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Assessing vulnerability of buildings to hydro-meteorological hazards using an expert based approach – An application in Nehoiu Valley, Romania

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ABSTRACT

As the number of reported natural disasters resulting in casualties and damages increases worldwide, assessing vulnerability of the built environment represents a fundamental step towards reducing the probability of loss. This is a challenge in areas where data are sparse, and where no vulnerability curves exist for different building types. The aim of this paper is to develop a new expert based approach that allows physical vulnerability assessment of buildings to hydro-meteorological hazards in areas with limited information about the hazard or the exposed elements. The methodology is based on three steps: firstly, a vulnerability index is calculated based on expert weighing of vulnerability indicators using Analytical Hierarchy Process analysis. Secondly, a set of vulnerability curves is selected from the literature and a generic vulnerability curve is calculated as the average of these input functions. Lastly, the vulnerability index together with the generic vulnerability curve is used to generate a specific vulnerability curve representative for the studied area. The applicability of this approach is demonstrated in Nehoiu Valley, Romania. The results show that vulnerability indices for the 60 sampled buildings vary between 0.2 and 0.6 for all hazard types, and no buildings exhibit indices lower than 0.2 for debris flows or slow moving landslides. The specific curves show generally lower values of degree of loss for similar inundation depths compared with the general vulnerability curve. The proposed methodology exploits two vulnerability models in a new, complementary manner and it can be used for decision-making support in disaster response and risk management.

1. Introduction

In recent years, there is evidence of a growing effort among national and international bodies in reducing risk to natural hazards. As a result, 'mortality risk associated with major weather-related hazards is now declining globally' [1]. Albeit these encouraging results, damage to the built environment continues to increase creating economic risk across all regions. As risk is being generated alongside economic growth, reducing vulnerability to local infrastructure, housing and livelihoods of communities affected by highly localized hazards, such as floods and landslides, is still a central issue.

The term *vulnerability* embodies a multitude of concepts which reflects the diversity of scientific disciplines and purposes for which it is used. In the field of natural hazard research, there are generally two main approaches used: (i) a technical/engineering approach, which defines (physical) vulnerability as 'the degree of loss to a given element, or set of elements, within the area affected by a hazard, expressed on a scale of 0 (no loss) to 1 (total loss)' [8]; and, (ii) a social approach, in which vulnerability describes those characteristics of the community or population that lead to differential impacts of natural hazards [9,10]. Elements at risk are generally the objects or systems which have the potential to be adversely affected [11]. Recently, various authors have emphasized the need for an overall understanding of vulnerability by integrating its different components (e.g. susceptibility of physical elements, coping capacity, adaptation, and exposure) in an overarching framework [4,7,12,13].

As opposed to social approaches, current engineering concepts recognize generally two main factors that determine the propensity of an element at risk to suffer damage: (i) the destructive potential of the impacting process, which is defined as a measure of intensity manifested with a specific spatial and temporal probability and, (ii) the capacity of the element to preserve its integrity and functionality amid the physical interaction with the natural process [2,3]. Recent studies emphasize the relevance of

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assessing physical vulnerability of buildings using a set of parameters that describe the resistance of the element at risk, in a qualitative [4], semi-quantitative [5], and quantitative [6] framework.

The present study applies a technical (engineering) approach of vulnerability assessment, focusing on the physical susceptibility of buildings likely to be impacted by a hydro-meteorological hazard of a given intensity. The expected degree of loss is defined as a fraction of the resulting structural damage and expressed in non-dimensional terms (between 0 – no loss, and 1 – total loss). Within this paper, four types of processes are considered: river floods, flash floods, slow moving landslides, and debris flows. Each process type can directly affect the physical object by a range of impact mechanisms (e.g. for landslides: burial, collision impact, earth pressure, compression or torque, plastic deformation, etc.; for floods: static/dynamic pressure, capillary rise, buoyancy, chemical reactions, scouring, etc.). A number of authors provide a detailed analysis of different types of physical impacts of landslides [14] and floods [15] on elements at risk. The degree to which a specific or a combination of impacts is manifested depends on the process type and complexity. A comparison of different landslides/floods impact types considered in this study is presented in Section 2.1.2.

Generally, four main approaches are used for the assessment of physical vulnerability: fragility curves, vulnerability (damage) curves, vulnerability matrices, and vulnerability indicators. Each is designed for different data requirements, a variety of levels of complexity and for a range of applications at various spatial scales. The fragility-, vulnerability-, and damage curves are essential components of the quantitative risk assessment process, as they relate the expected damage of an individual element at risk with the hazard intensity. Each curve type can be associated with one or more methods of estimation: empirical [6,16], engineering judgment [17], analytical [18,19], and hybrid [20]. Although these curves offer a great advantage in terms of risk calculation, they require a significant amount of input data and computation capabilities. A somewhat simpler approach is given by the use of vulnerability matrices, which are based on the assumption that a given element at risk (or set thereof) would display statistically the same level of damage when submitted to a hazard with similar intensities [21]. The method is adaptable to multiple types of hazards (e.g. earthquakes [22]; landslides [23,24]; floods [15]), and gives a semi-quantitative estimate of vulnerability. However, in comparison with the previous approach, the method cannot give an account of the different determinants influencing the elements at risk vulnerability due to the high degree of generalization. Modeling physical vulnerability using indicators can overcome the latter problem, as the focus of this method is to identify and better understand the principal factors that contribute to the configuration of vulnerability [12]. This qualitative approach enhances integrative (e.g. vulnerability of the urban place, [25]), as well as multi-hazard vulnerability analysis [4], and is particularly useful in areas where limited or no information on past damage events exit.

Despite this progress, insufficient attention has been given to the application of different vulnerability assessment methods in data scarce areas. Moreover, although the transferability of vulnerability curves between areas with similar environmental and socio-economic settings has been recognized as important, few studies investigate the application of such an approach [28,29] or operate upon the variation between comparable functions.

Taking into account the above mentioned challenges, the main objective of this research is to develop a new approach for assessing physical vulnerability of buildings to hydro-meteorological hazards applicable in areas with limited information about the hazard impact and the resistance of the element at risk. The present study takes into account four types of hazards: river floods, flash floods, slow moving landslides, and debris flows. To assess its feasibility, the methodology is applied in Nehoiu Valley located in Buzău County, Romania, and the results are compared with compensation data used as proxy for the degree of loss.

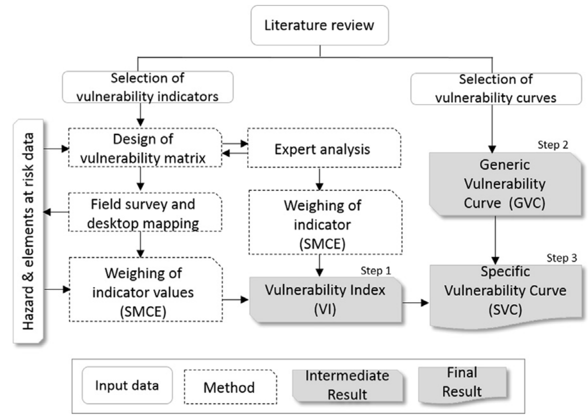

Fig. 1. Methodology for assessing physical vulnerability of buildings to hydro-meteorological hazards. The results associated with each methodological step are highlighted in grey.

2. Methodology

The methodology used in this study follows a three-fold procedure (Fig. 1): firstly, a specific vulnerability index (VI) that characterizes the building susceptibility of being damaged is generated using a set of weighted vulnerability indicators and their values applying Spatial Multi Criteria Evaluation (SMCE); in a second step, a generic vulnerability curve (GVC) is developed by averaging existing vulnerability (damage) functions transferred from other study areas located in comparable socio-economic contexts; finally, a new vulnerability curve specific for the investigated area (SVC) is obtained by plotting the vulnerability index (VI) within the range of variability of the generic vulnerability curve (GVC). These procedural steps are explained in detail below.

2.1. Development of the vulnerability index

2.1.1. Study area, data collection for hazard information and building characteristics

Generally, there are three spatial scales of analysis which can be associated with different levels of administrative organization: small – (national), medium – (regional), and large (local). Although, the impacts of natural hazards can have consequences beyond their natural boundaries of manifestation (i.e. indirect damages), practitioners and decision-makers usually focus on administrative units due to their dependency on institutional and regulatory frameworks based on which they operate; however, vulnerability analysis can be performed also at sub-administrative level (e.g. catchment, site-specific). When the area of investigation has been determined, information about the spatial and temporal characteristics as well as the destructive capacity of the impacting processes must be acquired. There is a large volume of published studies describing and discussing methods of landslide and flood hazard assessment (for an overview refer to [30–33]). However, in many study areas basic information about the nature of the peril is limited or completely missing, and thus, data collection about historic events and their magnitude must be obtained by means of field investigations, image interpretation, and archive studies. Definition of the elements at risk and their spatial representation (single elements at risk, wards, mapping-, or administrative units) is highly dependent on the objective and, consequently, scale of investigation. Several methods of spatial interpretation of high resolution images can be used for rapid inventory of elements at risk in densely populated areas [34–36]. For a detailed vulnerability assessment, this information has to be complemented by the combined use of censuses, cadastral maps, and field surveys, especially in areas where there is no spatial data associated with the elements at risk [37].

2.1.2. Selection of building vulnerability indicators for floods and landslides

Vulnerability is revealed following the impact of a natural hazard through the evaluation of subsequent consequences. According to Birkmann [38], vulnerability cannot be assessed adequately exclusively through data based on past events. However, documentation of preceding hazards and damage assessments aid the identification of variables that explain or influence the ability (or inability) of an element at risk to preserve its integrity and functionality amid the interaction with a natural process [4]. The selection of the most relevant variables affecting the behavior of a structure is determined by (i) the physical mechanism and type of impacting process, as well as (ii) the characteristics of the endangered object. On the basis of these considerations, and taking into account also past damage reports of buildings affected by landslides and floods in the study area, four major groups of vulnerability indicators for buildings are proposed:

2.1.2.1. Dimensional indicators. The height of a building from the ground level and the number of floors are considered key factors for reducing flood damage [44], as in most cases the extra height gained by an elevated lower floor provides the opportunity to use flood resistant designs for the ground floor and increases the flood-free area for storage of valuable contents in the upper floors. On the other hand, the number of floors or building height is generally less important in determining the vulnerability to slow moving landslides as, for example, structural type or foundation depth. Nevertheless, for rapid landslides (such as debris flows) generally the higher the building the lower the likelihood of suffering damage due to intrusion of material through openings [6,16].

2.1.2.2. Resistance indicators. A building is more prone to damage and losses if it has openings (doors, windows), especially opposite to the direction of flow [45]. Although openings are the weakest elements of a building they can in certain circumstances reduce the dynamic pressure of a debris front, in the case of a debris flow, and thus the likelihood of collapse [46]. The size, material, and height from the ground influence the extent of damage caused by the intruding material. According to the type of structure frame and wall (infill) material buildings exhibit different response to dynamic pressure of floods and landslides. For example, timber block walls offer lower protection against debris flows than against floods; meanwhile concrete walls are highly resistant to both types of processes [47]. Kelman and Spence [15] also state that timber buildings may float, if not anchored, whereas masonry buildings tend to be more stable. The type of foundation along with its depth (shallow, semi-deep, and deep) reflect the resistance ability of a structure [48]. Fotopoulou and Pitilakis [49] stress that the foundation and structure details are the main parameters that determine the capacity of a building to withstand slow moving landslide displacements. The presence of basement can also directly influence the damage level of a building. For instance, in European mountain areas, typical residential buildings have a basement which functions as a quasi-first floor towards the valley [50]. Basements with openings oriented towards the flow below the expected possible flood level increase the total vulnerability of the building and the potential damage level.

2.1.2.3. State indicators. The state of the structural and non-structural elements is essential for the integrity and stability of buildings not only facing earthquakes, but also landslides and floods. The state of maintenance is used as a susceptibility factor for reducing the capacity of a building against landslides [3]. Maldonado Rondón and Chio Cho [51] consider the presence of cracks in relation with the wall preservation conditions as one of the parameters than have a major influence on building resistance to landslides. Poor quality construction (either in the use of the materials, design, or construction techniques) can explain variations in vulnerability of buildings subjected to similar impact pressures.

2.1.2.4. Location-related indicators. The location of a building with respect to the damaging process and its proximity to other objects are not direct indicators of its inherent capacity to withstand the impact of a hydro-meteorological hazard. However, given the positive (reducing) or negative (enhancing) effect of adjacent buildings, mitigation structures, vegetation cover, etc. on hazard intensity levels location-related indicators are used, as in many cases these possibly interposing bodies are not included in the hazard modeling. Li et al. [48] for example calculated the intensity of a landslide in a quantitative vulnerability framework taking into account the location of a structure within or outside the landslide area. Van Westen et al. [52] examine the range of damage types associated with various locations of elements at risk with respect to a landslide body.

The indicators discussed above, are further compared in terms of their relevance for vulnerability of buildings to river floods, flash floods, slow moving landslides and debris flows. Thus, for example, the “foundation type” has the highest relevance as an indicator for slow moving landslides, whereas for debris flows and floods, medium and low, respectively. This comparison will provide the indicators' selection basis for the development of a vulnerability matrix for each investigated hazard. The purpose, design and application of the indicator matrix are explained in the following section.

2.1.3. Design of the vulnerability indicator matrix

The indicators for the vulnerability of buildings identified in Section 2.1.2 and Table 1 are further listed in a matrix in such a way that one indicator can be compared with any other using a rating system with the following descriptors: 1-least important, 2-less important, 3-equally important, 4-more important, 5-most important. Four types of vulnerability indicator matrices pertaining to the analyzed hazards were constructed and subsequently used in an expert based weighing process for the calculation of the vulnerability index. The application of the matrix is illustrated for river floods in Table 2: one expert can consider that given the hypothetical impact of a river flood on a residential building, the indicator ‘building size' (row) is considered to be *less important* than the indicator ‘floor height from ground level' (column).

2.1.4. Expert analysis and weighing of indicators and their values

Quantitative information concerning the factors influencing vulnerability of buildings to hydro-meteorological hazards in data scarce areas is generally difficult to collect due to primarily resources constraints. However, one method to overcome this obstacle is the use of expert judgment, as an expression of informed opinion, based on the knowledge and experience of investigators in responding to various technical problems [53].

In this study, a pre-selected group of 20 respondents with different levels of expertize (seniors to early stage researchers) in natural hazard and risk assessment performed the weighing process of vulnerability indicators. The respondents were ensured with prior knowledge of the study area as a result of field

Table 1
Indicators used for the design of vulnerability matrices and a comparison of their relevance (H – high relevance, M – medium relevance, L – low relevance, '–'no relevance) for each hazard type: river floods (RF), flash floods (FF), slow moving landslides (SML), and debris flows (DF) (Adapted and modified after [4]).

Building indicators	RF	FF	SML	DF
Floor height from ground level	H	H	L	M
Number of floors	H	H	L	M
Number of openings	H	H	–	H
Openings towards slope	–	L	L	H
Building size	L	M	M	M
Structural type	M	M	H	H
Foundation type	L	L	H	M
Foundation depth	L	M	H	M
Wall material	M	H	M	H
Quality of construction	M	H	M	H
Building maintenance	L	M	M	M
Presence of basement	H	H	L	M
Cracks in the structure	L	M	H	M
Wall around the building	H	H	M	M
Building located on slope	–	L	H	M
Building located close to slope	M	L	M	H
Presence of in between buildings	–	H	L	H

investigations and past research experience. Each individual was asked to compare the relative importance of different building vulnerability indicators towards a given hazard, using the rating system described in Section 2.1.3. The respondents were given the choice to incorporate additional indicators in the matrix, if considered relevant. The weights given for different vulnerability indicators were normalized and computed in a final index using a Multi Criteria Decision-Making technique, i.e. Multi Criteria Evaluation (MCE) based on Analytical Hierarchy Process (AHP) analysis [54].

An extensive number of studies in the field of natural hazards vulnerability assessment have investigated the application and development of MCE techniques, allowing the use of expert knowledge to enhance the understanding of a specific research problem [55–58]. Generally, these techniques follow a three-fold procedure: (i) determining the relevant criteria and alternatives, (ii) attaching numerical measures to the relative importance (i.e. weights) of the criteria and to the impacts of the alternatives in terms of these criteria, and (iii) processing the numerical values to determine a ranking of each alternative [59].

In this study, the implementation of the second and third step within the MCE was performed using the Spatial Multi Criteria Evaluation (SMCE) module of ILWIS 3.3 software package [60]. The relative importance of the indicators was assessed using the pairwise comparison method, from which normalized weights were then calculated. The same procedure used for weighing the building indicators (e.g. number of floors) was repeated for the respective indicators' observed value (e.g. two floors as estimated through field survey or desktop mapping).

2.1.5. Calculation of the vulnerability index (VI)

The vulnerability index (VI) of each building is calculated using the normalized weights of the characteristic indicators (A_i) and the normalized weights of the observed indicator values (a_j), as shown in Eq. (1):

$$VI = \sum_{i,j=[0,1]}^{n} A_i a_j \qquad (1)$$

where,

A_i is the normalized weight of the indicator (e.g. number of floors), and a_j is the normalized weight of the indicators' observed value (i.e. for number of floors: two floors).

Table 2
Matrix used for weighing indicators relevant for vulnerability to river floods.

River Flood	Floor height from ground level	Number of floors	Structural type	Building size	Wall material	Presence of basement	Height of openings	Quality of construction	Building maintenance	Wall around the building
Floor height from ground level										
Number of floors	4									
Structural type	2	4								
Building size	2	2	2							
Wall material	5	4	3	4						
Presence of basement	4	3	4	4	2					
Number of openings	4	4	4	4	4	3				
Quality of construction	2	4	2	4	3	2	1			
Building maintenance	2	3	2	4	2	2	1	1		
Wall around the building	3	4	3	4	4	4	3	4	5	

1 – least important, 2 – less important, 3 – equally important, 4 – more important, 5 – most important

2.2. Development of the generic vulnerability curve (GVC)

Initially various vulnerability (stage-damage) curves for landslides and floods for reinforced concrete (RC), brick masonry, and wooden buildings were collected from the literature. The selection process took into account the need to ensure a good comparison between the curves (functions) in terms of characteristics of the elements at risk (e.g. number of floors, building structural type, etc.), as well as the intensity proxy used to characterize the severity of the hazard (inundation depth – for floods, and deposition height – for landslides). In terms of debris flow vulnerability modeling, empirically as well as numerically derived vulnerability curves were used to compensate for their limited availability in the literature. The expression of degree of loss (e.g. damage percentage, damage ratio, damage factor, damage degree) for flood curves was brought to a common denominator on a scale from 0 to 1. For this study, the set of functions chosen for river floods and debris flows is presented in Figs. 2, 3, and 4. After the selection of the curves, the generic vulnerability curve (GVC) is calculated by computing the average of the input curves. The variation between functions is calculated as standard deviation (σ) from the mean (μ) and plotted as an envelope showing the range of variability (see Fig. 5).

2.3. Calculation of specific vulnerability curve (SVC)

Finally, the vulnerability index (VI) together with the generic vulnerability curve (GVC) is used to calculate a specific vulnerability curve (SVC) for a given building. As the VI is derived considering multiple characteristics of the building that contribute to its degree of loss, it can be used to calculate vulnerability values associated with a given hazard intensity. The key assumption behind this step is that the calculated GVC defines well the relationship between the hazard intensity and the expected degree of loss in the area of investigation. That means also that the minimum and maximum VI values (0–1) are well represented within the range of variability of the GVC (grey area enclosed by two dotted black lines in Fig. 5). Fig. 5 illustrates two specific vulnerability curves derived for two wooden buildings with different degrees of loss.

After the intensity and the vulnerability index have been assessed, each building can be represented by a curve using a set of XY points plotted within the GVC envelope (X – intensity; Y – VI, where the GVC represents the 0.5 VI value). The degree of loss is then read for each point along the curve on the left ordinate. For example, given an inundation depth of 1 m and a VI equal to 0.4 for Building 1, the estimated degree of loss is 0.42. For Building 2, an inundation depth of 0.9 m will hypothetically result in a degree of loss of 0.56 when VI equals 0.9. In other words, knowing the vulnerability index of a building and the hazard intensity to which it is exposed, the degree of loss can be estimated provided that a generic vulnerability curve is available.

3. Application of methodology

The chosen test area is Nehoiu Valley, situated within the administrative boundaries of Nehoiu City, Buzău County, Romania. The selection of this case study gave the opportunity to apply the methodology in an area where recurrent floods and landslide events occur and no prior information about the vulnerability of the elements at risk exists. Moreover, despite the limited damage information, an attempt was made to validate the method against actual compensation data received per household in the aftermath of a hydro-meteorological event.

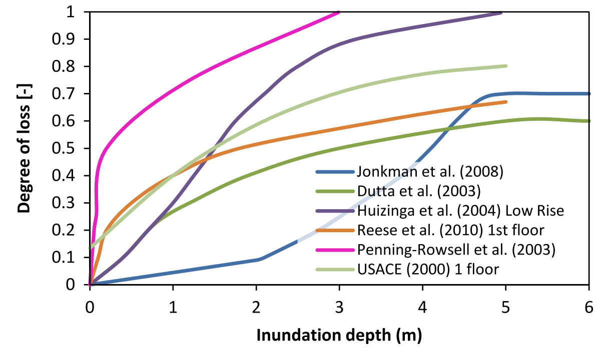

Fig. 2. Selected flood vulnerability curves for RC buildings [61–67].

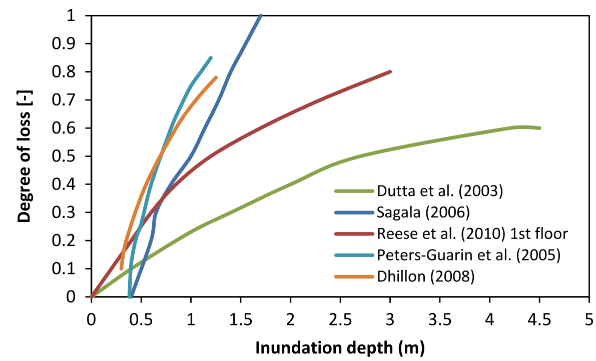

Fig. 3. Selected flood vulnerability curves for wooden buildings [44,62,65,68,69].

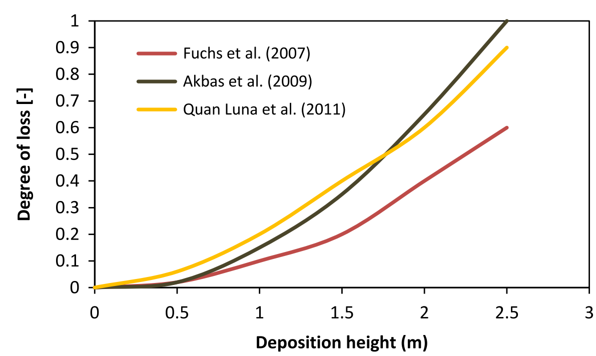

Fig. 4. Selected debris flow vulnerability curves for brick masonry buildings [16,70,71].

3.1. Determination of the study area, data collection for hazard information and building characteristics

Nehoiu Valley (Valea Nehoiului) is situated in Buzău County, in the south-eastern part of Romania. The valley stretches between about 350 m at the lowest point to 1346 m on the highest peak, and is drained by the Nehoiu River (14 km long), a right-hand side tributary of Buzău River. Geologically, Nehoiu Basin is constituted of Paleogene flysch deposits (mainly low – Oligocene, low-mid Eocene sandstones with schistose intercalations, and mid-Miocene schists), disposed in NE – SW direction as a result of thrusting and folding during the SW – SE Miocene tectonic compression [72]. The basin area (equal to 36 km^2) is morphologically controlled by the structure and lithology as well as the seismic mobility of the Vrancea region to which it pertains, and which is severely affected by a wide range of mass movements and erosional processes [73]. The valley displays steep slope fronts (over 35–40°) adjoining the river channel in the middle part of the catchment, with mean slope values (between 15° and 30°) in the low-lying areas, and

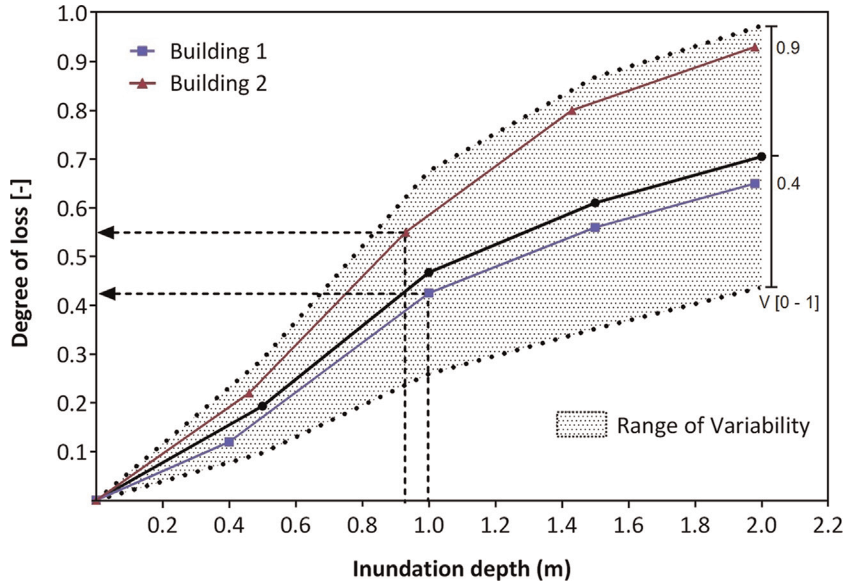

Fig. 5. Specific vulnerability curves derived for wooden buildings hypothetically damaged by floods (similar to relative damage curves in the literature). The vulnerability values for Building 1 and Building 2 are indicated with black dashed arrows. The GVC is shown in black color.

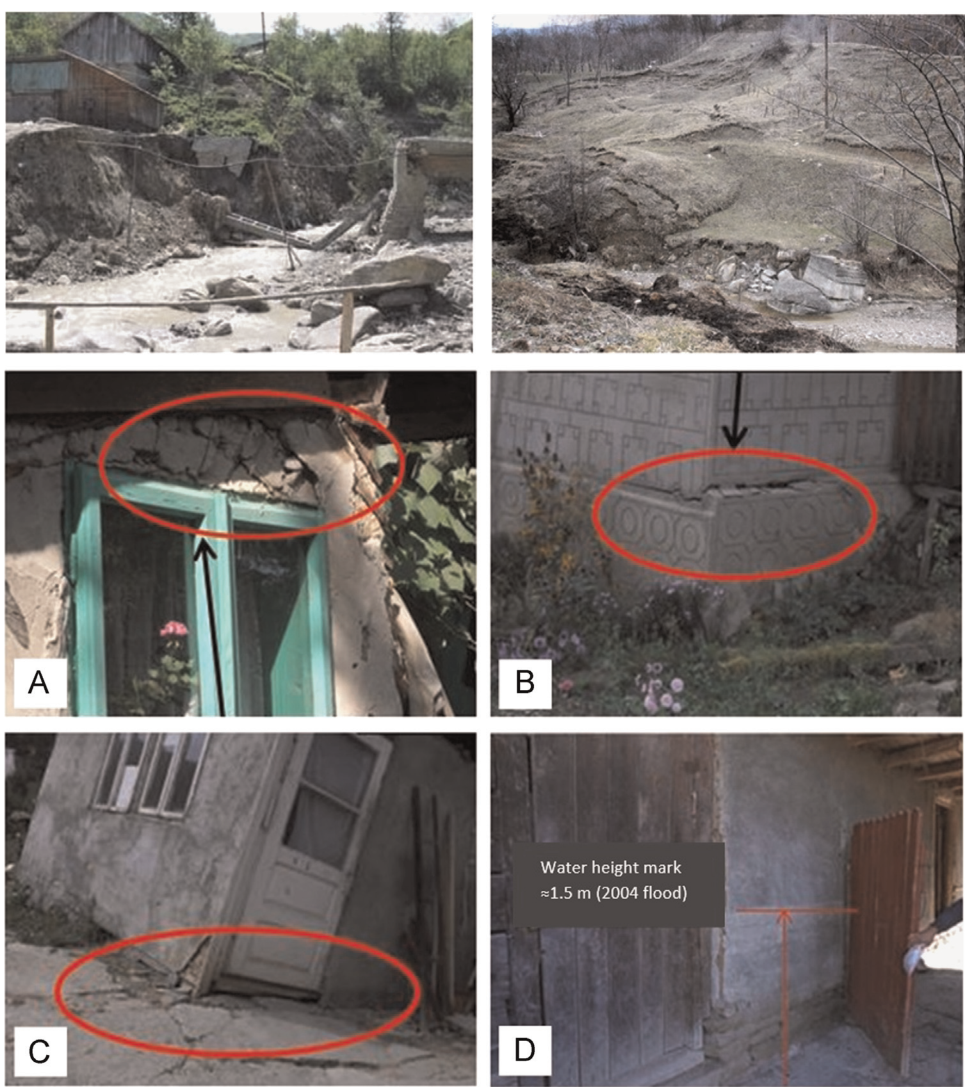

Fig. 6. Photos taken after the 2004 (upper left) and 2005 (upper right) hydro-meteorological events (Source: Emergency Situation Inspectorate). Examples of buildings damaged during 2004–2010 events. A and C – functional damage caused by slow moving slides; B and D – superficial damage caused by deep-seated slide and flood, respectively.

very steep slopes (with over 45°) above 1100 m. The multi-annual (1961–2007) mean rainfall quantities correspond to 640 mm (at Pătârlagele weather station, 13 km south of Nehoiu), however the precipitation regime is characterized by high annual variability with exceptional quantities cumulated in short time intervals (1–3 July 1975, 203.8 mm and 19–21 September 2005, 93.3 mm in 72 h) [74].

As a result of these boundary conditions-and considering also the probable effects of the socio-economic changes in the last 20 years such as depopulation and deforestation [75] – the study area is prone to flash floods, shallow-, and deep-seated landslides. The most recent excessive rainfall period (2004–2006) gave rise to several episodes of slope instability and flooding in the region. On 28 July 2004, a flash flood with an estimated peak discharge of 250 m^3/s (larger than 1% probability; Buzău – Ialomița Water Basin Authority, 2013) caused damages to the transportation infrastructure and affected approximately 133 households, out of which 3 houses were completely destroyed. According to municipality reports, the direct estimated financial loss amounted to over 1 million Euro. In the following year (4–8 May 2005), a second extreme rainfall event (50.3 mm in 16 h [76]) generated another flood and shallow landslides which affected the transportation network (370 households being isolated), river regulation works, water supply and electrical network in the ill-recovered community (Fig. 6). Other significant hydro-meteorological events in the catchment were registered in 1975, 2006, and 2010 (Table 3).

General information about previous hazard events was collected from official reports provided by the municipality, County Prefecture and Emergency Situation Inspectorate Buzău; however, detailed data about the damage degree at building level was not readily available. A landslide map was generated using ortophoto interpretation (2005, 2008) subsequently validated and updated in the field. In terms of hazard zonation, the General Urbanistic Plan of Nehoiu Valley (dated December 2004) includes only information regarding the temporary restricted construction zones due to

Table 3
Reported hydro-meteorological events in Nehoiu Valley (Source: Emergency Situation Inspectorate, Buzău Prefecture).

Date of event	Hazard type	Damaged elements at risk	Total estimated costs (€)
July 1975	Flash flood	n.a.	n.a.
28 July 2004	Flash flood	150 buildings flooded, 370 buildings isolated, river works transportation infrastructure	> 1 Mil.
7 May 2005	Flash flood and landslides	133 buildings, electrical, water supply networks, transportation	n.a.
2 January 2006	Landslides	Electrical network, transportation infrastructure	814.000
22 February 2010	Landslides	Transportation infrastructure, 28 buildings isolated	n.a.

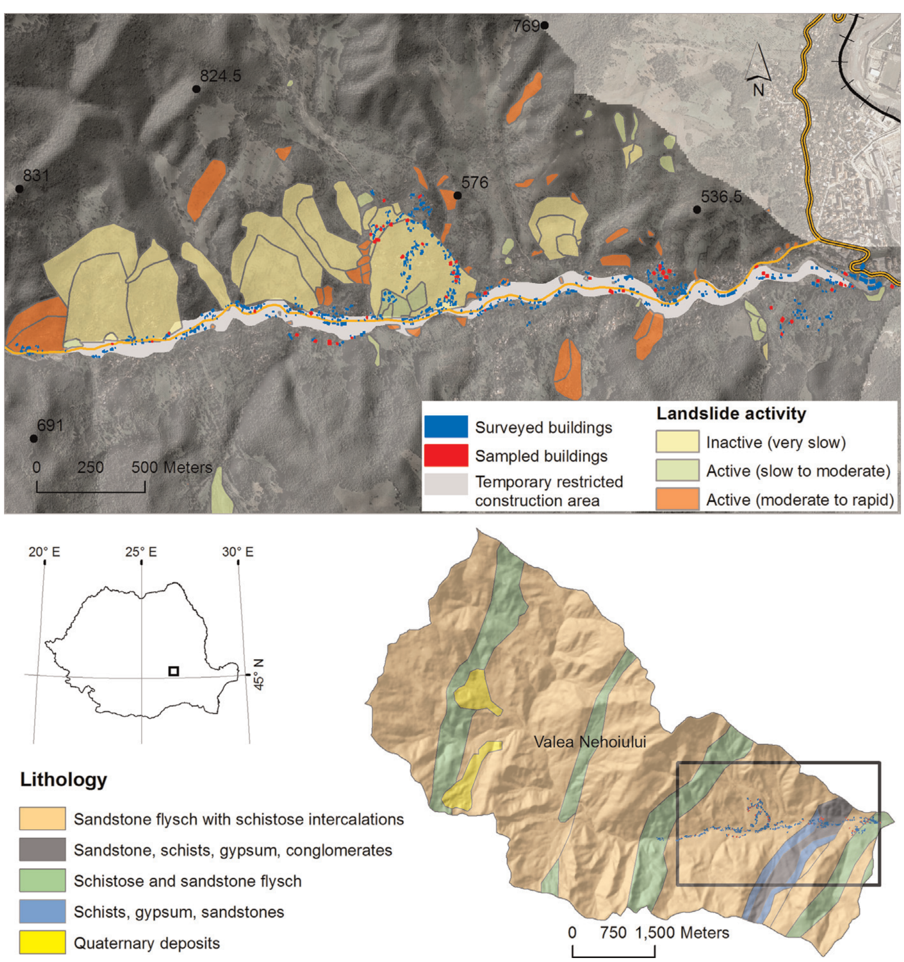

Fig. 7. Location of buildings with respect to landslide bodies in the lower part of Nehoiu Valley. Bottom right: simplified lithological map (scale 1:200,000. Source: Geological Institute of Romania).

landslides, floods, and erosional processes (Fig. 7). No landslide/flood hazard or risk maps were accessible.

3.2. Selection of building vulnerability indicators for floods and landslides

No previous data about building characteristics was available, thus a thorough field investigation complemented by local interviews and ortophoto interpretation was performed. 689 residential buildings were surveyed in order to collect information about occupancy and structural type, state of maintenance, and number of floors. Detailed data on the remaining indicators (Table 4) and hazard intensity (inundation depth and debris height) was obtained by interviewing owners of 60 sampled residential buildings. The sample criteria were the willingness of the owners to perform the interview and the prior impact of a hydro-

Table 4
Indicators selected for the vulnerability analysis in Nehoiu Valley.

Code	Indicator	Source of information	Value
HGF	Floor height from ground level	Interview	Number
NOF	Number of floors	Field mapping	Number
ONO	Number of openings	Interview	Number
OTS	Openings towards slope	Interview	Number
BSZ	Building size	Ortophotos interpretation	Number
STY	Structural type	Field mapping	RC, Steel, Masonry, Wood
FT	Foundation type	Interview	Stone+Adobe, Brick+Adobe, Stone+Concrete
FD	Foundation depth	Interview	Number
WM	Wall material	Interview	RC+Brick, Brick+Wood, Wood, Wood+Adobe
QCS	Quality of construction	Interview	High, Medium, Low
BMN	Building maintenance	Field mapping	High, Medium, Low
PBS	Presence of basement	Interview	Yes, No
CST	Cracks in the structure	Interview	Yes, No
WAB	Wall around the building	Ortophotos interpretation	Yes, No
BOS	Building located on slope	Ortophotos interpretation	Yes, No
BCS	Building located close to slope	Ortophotos interpretation	Yes, No
PiBB	Presence of in between buildings	Ortophotos interpretation	Yes, No

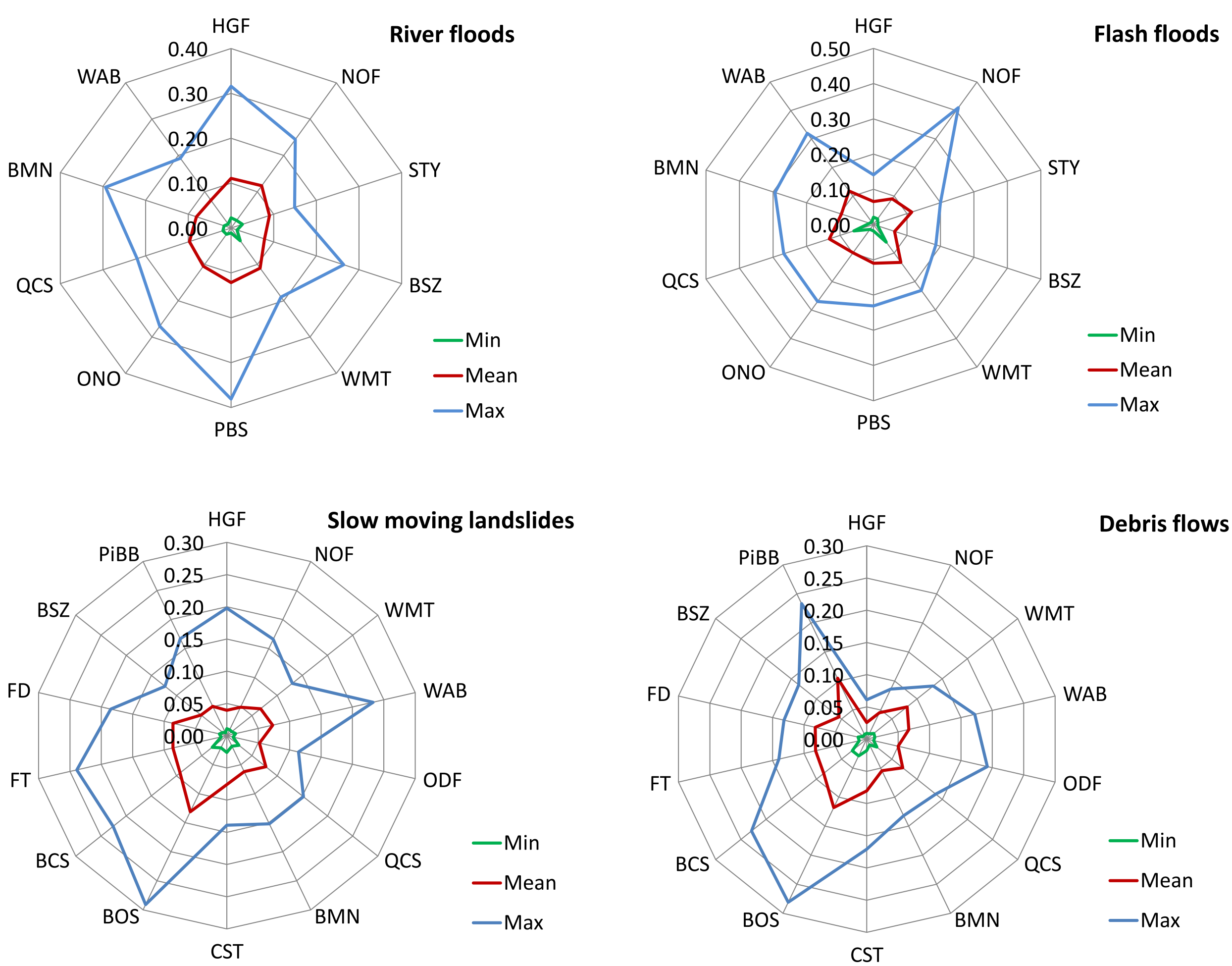

Fig. 8. Normalized weights (minimum, mean, maximum) of building indicators as assigned by the experts group (see Table 4 for indicators´ code).

meteorological hazard on the structure.

3.3. Weighing of indicators and their values, calculation of vulnerability index and development of generic and specific vulnerability curves

The weighing of indicators was performed through the application of the vulnerability indicator matrix as explained in Section 2.1.3 for all four hazard types. The minimum, maximum and mean normalized weights assigned through the MCE process by the group of experts are illustrated comparatively in Fig. 8.

In a second step, the indicator values (e.g. 0–2 m, for "floor height from ground level" indicator; 1–2 floors, for "number of floors" indicator, etc.) were assigned based on interviews, observations during field work and mapping, as showed in Table 4. The relative importance (weight) of each indicator value was evaluated based on a thorough literature review and local damage reports. The normalized weights were computed using the pairwise comparison within the SMCE module (Table 5). An Inconsistency Ratio (IR) was calculated for all indicators where the number of possible values was larger than 3. IR (0–1) shows whether the pairwise comparisons are sufficiently consistent; a value of 0 indicates complete consistency; a value larger than 0.1 indicates inconsistency [60].

Mean normalized weights of indicators and indicator values are further used for the computation of the vulnerability index (VI) as indicated in Eq. (1). An example of computed vulnerability index (VI) for a building affected by river floods is given in Table 6.

The total building stock in the area of study is characterized by the prevalence of wooden structures (67%). For the 60 sampled residential buildings, 86.7% are wooden structures, 8.3% masonry, 1.7% RC, and 3.3% other.

Given the limited availability of vulnerability curves for the calculation of GVC for slow moving landslides and flash floods, the construction of SVC is demonstrated only for wooden buildings affected by river floods. Fig. 9 compares the GVC and SVC obtained for six buildings within this category. One SVC (19WE04) exceeds the average vulnerability value for all intensity classes, whereas the rest are estimated below the GVC. The lowest VI (and overall vulnerability) is attributed to building 20TH04 due to its good maintenance state and construction quality as well as the higher number of floors; another factor possibly reducing its vulnerability is the presence of a wall around the building (Table 7). In contrast, building 19WE04 has a higher surface area distributed on one single floor level.

The spread of SVCs is observed markedly for intensity classes higher than 0.5 m, but it is contained within the range of variability of the GVC. Table 8 shows the mean and standard deviation values of all vulnerability functions used to calculate the river flood generic vulnerability curve (see also Fig. 9).

Vulnerability indices for the sampled buildings were computed for all investigated hazards. The results (Fig. 10) show that their value ranges mostly between 0.2 and 0.6 for all hazard types. The lowest frequencies were registered for the 0–0.2 class (1 building – river floods, 4 buildings – flash floods) and 0.6–1 class (3 buildings – river floods, 2 buildings – slow moving landslides). Overall, the highest frequency (37 buildings) was recorded for vulnerability indices between 0.4 to 0.6 for river floods. No buildings within the sampled set exhibited vulnerability indices lower than 0.2 for debris flow or slow moving landslides.

An attempt to validate the vulnerability index was made by comparing it with the actual material compensation received per household in the aftermath of the 28 July 2004 event. For this purpose, the compensation data, provided by the Nehoiu Local Municipality, was used to obtain a monetary value which directly reflects the physical damage suffered by the structure and not for example its content or other indirect losses. Each household received a certain amount of construction materials (e.g. cement, timber, tiles, bricks, asphalt boards, etc.) which was further evaluated into currency (as indicated by municipality reports) and indexed to 2004 values in Euro. The results suggest (Fig. 11) that the observed outcomes are generally comparable with those predicted by the model (i.e. the greater the aid value, the higher the vulnerability index); however, there is evidence (coefficient of determination $R^2=0.57$) of variation in the value of aid per household that cannot be explained by the vulnerability index, as for buildings 19WE02, 01MO01, for example. The modeled increase in VI could be attributed to the effects of subsequent hydro-meteorological events (e.g. 2005, 2006, 2010) on the resistance and state of these two residential buildings.

Table 5
Normalized weights of indicators' value for landslides and floods using pairwise comparison.

Indicator	Indicator value	Normalized weights
Floor height from ground level (m) (*IR*=*0.1*)*	0	0.649
	0–2	0.201
	2–5	0.11
	≥5	0.041
Number of floors	1	0.875
	2	0.125
Number of openings (*IR*=*0.08*)	0–2	0.643
	2–5	0.209
	5–10	0.097
	≥10	0.051
Openings towards slope	Yes	0.9
	No	0.1
Structural type (*IR*=*0.02*)	RC, Steel	0.07
	Masonry	0.178
	Wood	0.751
Foundation type (*IR*=*0.1*)	Stone+Adobe	0.487
	Brick+Adobe	0.435
	Stone+Concrete	0.078
Foundation depth (cm) (*IR*=*0.08*)	0–20	0.297
	20–50	0.088
	> 50	0.047
	n.a.	0.568
Wall material (*IR*=*0.1*)	RC + Brick	0.04
	Wood+Brick	0.079
	Wood	0.242
	Wood+Adobe	0.64
Building maintenance, Quality of construction	High	0.058
(IR=0.09)	Medium	0.207
(*IR*=*0.09*)	Low	0.735
Presence of basement, Cracks in the structure	Yes	0.9
	No	0.1
Wall around the building, Presence of in between buildings	Yes	0.1
	No	0.9
Building located close to/on slope	Yes	0.9
	No	0.1

* Inconsistency ratio.

Table 6
Vulnerability index (VI) for building 19WE05 affected by river floods.

Indicator	Building 19WE05	Mean normalized weight of indicator*	Normalized weight of indicator value
Floor height from ground level (m)	2	0.142	0.201
Number of floors	1	0.135	0.875
Structural type	Wood	0.085	0.751
Building size (m²)	182	0.093	0.041
Wall material	Wood + adobe	0.121	0.640
Presence of basement	Yes	0.074	0.900
Openings (number)	4	0.105	0.643
Quality of construction	Low	0.088	0.735
Building maintenance	Low	0.082	0.735
Wall around the building	No	0.075	0.900
Vulnerability Index		**0.618**	

* See Fig. 8.

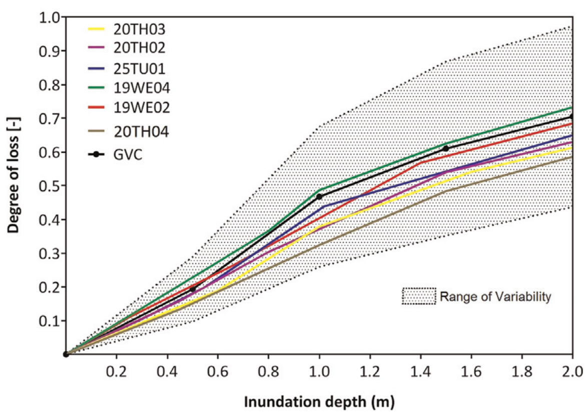

Fig. 9. River flood Specific Vulnerability Curves (SVC) for wooden buildings.

Table 8
Mean (μ) and standard deviation (σ) values for river flood vulnerability curves used to calculate the GVC.

Inundation depth (m)	μ	σ
0.5	0.19	0.10
1	0.47	0.21
1.5	0.61	0.26
2	0.71	0.27

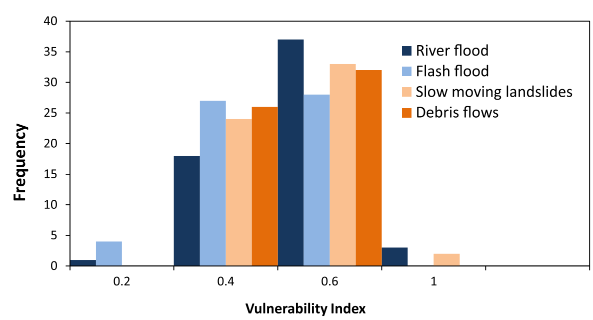

Fig. 10. Frequency distribution of vulnerability indices per hazard types.

4. Discussion and conclusions

In this study, two vulnerability models (i.e. vulnerability curves and indicators) were jointly used to tackle the challenge of limited or generalized description of building's physical characteristics used for the development of vulnerability curves. It is broadly agreed that the latter are models which look at one (e.g. structural type) at most two building characteristics in order to define a relation (function) between the hazard intensity and the degree of loss. The current methodological approach takes into account a set of observable characteristics such as building material, orientation and height of openings, state of maintenance, etc. resulting in a more advanced differentiation of vulnerability based on asset scale information.

A set of vulnerability (damage) curves for landslides and floods was used in order to calculate a generic function that can be transferred in the area of investigation. The findings suggest that even after considering the compatibility of building characteristics (number of floors, presence of basement, etc.) and selection of intensity proxies, the functions differ (especially for floods). This might be related with variability in building sample size as well as the spatial level of detail in the analysis [77]. Another explanation is that for the same type of building, various construction styles (e.g. dimension, position of structural elements, etc.) may be used. Moreover, the addition of detachable elements which do not modify the building type but increase its overall susceptibility (e.g. solar panels) can inflate the potential degree of loss. Another likely cause might be the heterogeneity of similar impacting processes and the selection of intensity proxies. An illustration of such a case is the set of vulnerability curves for buildings affected by river flooding depicted in Figs. 2 and 3. Steeper curves indicating a higher degree of loss might be related to an increase in velocity; however, data concerning this parameter may not have been readily available and thus a second-order intensity proxy like water depth was used.

Table 7
Vulnerability indices (VI) for wooden buildings affected by river floods (for indicators´ code see Table 4).

Building ID	HGF	NOF (G=1)*	BSZ (m^2)	WM	PBS	ONO	QCS	BMN	WAB	VI
19WE02	0	1	44	wood	NO	2	medium	good	no	0.50
19WE04	0.5	1	101.3	wood + adobe	NO	8	low	low	no	0.52
20TH02	0.5	1	46.33	wood + adobe	NO	8	low	medium	no	0.46
20TH03	0.5	1	20.87	wood	NO	5	medium	medium	no	0.41
20TH04	10	2	22.15	wood + adobe	YES	9	good	good	yes	0.28
25TU01	10	1	35.43	wood + adobe	NO	5	good	good	no	0.48

* G = ground floor is counted as first floor.

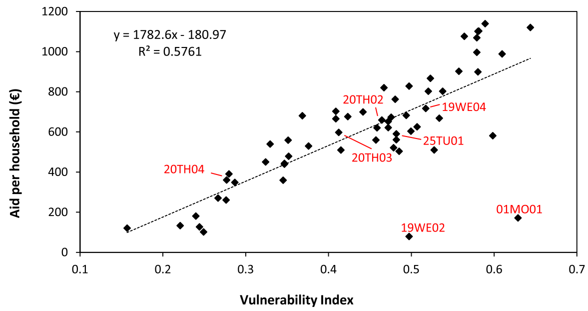

Fig. 11. Calculated vulnerability index vs. compensation values per household after the 28 July 2004 event (see also Fig. 9 for buildings' SVC).

Based on the step-wise methodological procedure, three main results can be indentified in this study: (1) firstly, the vulnerability index (VI) was obtained through an expert based weighing process using the Spatial-Multi-Criteria-Evaluation (SMCE) analysis tool. Despite this proved to be important for the identification and prioritization of indicators and their values, a side effect of subjective judgment elicitation is the introduction of epistemic uncertainties (expert bias). An indicative measure of the magnitude of error introduced through the use of AHP ranking process (pairwise comparison) was given by the Inconsistency Ratio (IR). In all cases, the results showed a reasonable coherent set of assessments ($IR \geq 0.1$). Nonetheless, methodological improvement can be considered in the future through the introduction of MCE techniques that allow for characterization and quantification of uncertainty (e.g. DS/AHP method; [84] or by improving the accuracy of the AHP by using additional information (e.g. probabilities or ranges of values/scores, etc.). Nevertheless, the SMCE module and the vulnerability indicator matrix are relatively straightforward tools in the hands of practitioners and experts who require a measure of building exposure to different types of hazards.

Current studies take into account changes in physical vulnerability of elements at risk using a hazard-based scenario approach (for example, [48,83]). Yet the temporal variability of buildings characteristics is rarely considered in modeling procedures; the difficulty originates in the agreement that must be obtained between the scale of analysis, the rate at which significant changes in building characteristics take place and the resources available. In the proposed approach, as new information about the characteristics of the buildings is acquired, the specific vulnerability curve can be improved and updated by re-calculating the vulnerability index.

(2) The generic vulnerability curve (GVC) is obtained in a second step and it reflects the variability of the functions it derives from. This might be related (in addition to the causes mentioned earlier) with the use of different methods for estimating the probability distributions (e.g. gamma, beta, triangular, etc.) and their parameters [79,80,42]. A possible source of uncertainty in calculating the GVC is the selection of the averaging method as well as the number of functions available. Further work must be invested in the use of vulnerability curves for which uncertainty is already quantified.

(3) Lastly, the specific vulnerability curve (SVC) is obtained using the vulnerability index and the generic vulnerability curve, which implies possible uncertainty propagation from one step of analysis to another. In this study, the SVC was obtained by plotting a limited number of building points which might reduce the representativeness of the results obtained. An alternative solution to overcome this issue is to construct one specific vulnerability curve (SVC) per building type using all available buildings pertaining to this category (one building representing one point in the *XY* space, with *X* being the intensity and *Y*-vulnerability index). Consequently, uncertainty related with the interpolation between a limited number of points will be reduced and the representativeness of the curve will increase. However, one still needs to account for the uncertainty related with the selection of the interpolating (non-linear) function.

Validation of the methodology was performed for the vulnerability index through comparison with compensation data at household level. However, as suggested by the goodness of fit test, the observations are not completely explained by the modeled outcomes. This seems to confirm the findings of Pistrika et al. [77] who demonstrated that a higher spatial level of detail results in a lower level of correlation between predictions and observations. Further testing should focus on calibrating and validating the methodology in areas where damage data is more reliable and readily available.

In addition to the observations above, some limiting factors in the application of the methodology can be identified: (i) the data collection phase for the generation of building database can be considered time consuming, depending on the size of the investigated area. In this study, 60 buildings out of over 600 surveyed were actually used for the calculation of the vulnerability index and development of specific vulnerability curves. Although this might be considered a fairly reasonable sample number, increasing the building sample size would result in more reliable results. This process can be aided by the use of alternative data collection methods (e.g. questionnaires sent to the inhabitants, participatory mapping, etc.). (ii) The time span between the data acquisition/analysis and the actual occurrence of the 2004 event might may have resulted in changes in the building stock. However, given the communities' socio-economic characteristics as well as the traditional practices of building in the region, it is likely that the rehabilitation of the impacted structures followed a similar construction pattern as prior to the event. (iii) Lastly, the reduced number of functions available for slow moving landslides and flash floods and limited information about the hazard intensity might have affected the accuracy of the obtained results. Yet, although the methodological framework is completely tested only for river floods, the procedural steps are similar for all hazard process types. Future investigations on hazard modeling (statistical, deterministic, physical) could improve the quality of the results notably and allow for an extensive vulnerability assessment at community level.

In this paper, a new physical vulnerability assessment method for buildings impacted by floods and landslides is introduced. The specific methodology is based on the innovative use of two complementary models: vulnerability (damage) curves and indicators. The main idea was to enable assessing buildings' degree of loss in study sites where limited information about the hazard impact and the resistance of buildings exist by using expert elicitation and transferred functions to derive a specific vulnerability curve representative for the investigated area. The results of this study show that the proposed methodology makes it possible to use vulnerability indicators in order to calibrate vulnerability values transferred from different areas for new buildings in comparable socio-economic contexts. The results also demonstrate that a minimum of (mandatory) information concerning the impacting process and the damage level of the buildings exposed is necessary to perform the assessment and validate the outcome. The proposed method can be used as a tool for decision-making support in disaster response and risk management.

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