# A NEW VULNERABILITY FUNCTION FOR DEBRIS FLOW

## THE IMPORTANCE OF PHYSICAL VULNERABILITY ASSESSMENT IN ALPINE AREAS

**Maria Papathoma-Köhle[1],** Reinhold Totschnig[2], Margreth Keiler[3] and Thomas Glade[4]

## ABSTRACT

Alpine hazards such as debris flows, landslides, snow avalanches and floods can cause apart from loss of life significant damage of the built environment and infrastructure. Since the possibilities for human intervention in the physical processes are limited risk reduction strategies additionally have to focus on physical vulnerability analysis, assessment and reduction of the elements at risk in order to reduce not only loss of life but also economic costs. Vulnerability assessment is a topic that is growing in importance also due to climate and environment change. Climate change influences the frequency and intensity of some events and the continuous development changes the spatial pattern of exposure and vulnerability. In this paper the growing importance of the assessment of physical vulnerability is highlighted through the introduction of a methodology to develop a vulnerability function for debris flows. The methodology is applied in South Tyrol, Italy. The final product can assist local authorities, emergency and disaster planners in decision making, cost benefit analysis of mitigation protection measures and assessment of potential costs of future events. Finally, recommendations for improved damage assessment that could enhance the quality of input data and thus the reliability of the function are made. The work presented in this paper has been carried out within the framework of an FP7 European project called MOVE (Methods for the Improvement of Vulnerability Assessment in Europe).

**Keywords**: physical vulnerability, vulnerability functions, debris flow, damage assessment

## INTRODUCTION

Alpine hazards such as debris flows, floods, snow avalanches, rock falls and landslides pose a significant threat to local communities. These natural processes can cause damage to lifelines, critical infrastructure, agricultural lands, housing, public and private infrastructure, but also loss of life. The assessment of the vulnerability of the built environment to these hazards is a topic that is growing in importance due to the impact of global change (including climate and environmental change) as well as changes of the society and the economic system. Moreover, our society and the public authorities have to meet the challenges of financial restrictions also in the field of hazard mitigation and risk reduction.

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). However, for the authors of the present study vulnerability is considered connected to 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 could be defined as "the characteristics and circumstances of a community,

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[1] Dr. Maria Papathoma-Köhle, Department of Geography and Regional Research, University of Vienna, Universitätsstrasse 7, 1010 Vienna, Austria (e-mail: maria.papathoma@univie.ac.at)

[2] DI. Reinhold Totschnig, MSc., Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Vienna, Austria

[3] Dr. Margreth Keiler, Institute of Geography, University of Bern, Switzerland

[4] Prof. Thomas Glade, Department of Geography and Regional Research, University of Vienna, Austria

system or asset that make it susceptible to the damaging effects of a hazard" (UNISDR 2009). It is a fact that a better understanding of vulnerability will lead to more effective risk assessment, emergency management and to the development of mitigation and preparedness activities that may reduce the loss of life and economic costs following a disastrous event. Therefore, a detailed investigation on the relation of the degree of loss and the intensity of the processes as well as on the identification of factors influencing this relation is presented. In this study the importance of physical vulnerability assessment is demonstrated through a case study in South Tyrol, Italy. The results of the case study are integrated in a general framework of vulnerability assessment and will be discussed critically.

## PHYSICAL VULNERABILITY ASSESSMENT FOR ALPINE HAZARDS

The majority of the studies concerning mountain hazards focus on hazard assessment, modelling, monitoring and risk management. Vulnerability assessment of alpine hazards is a relative new field of research and the number of studies focusing on vulnerability assessment for these types of hazards, is limited. In a review of existing physical vulnerability assessment methods for alpine hazards Papathoma-Köhle et al. (2011) identify the gaps and difficulties of existing vulnerability assessment methodologies and point out the future needs for vulnerability assessment to alpine hazards, which can serve as a tool for effective emergency and disaster management. In more detail, Papathoma-Köhle et al. (2011) suggest that there is (i) a lack of common language between scientists, (ii) many difficulties in the implementation of the existing methodologies (e.g. data availability, time consumption), (iii) differences between them regarding their scale, (iv) the consideration of the hazardous phenomenon and its properties, (v) the consideration of important vulnerability indicators and (vi) the use of technology such as GIS and remote sensing. The development of vulnerability functions is one of the methods that have been used in the past for some mountainous hazards such as debris flows (Fuchs et al. 2007, Akbas et al. 2009), fluvial sediment transport (Totschnig et al. 2011) and snow avalanches (Wilhelm 1997, BUWAL 1999, Keiler et al. 2006). Although the method has a number of disadvantages, it provides a very good picture of the economic loss under different scenarios (intensity and development). It can also be used as a supporting tool for cost benefit analysis of structural protection measures.

## METHODOLOGY AND RESULTS FROM SOUTH TYROL

In this paper, a methodology for the development of a vulnerability function for debris flows is presented. The function can be also used for the development of vulnerability functions for other alpine hazards, provided that the required data are available. Moreover, the same methodology can be also used theoretically for different elements at risk such as agricultural areas and open spaces or infrastructure. In this study the methodology is used for debris flow events that have affected buildings. The methodological steps can be seen in Figure 1.

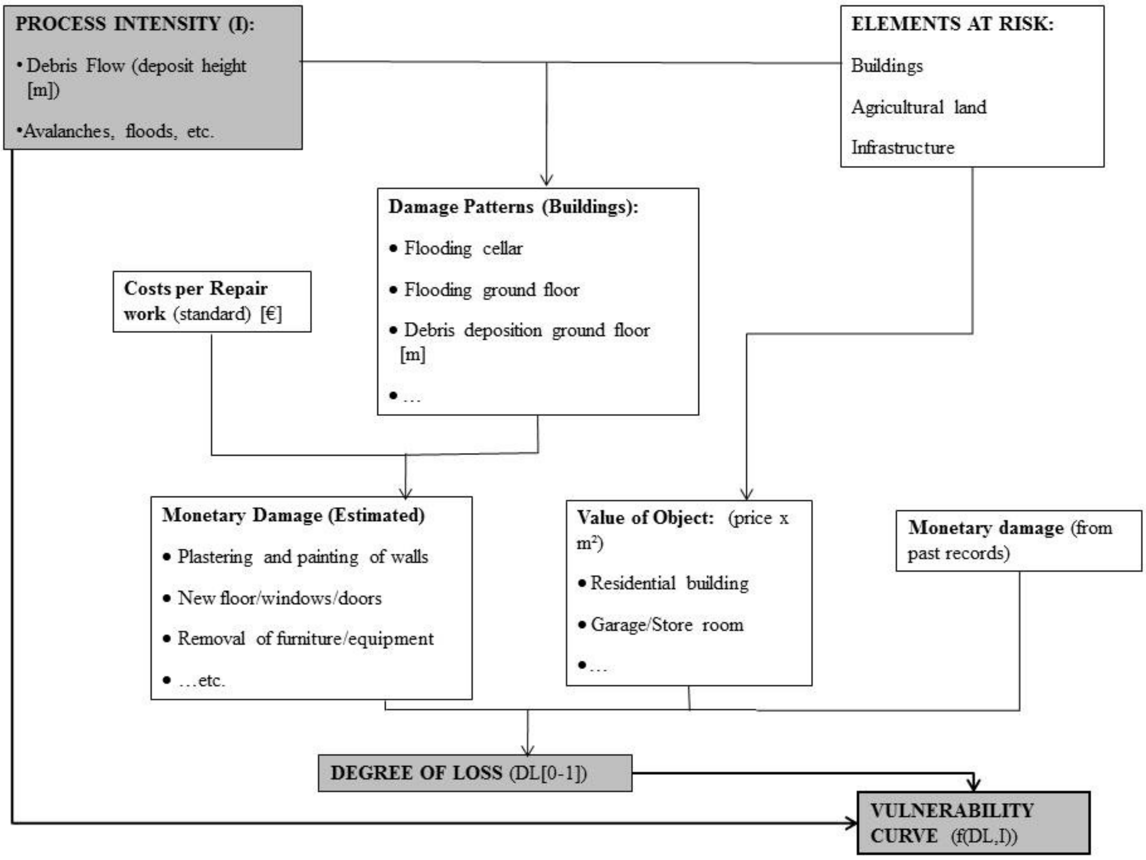


**Fig.1** The methodological steps and the data required for the development of the vulnerability function. The information required for the assessment of the degree of loss (object value, monetary damage) is indicated.

The vulnerability function is a function of the **intensity of the process** and **the degree of loss**. In the absence of detailed information regarding the intensity of the process on individual buildings (e.g. debris flow height, velocity, impact pressure or time that the building remained under water and debris) and detailed damage on properties the required information had to be acquired from photographic documentation of a number of debris flow events and their consequences in South Tyrol (Figure 2). The data were made available by the Autonomous Province of Bozen/Bolzano - South Tyrol (Department 30) and the municipality of Martell (South Tyrol). The data included basic information regarding different events, photographic documentation of damaged buildings and some compensation data. Information regarding the exact damages of buildings and the intensity of the process on each building were not available. Although in the absence of detailed documentation of the damage, the photos can provide useful information regarding the intensity of the process and its consequences, there many uncertainties related to the use of photos form damage assessment. For example, the photos often show mainly external damages and not the interior of the building increasing the uncertainties of the methodology.

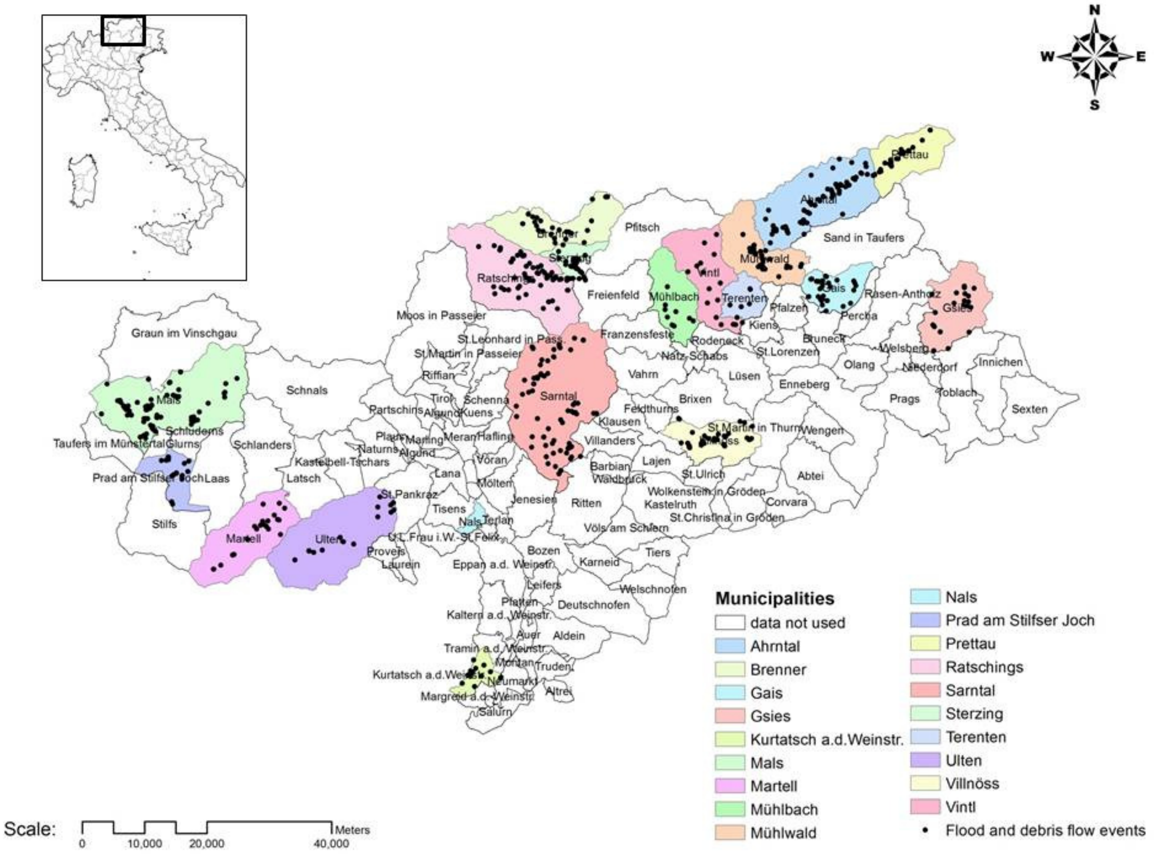


**Fig.2** Location of the data (event documentation) used for the present study within the municipalities of South Tyrol (Source: Autonomous Province of Bozen/Bolzano - South Tyrol)

Some buildings that have suffered damages during different events in South Tyrol can be seen in Figure 3. 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 damage pattern by analyzing the process impact on the building.

The **intensity of the process** on individual buildings is expressed as deposit height. 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 2.6m) . 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 and different consequences of a specific event.

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. Therefore, the value of the building and cost of reconstruction have to be determined.

Building values: The value of the building is estimated by the reconstruction value (standard prices/m$^2$) for different building types and functions as they are also used for insurances purposes (c.f. e.g., Keiler 2004). For this study data for the element at risk (building use and size, photos) and reconstruction values were provided by local authorities (Province of South Tyrol and Municipality of Martell) that were combined and adapted for the basement and the roof from the Austrian prices given in a study from Keiler (2004) and Keiler et al. (2006).

Reconstruction costs: The cost of the repair works that are required according to the damage that a building has suffered were taken from a report listing the reconstruction costs following a flood event taking as an example a typical South Tyrolean residential building of 100m$^2$ building area and a 40m$^2$ basement (Kaswalder 2009). 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, information regarding wall reconstruction caused by the impact of the debris on the building was taken from an official catalogue of fixed base prices for civil engineering operations (Autonome Provinz Bozen 2010).

**Fig.3** Photos of damaged houses in South Tyrol (Source: Autonomous Province of Bozen/Bolzano – South Tyrol)

By determining the intensity of the process and the degree of loss as described above and illustrated in Figure 1 the specific relation of intensity and degree of loss for each building could be represented as a point in a two-dimensional illustration in form of a scatter plot (Figure 4 and 5).

The process intensity is plotted on the abscissa, and the degree of loss is plotted on the ordinate. In order to find functions that fit best to the data, a nonlinear regression approach, as outlined by Totschnig et al. (2011), was applied. The following cumulative extreme value distributions were tested: Weibull, Frechet and Log-Logistic. These distributions were modified to introduce further fittable parameters and had to fulfil the following mathematical requirements (Totschnig et al. 2011):

- Vulnerability as the depending variable is defined in a both-sided confined interval [0,1];
- the distribution is continuous and monotonic increasing within the interval of its explaining variable (intensity); and
- the explaining variable is defined either in a both-sided unconfined interval (-∞, +∞) or in a left-sided confined interval [0, +∞).

Apart from these distributions a logistic distribution was also tested. An unmodified Logistic distribution complies with the requirements mentioned above. However, the Logistic distribution does not go through the point of origin, i.e. the degree of loss is not equal to zero in case of zero intensity. The nonlinear regression approach used to find the unknown parameters of all the tested distributions applied a sequential quadratic programming algorithm based on a nonlinear least squares estimation.

In Figure 4, the distributions based on the presented methodology are shown. The intensity parameter is hereby grouped in steps of 0.5 m. Due to the fact that the Logistic distribution does not go through the point of origin, the Weibull distribution (Eq. 1) was selected as best-fitting function, although the Logistic distribution showed a slightly higher coefficient of determination. The coefficient of determination of the Weibull distribution is equal to 0.786, where as the coefficient of determination of the Logistic distribution is equal to 0.796.

$$V = 1 - e^{-1.528\left(\frac{I+2.432}{2.432}-1\right)^{2.285}} \tag{1}$$

where V = vulnerability of the building and I = intensity in form of deposition height.

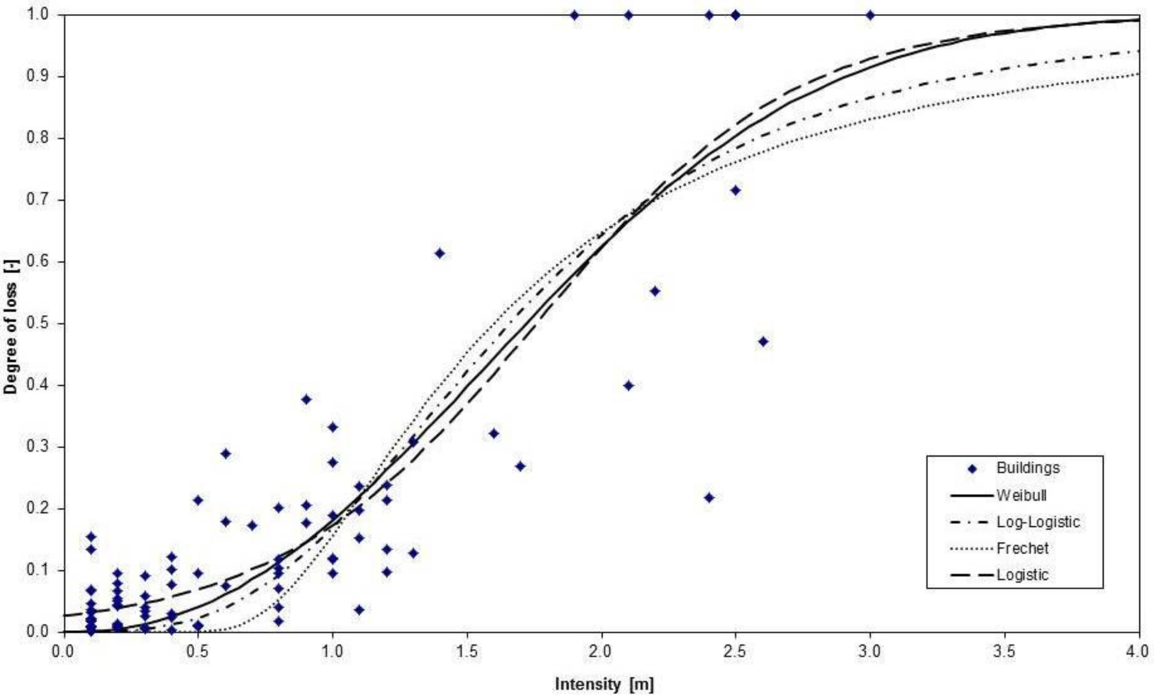


**Fig.4** Comparison of different vulnerability functions. Vulnerability values originating from the study sites and based on the presented methodology are indicated by blue dots. Based on the R2 and on the prerequisite that the function should go through point (0,0), the chosen best-fitting function to describe the range in the analyzed data is the Weibull function.

In Table 1, the mathematical notation, the coefficient of determination and the interval of the explaining variable (intensity) of the tested distributions based on the presented methodology are summarised.

**Tab. 1** Compilation of the tested distributions

| Distribution | Mathematical notation | Coefficient of determination | Interval of the explaining variable |
|---|---|---|---|
| Weibull | $V = 1 - e^{-1.528\left(\frac{I+2.432}{2.432}-1\right)^{2.285}}$ | 0.786 | [0,+∞] |
| Frechet | $V = e^{-1.208\left(\frac{I+1.226}{1.226}-1\right)^{-2.091}}$ | 0.758 | (0,+∞) |
| Log-Logistic | $V = \frac{1}{1+\left(\frac{I+1.658}{1.658}-1\right)^{-3.132}}$ | 0.778 | (0,+∞) |
| Logistic | $V = \frac{1}{1+e^{(-2.036I+3.627)}}$ | 0.796 | (-∞,+∞) |

The vulnerability function in Figure 5 shows, as it was expected, that the larger the height of the debris deposit, the higher the degree of loss. The fact that the function 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 and more damage to take place in the interior of the building. Total loss and need for total building replacement according to the function can be observed after the intensity of 1.7 m.

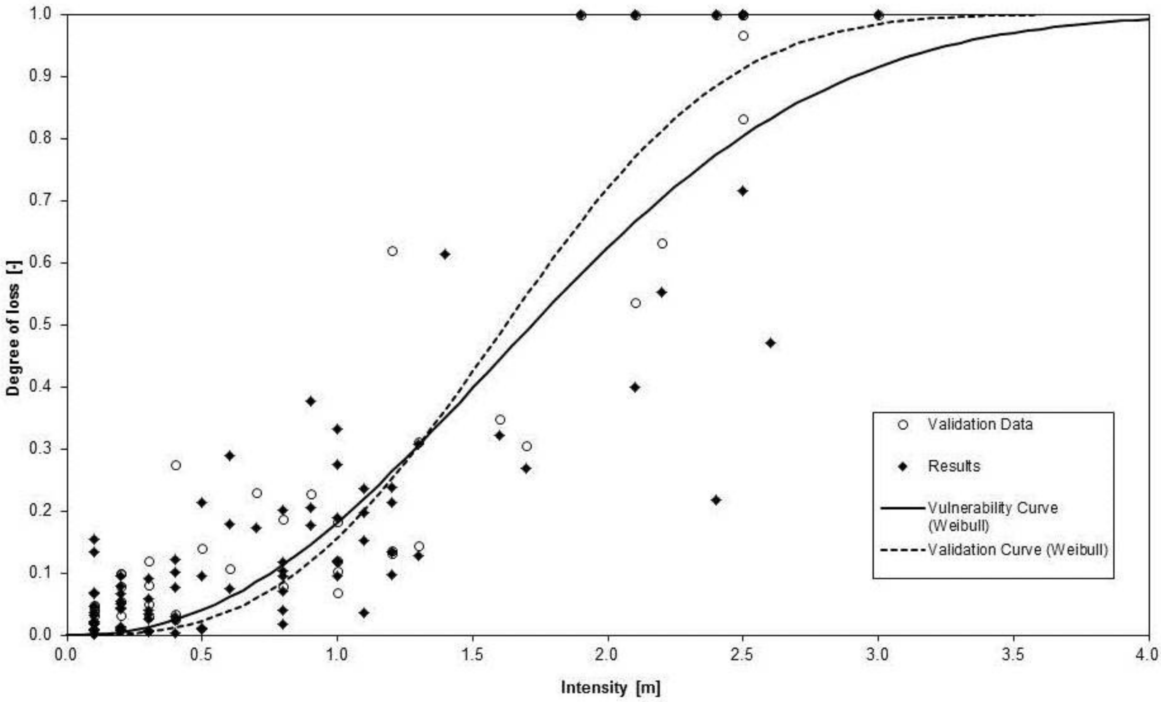


**Fig.5** Comparison of the best-fitting vulnerability function and the corresponding validation function. Vulnerability values based on the presented methodology are indicated by white circles and vulnerability values based on the validation data are indicated by black rhombi.

Individual cases of buildings with relatively high degree of loss for lower intensities can be attributed to significant destruction in the basement. The fact that some buildings have experienced low degree of loss and high process intensity can be explained by relative high building value due to a larger number of floors.

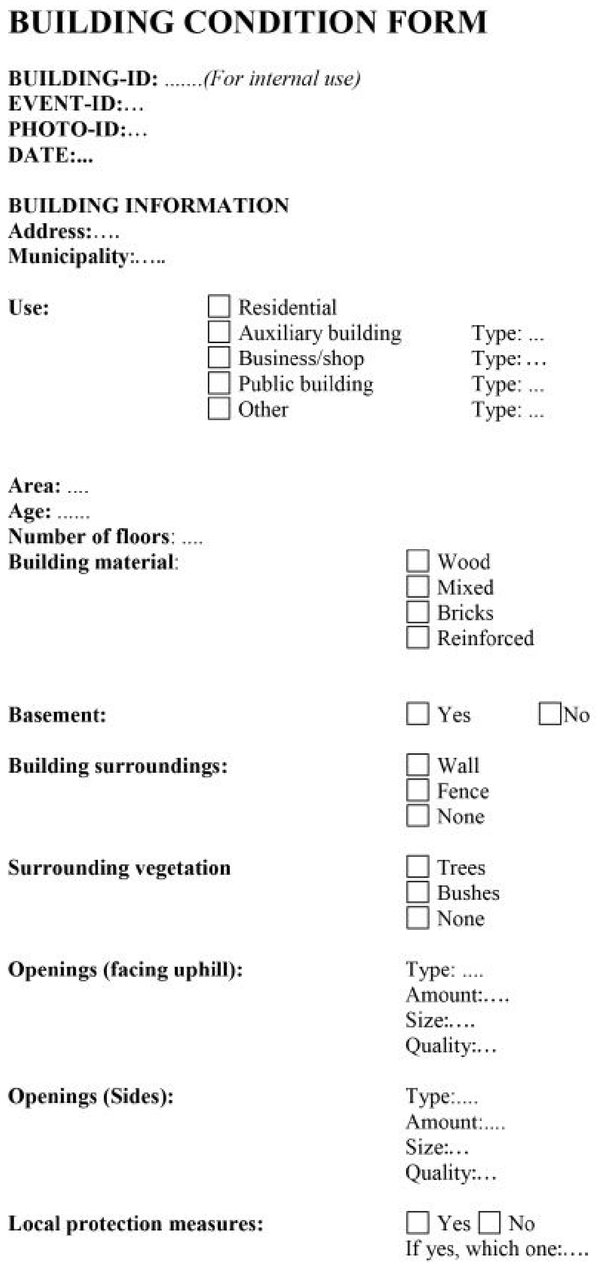
A validation function was developed using real data concerning the compensation that was given to some property owners. The compensation data was provided by the Department of Domestic Construction of the Autonomous Province of Bozen/Bolzano - South Tyrol in Italian Lire of 1989 and it was later converted into Euro and indexed to 2009 values in order to be comparable with the results. However, as not all building owners were eligible for compensation, only 43 values of degree of loss calculated by the presented methodology were validated. Although the visual comparison (Figure 5) between the developed function and the validation function is satisfactory, in some cases, significant differences could not be explained by looking at 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. It was assumed that relocations of buildings that might not be clear in the compensation form or internal arrangements that were not clearly recorded accounted for these differences.

## DISCUSSION

The resulting vulnerability function 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 function, not only to calculate the costs of a future 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). Last but not least, the cost effectiveness of protection measures can also be demonstrated by using this function. Protection measures can change the intensity of a process on specific buildings and thus, their potential degree of loss and costs of reconstruction. Moreover, by adding information regarding the consequences of new events, the vulnerability function can be significantly improved and its reliability can be increased.

Data availability was the most significant drawback of the study. Lack of detailed information regarding the consequences of past events on individual buildings led to a series of assumptions that increased the uncertainty of the results. In order to increase data availability and quality a new method of damage documentation should be introduced. The new documentation consists of two parts: the condition documentation form and the damage documentation form (Figure 6 and 7). The condition documentation form 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. The damage assessment documentation includes a detailed description of the damages (damage pattern) following an event such as information on whether material entered the basement or ground floor, recording of any broken windows and doors etc. as well as information regarding the intensity of the process. The new damage documentation form is user friendly (e.g. the user can record the damage pattern of the building and also the characteristics of the process in an easy and fast way) and does not require any special training or skills. The proposed documentation forms have not been validated yet, however, during a Stakeholder Workshop in Bozen, South Tyrol (17 June 2011) they were introduced to the relevant stakeholders (e.g. representatives of civil protection authorities, the department of hydraulic engineering, and other local authorities) receiving a very positive feedback.

A future development of the present study would be the integration of the resulting function and documentation to a integrative tool that would have a dual function: a) it could assess the potential costs of future events under different scenarios and b) it could be used for the recording of new events and their consequences in order to improve the existing vulnerability function by the input of more data. Moreover, by collecting information regarding individual houses as it is suggested by the documentation form shown in Figure 6 the temporal pattern of the physical vulnerability of the elements at risk can be identified. In other words changes regarding not only the location of buildings but also their individual characteristics through time can be recorded and changes in physical vulnerability through time can be visualised. Although the methodology is applied on a case study for debris flow events, the approach can be extended or modified to include more processes (e.g. snow avalanches, floods, landslides) and more elements at risk (e.g. agricultural areas, infrastructure). The resulting vulnerability function is not transferable to other places in the world where the dominant architecture, shape and quality of the buildings are different than the one in South Tyrol. However, the methodology itself is transferable 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.



## BUILDING CONDITION FORM

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

**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 (facing uphill):**
Type: ....
Amount:....
Size:....
Quality:...

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

**Local protection measures:** ☐ Yes ☐ No
If yes, which one:....

**Fig. 6** The proposed condition documentation form

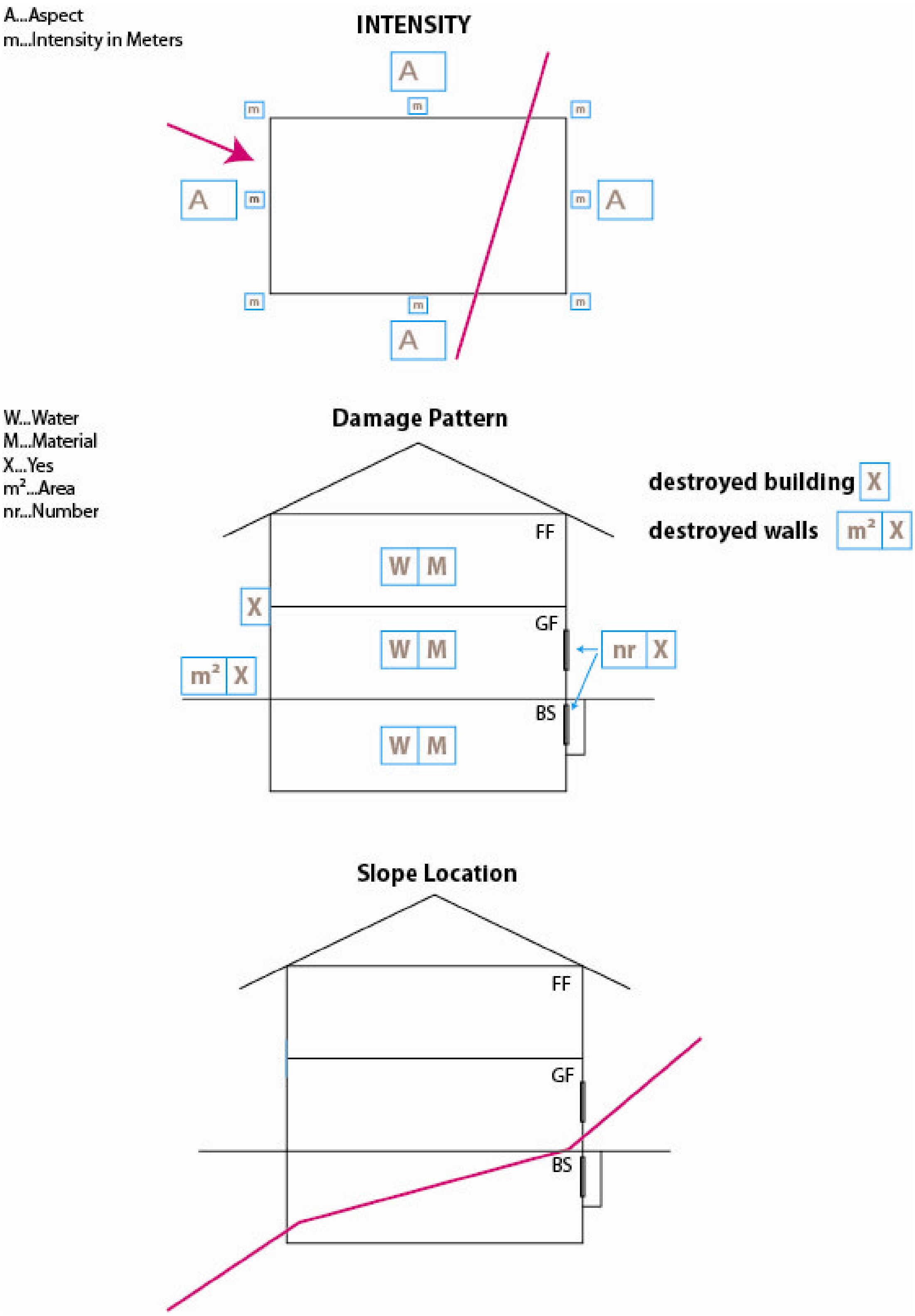


**Fig.7** The recommended damage documentation form. The red lines at the top of figure indicate the debris direction and the part of the house which has been affected. The red line at the bottom figure indicates the location of the building on the slope. (FF: Fist floor, GF: ground floor, BS: basement)

## CONCLUSION

In the present study a valuable tool 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 will increase the capacity of local actors to improve risk management, conceptualize strategies for vulnerability reduction and to conduct cost benefit analysis for mitigation measures. Finally, 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. The methodology and results presented in this study emphasise the importance of the analysis, assessment and reduction of physical vulnerability.

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