{1.287}-1\right)^{2.974}}$$
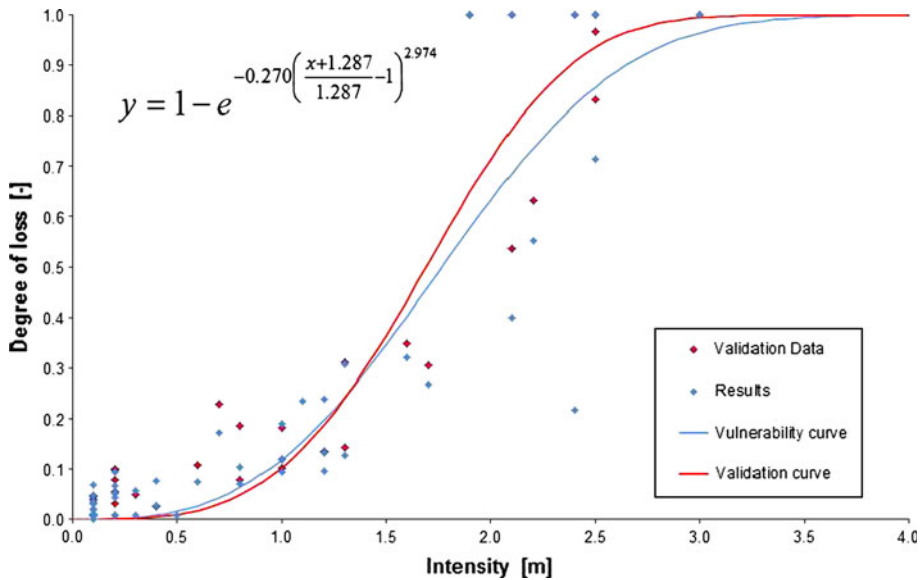
Fig. 5 The vulnerability curve (51 buildings) and the validation curve (based on compensation data for 34 buildings) using a Weibull distribution

dimensional illustration in form of a scatter plot. The vulnerability curves were developed for 51 buildings that suffered damages during the 1987 event (Figs. 4, 5).

As displayed in Fig. 4, different vulnerability curves were developed applying the four statistics of Weibull, Log-Logistic, Frechet, and Logistic. In particular, based on the coefficient of determination (R^2) and on the prerequisite that the curve has to go through 0 (intensity 0 means that there will be no damage), the Weibull function was chosen. Due to this reason, the Weibull distribution was selected as best-fitting function, although the Logistic distribution showed a slightly higher coefficient of determination. However, the Logistic function does not go through the point of origin, that is, the degree of loss is not equal to zero in case of zero intensity, which is a prerequisite for this application. The equation representing the selected Weibull vulnerability curve is:

$$y = 1 - e^{-0.270\left(\frac{x+1.287}{1.287}-1\right)^{2.974}} \tag{1}$$

with y as degree of loss [–] and x as debris flow intensity expressed as height of deposition [m]. The coefficient of determination of the Weibull distribution is $R^2 = 0.835$.

The vulnerability curve shows clearly the expected relation: the larger the height of the debris deposit, the higher the reconstruction costs of the building. Moreover, the fact that the curve becomes significantly steeper after the intensity of 1 m can be explained by the presence of windows or other openings that allow the material to enter the building. Consequently, more damage takes place in the interior of the building. According to the vulnerability curve, the need for total rebuild of buildings starts with intensities of 1.7 m. Cases of buildings with relatively high degree of loss for lower intensities can be related to significant destruction in the basement. Buildings with low degree of loss and high process intensity can be explained after examination of individual cases by relative high building value due to a larger number of floors.

A second curve (validation curve) was developed using data regarding the actual compensation that was given to 34 of the owners of these buildings. The compensation data provided by the Department of Domestic Construction of the Autonomous Province of Bozen/Bolzano—South Tyrol in Italian Lire of 1989 were later converted into Euro and indexed to 2009 values in order to be comparable with the results. The compensation data were calculated for direct damages that involve the structure of the building and not, for example, its content or indirect costs. The best-fitting function to describe the range in the validation data (highest coefficient of determination) was, apart from the Logistic distribution, also the Weibull distribution. The corresponding coefficient of determination is equal to 0.898.

The visual comparison between the developed curve and the validation curve is satisfactory. However, in some cases, there were significant differences that were difficult to explain by analyzing the photographic documentation. Buildings that were not seriously damaged received compensation to be entirely rebuilt, and in some cases, buildings that were significantly damaged were only partially repaired. We assume that these differences can be due to relocation of buildings that might not be explicitly mentioned in the compensation form, internal arrangements that were not clearly recorded, or speculative overestimation of damage for claiming purposes. This indicates that only visual interpretation of damage is not sufficient; however, in the present study, these rare cases were not quantified. It is assumed that their influence on the result of the overall study is negligible at the current stage.

4.2.1 Comparison with existing curves

The resulting vulnerability curve can be compared with other existing vulnerability curves for debris flows such as the ones proposed by Fuchs et al. (2007), Akbas et al. (2009), and Quan Luna et al. (2011) (Fig. 6). The results of vulnerability curves are displayed using different mathematical approaches and distributions; therefore, a direct comparison has to be carefully interpreted (cf. Totschnig et al. 2011 using different approaches for the same data). The vulnerability curve of Totschnig et al. (2011) was developed for fluvial sediment transport rather than debris flows. However, since in one event more type of processes can take place at the same time, the specific curve is also considered in the following comparison.

The developed curve coincides up to an intensity of 2 m with the curve of Akbas et al. (2009). As Akbas et al. (2009) used a second-order polynomial function that does not converge toward one, the two curves divagate after an intensity of 2 m. From the intensity of 2 m on the presented vulnerability curve coincides more with the one of Quan Luna et al. (2011). Both curves (Quan Luna et al. 2011 and our study) exhibit a concave shape for high process intensities. The developed vulnerability curve shows in general a low similarity with the curve of Fuchs et al. (2007) who used a second-order polynomial function, a common slope exist only until the intensity of 1 m. As far as the curve developed by Totschnig et al. (2011) is concerned, the two curves show few similarities. The main difference is that degree of loss 1 (total reconstruction of the building) in the case of Totschnig et al. (2011) corresponds to intensities of 4 m, whereas, in the case of the curve presented here, degree of loss 1 is possible with lower intensities (e.g., 3.5 m). This may be explained by the fact that Totschnig et al. (2011) have developed their curve for fluvial sediment transport and not for debris flow. Thus, the process intensity must be larger in order to receive the same damage at the buildings. This difference can also be
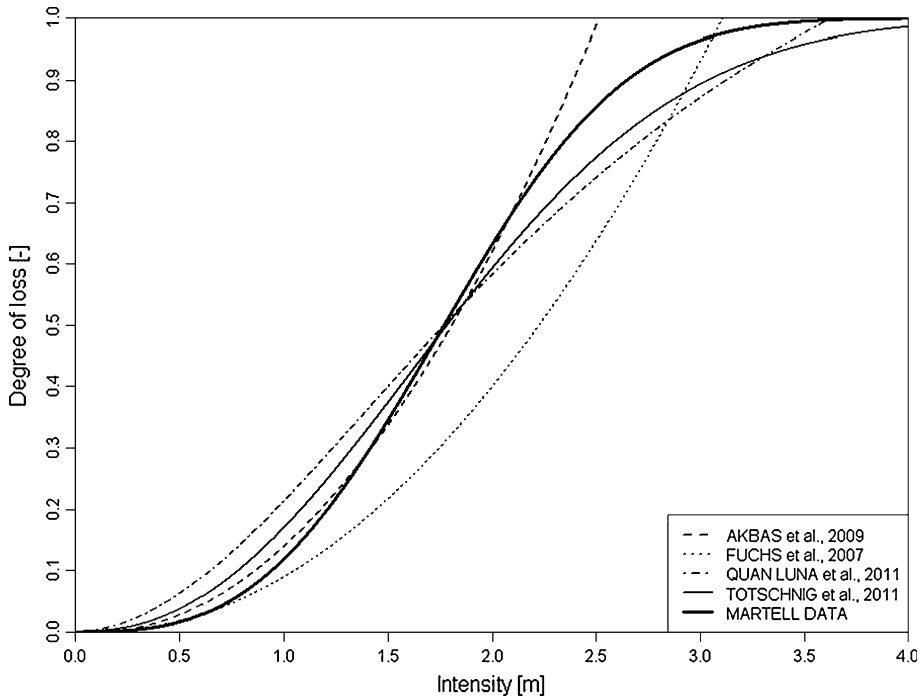
Fig. 6 Comparison of the developed vulnerability curve with existing vulnerability curves for debris flows from the literature

explained by the lower destructive power of water in contrast to debris flows due to largely reduced sediment transport in the flow. The general differences between the four vulnerability curves can be attributed to the following facts:

- The vulnerability curve developed in the present paper is based on more points (51 buildings) in comparison with Akbas et al. (2009) and Quan Luna et al. (2011). They use only 13 buildings in the same study area for the development of their curve. Fuchs et al. (2007) analyze 16 buildings.
- Intensity was mostly assessed in different ways. For example, Fuchs et al. (2007) assessed the intensity based on information that was collected by the Austrian Torrent and Avalanche Control Service following the event under investigation. In contrast, Quan Luna et al. (2011) used information acquired through the modeling of a past event.
- The type of housing of the buildings used for the development of the curves in all four case studies might be slightly different. Two of the studies (Akbas et al. 2009; Quan Luna et al. 2011) use the same buildings in Selvetta (Italy). Fuchs et al. (2007) analyzed data from Austria (East Tyrol), and the present study refers to buildings from South Tyrol (Italy). Although the differences between the architecture in north Italy and Austria are not significant, there might be differences in the material and construction techniques that will make some buildings more vulnerable or more stable to the impact of debris flow than others.

5 Discussion: possible application of the vulnerability curve and limitations

The developed vulnerability curve can be applied in the risk equations regarding debris flow events which were derived from a standardized approach. It is recommended to replace obscure and estimated values used in national guidelines (e.g., South Tyrol, Switzerland) with values calculated with a generalized methodology. Furthermore, the vulnerability curve showed clearly that the costs of reconstructing the building and consequently the degree of loss rises as the intensity of the process increases. The sudden increase in the degree of loss after the deposit height of 1 m indicates the importance of building characteristics (physical vulnerability indicators) such as the existence of windows or other openings and their height, condition and possibly size, to name some characteristics only. This kind of information derived and proofed by the presented vulnerability curve is important for risk reduction management. It should be used in order to make recommendations for building reinforcement in hazardous areas. Possible recommendations for specific objects to reduce their vulnerability could include the scrapping of windows on the slope side or the reconsideration of their design. In Switzerland, for example, the "Association of Cantonal Fire Insurances" (Vereinigung Kantonaler Feuerversicherungen) recognizes the importance of the material of the windows in the case of a debris flow and proposes that windows at the side of the building can be protected by having the right size and glass material. The windows facing directly a possible debris flow should be protected by multiple panes, protective plates, and stop-logs that can be placed seasonally in front of the windows (Egli 2005).

A further important advantage of the presented methodology is that it takes into consideration climate and socio-economic change. The methodology and the resulting vulnerability curve can provide the decision makers with detailed information regarding the costs of events for different process intensities in the future or under different development setting. The end user can use the curve not only to calculate the costs of a future damaging event of a specific intensity but also to calculate the costs of an event if the setting of the built environment changes (e.g., removal of buildings or building of new settlements). Although an uncertainty of the presented data is given, a proper damage documentation following an event can reduce this uncertainty, improve the reliability of the curve, and increase its soundness. Finally, the cost-effectiveness of protection measures can also be demonstrated by using this curve. Protection measures can change the intensity of a process on specific buildings and thus, their potential degree of loss and costs of reconstruction. For example, by introducing a protection wall in a segment of a river bank, an amount of buildings will be protected in such a way that under a specific scenario, the intensity of the debris flow on the specific buildings will be reduced. Egli (2005) presents a series of protection measures against debris flow impact such as window protection, splitting wedges, distracting walls, catchment dams, etc. The effectiveness of such measures can be tested through the presented methodology by changing the intensity of a potential event on protected buildings and by calculating the influence of the existence of these structural protective measures on the resulting economic loss. The difference between the potential economic loss with and without structural protective measures can be then compared with the costs of the construction of such structures.

The present study and the development of the vulnerability curve face some limitations and difficulties. One limitation was the availability of data regarding the detailed damages that individual buildings suffered following a catastrophic event—which is the general problem regarding the calculation of vulnerability curves (cf. Douglas 2007). The photographic documentation provided a significant amount of information regarding the

intensity of the process and its consequences; missing information were deduced by applying basic assumptions following defined criteria and rules (e.g., the material has entered the ground floor, thus, the floor or the internal doors have to be replaced). These assumptions may lead to an increasing level of uncertainty; however, the results are comparable within the study. Another challenge for this study was the lack of a "standard price" list for reconstruction of buildings following a natural disaster as well as a standard way of calculating the value of buildings. Suggestions on how to meet this challenge were provided. For example, a nationwide application of the same procedure would allow the collection of comparable data, which could be consequently used for more precise analysis. Better access to data and a more detailed documentation of events, consequences, and compensation would increase the accuracy of the analysis and thus, improve the resulting vulnerability curves.

In order to improve the curve and increase its reliability, it is very important to control the quality of the input data. Detailed information on the consequences of a specific event intensity on a structure is very important in order to understand the way different types of buildings react to the impact of a process. In this way, we can comprehend the factors and their characteristics that increase or reduce the physical vulnerability of a structure and use later this information in planning the necessary actions for the reduction of its vulnerability and the overall risk. For this reason, emphasis has to be given in the way the damage assessment is being carried out in the post-disaster phase.

We present here a new condition assessment documentation form which contains important information regarding the building that includes building specific characteristics such as its use, material, number of floors, etc. and information regarding its surroundings, the surrounding vegetation, and the presence of protection measures (Fig. 7a). The condition documentation form for a building should complement the damage assessment documentation that includes a detailed description of the damages following an event. Information such as whether material entered the basement or the ground floor, recording of any broken windows and doors, etc. should be recorded (Fig. 7b). The new damage documentation form is user friendly since it does not require users with training or special qualifications. The user is able to record the damage pattern of the building and also the characteristics of the process in an easy and fast way (e.g., by ticking boxes). The proposed forms are in line with existing damage documentation forms from insurance companies (e.g., UNIQA 2012) or other organizations dealing with damage and loss assessment (e.g., FEMA 2010). However, these forms are not really user friendly because they are mainly based on description and not on schematic representation of the damage. Furthermore, they do not contain information regarding the condition and characteristics of the damaged house or at least not in detail. Finally, most of the forms used by insurance companies do not include information regarding the intensity of the event on individual buildings.

6 Future perspectives: necessary steps for further improvements

A beneficial future development of the present study is the integration of the new documentation forms and the vulnerability curve in a tool that would have a dual function. It could use the curve for direct calculation of costs of future events, and it could also improve the existing curve by including more data regarding the consequences of new events. The tool could be extended to include more vulnerability curves regarding other types of hazards such as floods, snow avalanches, and landslides. It will also allow developing curves for other elements at risk such as infrastructure (roads, sewage lines,

(a)

BUILDING CONDITION FORM

BUILDING-ID ....*(For internal use)*
EVENT-ID...
PHOTO-ID...

BUILDING INFORMATION
Address:....
Municipality:.....

Use:	
☐ Residential	
☐ Auxiliary building	Type: ...
☐ Business/shop	Type: ...
☐ Public building	Type: ...
☐ Other	Type: ...

Area: ....
Age: ......
Number of floors: ....
Building material: ☐ Wood
                         ☐ Mixed
                         ☐ Bricks
                         ☐ Reinforced

Basement: ☐ Yes   ☐ No

Building surroundings: ☐ Wall
                             ☐ Fence
                             ☐ None

Surrounding vegetation   ☐ Trees
                              ☐ Bushes
                              ☐ none

Openings (Slope side):   Type: ....
                             Amount:....
                             Size:....
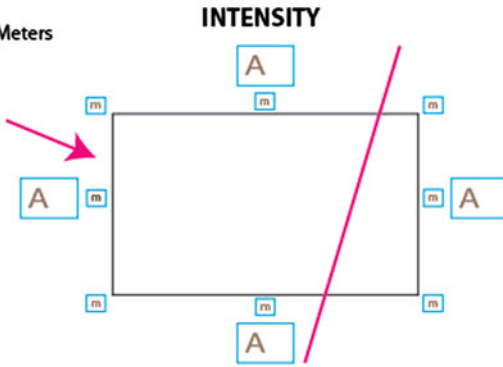   Quality:...

Openings (Sides):   Type:....
                        Amount:....
                        Size:...
                        Quality:...

Protection measures: ☐ Yes ☐ No
                           If yes, which one:....

Fig. 7 **a** New documentation form recording the condition of buildings prior to a catastrophic event. **b** New documentation form to assist damage assessment (*FF* first floor, *GF* ground floor, *BS* basement)

(b)

A...Aspect
m...Intensity in Meters

INTENSITY

W...Water
M...Material
X...Yes
m²...Area
nr...Number

Damage Pattern

destroyed building X

destroyed walls m² X

FF

W M

X

GF

W M

nr X

m² X

BS

W M
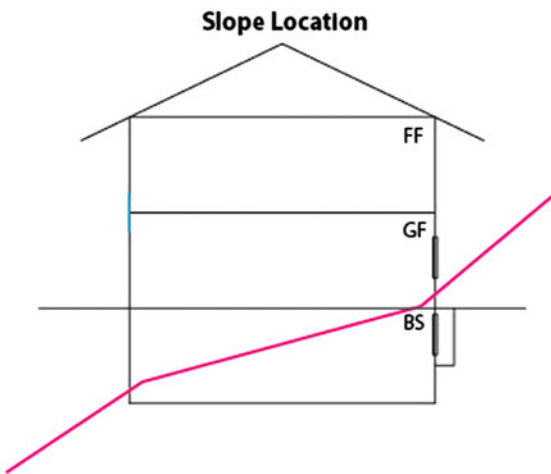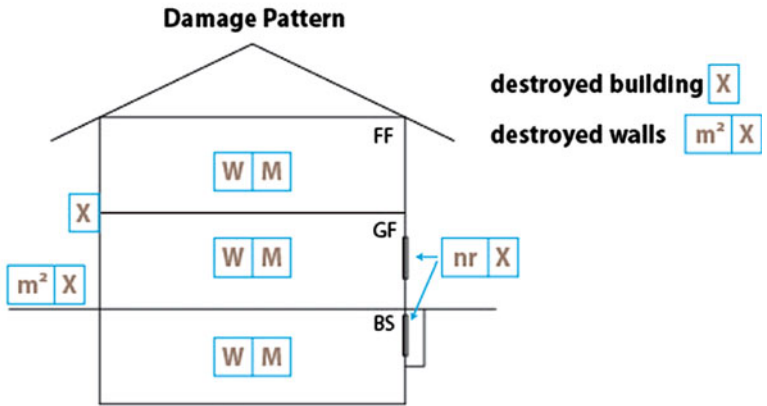
Slope Location

FF

GF

BS

Fig. 7 continued

power supply) and agricultural areas. Indeed, further investigations on how to express and assess the intensity of the processes on these elements have to be carried out.

As far as the uncertainties involved in this study are concerned, an uncertainty analysis is being currently carried out in a partner institute and the results will soon be available. Finally, the results of this study might not be transferable to other places in the world where the architecture and material of the buildings is significantly different. However, the method itself is transferable especially because it can be implemented in the lack of detailed information regarding the damages since alternative sources of information (photographic documentation and interviews with building owners) can be used.

The study presented here and its results concentrate only on one or two dimensions of vulnerability (economic and physical) and do not consider multiple vulnerability indicators that also play a significant role in the overall vulnerability of an element at risk. However, the economic and physical dimension of vulnerability is connected to other dimensions of it such as the institutional and social dimension (Fuchs 2009). In the present study, a valuable multi-step method is provided that will enable stakeholders and relevant institutions to reduce risk and the consequences of natural disasters strengthening in such a way institutional vulnerability. Moreover, our recommendations for new documentation of events and damage assessment might increase the capacity of local actors to improve risk management, to conceptualize strategies for vulnerability reduction and to conduct cost–benefit analysis for mitigation measures. Last but not least, the results of the proposed methodology can help the estimation of future damage costs not only in the present climate and development setting but also taking into consideration climate change and changes in the socio-economic development.

7 Conclusions

In the present paper, a multi-step methodology for the development of a vulnerability curve is presented and tested. The comparison with the vulnerability curve deduced from the compensation data in the study area as well as with other vulnerability curves from different study areas indicates reasonable results. Although the case study is using the methodology for debris flow events, theoretically, the methodology can be extended to other natural processes (snow avalanches, floods, landslides) and further elements at risk (agricultural areas, infrastructure). However, this requires major modifications, and the challenge of assessing the intensity of the process on elements at risk will have to be tackled. The methodology is transferable to other places in the world and especially to places where detailed information regarding the consequences of the process on the built environment is limited, since it offers alternative ways to acquire this information. However, having recognized the importance of a detailed damage assessment following an event, the authors of the present study emphasize that there is a need for a new way of documenting damages in order to collect all this information which is relevant to the physical vulnerability of a building and it will enable vulnerability assessment and reduction, as well as assessment of future economic losses.

and his contribution at the earlier stages of this study. Last but not least, the authors would like to thank Jan Blahut and an anonymous reviewer for their comments on an earlier draft of this article.

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