Physical vulnerability assessment to flash floods using an indicator-based methodology based on building properties and flow parameters

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Abstract
This study focuses on the physical vulnerability of buildings to flash floods using an indicator-based methodology. A physical vulnerability index (PhVI) that combines intrinsic vulnerability (IV) of buildings and flash flood intensity (FFI) is proposed. IV evaluates the propensity to suffer damage, resulting from indicators related to building properties. FFI estimates the potential to cause damage, resulting from indicators related to flow parameters. PhVI was applied to a critical section of a small drainage basin in Portugal where flash floods are frequent. Evaluating IV and the intensity of natural hazards is essential in physical vulnerability assessments. This study addresses two problems found in the literature: the lack of flash flood-dedicated physical vulnerability assessments and the difficulties in assembling building properties and the intensity of natural hazards in a vulnerability index defined from indicator-based methodologies. PhVI is a useful tool where damage records are rare or non-existent, allowing the prioritisation of resources and application of local protection measures. This index can be adapted to other study areas and natural hazards, although more research is needed to improve the knowledge on the indicators and weights of IV and FFI.

KEYWORDS
building properties, flash floods, flow parameters, indicator-based methodology, physical vulnerability

1 INTRODUCTION

Meteorological, geological, geomorphological, hydrological, and land use characteristics influence the spatial distribution of flooding occurrences (Diakakis, Deligiannakis, Pallikarakis, & Skordoulis, 2016; Norbiato, Borga, Degli Esposti, Gaume, & Anquetin, 2008). On the other hand, the expected increases in rainfall intensities resulting from climate change make flash floods more frequent and of greater magnitude (Botzen, van den Bergh, & Bouwer, 2010; Jha, Bloch, & Lamond, 2012; Marchi, Borga, Preciso, & Gaume, 2010), and the expansion and densification of built-up areas in flood-prone areas increase exposure and vulnerability to this natural hazard (Diakakis et al., 2016; Faccini et al., 2018).
Vulnerability is the most difficult risk component to define, assess, and quantify due to its several dimensions, interpretations, assessment methods, and researchers’ scientific area background (Birkmann et al., 2013; Camarasa-Belmonte, López-Garcia, & Soriano-Garcia, 2011; Karagiorgos, Thaler, Heiser, Hübl, & Fuchs, 2016; Mazzorana et al., 2014; Messner & Meyer, 2006). This study focuses on the physical vulnerability of buildings to flash floods, a less addressed topic when compared to other natural hazards (Karagiorgos et al., 2016). Physical vulnerability is understood as the combination of the predisposition of the exposed elements to suffering damage and the potential of natural hazards to cause damage (Papathoma-Köhle, GEMS, Sturm, & Fuchs, 2017; Pereira et al., 2020). There is no uniform methodology to assess physical vulnerability (Glade & Crozier, 2012; Papathoma-Köhle, 2016), which can be explained by multiple reasons: (a) complexity of the term, its scope, and the lack of a stabilised definition (Fuchs, 2009; Gaume et al., 2009); (b) difficulties in using the same methods for assessing vulnerability to different natural hazards (Kappes, Papathoma-Köhle, & Keiler, 2012); (c) different nature (quantitative or qualitative) of the elements that influence vulnerability (Fekete, 2009); (d) different spatial (national, regional, and local) and temporal scales used in vulnerability assessment (Birkmann, 2007; de Moel et al., 2015; Fekete, Damm, & Birkmann, 2010; Marchi et al., 2010); (e) lack of parameterisation data regarding damage caused by past events (Papathoma-Köhle, Kappes, Keiler, & Glade, 2011); and (f) reduced time for data collection in the field due to the intervention of technical services to restore the basic functions of the system and the security of infrastructures (Ettinger et al., 2016). Vulnerability curves and indicator-based methodologies are the two main methods for assessing physical vulnerability (Papathoma-Köhle, 2016). Vulnerability matrices are another method applied for landslides, debris flows, or floods (e.g., Garrote, Díez-Herrero, Escudero, & Garcia, 2020; Hu, Cui, & Zhang, 2012; Leone, Asté, & Leroi, 1996; Rojas, Mardones, Rojas, Martinez, & Flores, 2017), although impaired by high subjectivity involved (Papathoma-Köhle et al., 2017).

Vulnerability curves or stage-damage curves look at vulnerability as a degree of loss, being the most widely used methodology to assess vulnerability to floods at a local scale (Büchele et al., 2006; Hammond, Chen, Djordjević, Butler, & Mark, 2015; Papathoma-Köhle et al., 2011; Penning-Rossell et al., 2005; Smith, 1994; Spekkers, Clemens, & Ten Veldhuis, 2015). However, they have some limitations when applied to flash floods (Freni, La Loggia, & Notaro, 2010; Merz, Kreibich, Thieken, & Schmidtko, 2004): (a) common use of water depth as the only impact parameter, not contemplating other factors, such as velocity or solid charge (Middelmann-Fernandes, 2010); (b) construction materials are often the only building property used, not considering other intrinsic elements (Kappes et al., 2012); and (c) those can only be adapted to a specific location and can hardly be applied to other regions (Papathoma-Köhle et al., 2017; Papathoma-Köhle, Cristofari, Wenk, & Fuchs, 2019).

As the characteristics of the exposed elements are frequently unconsidered (Fuchs, 2009; Papathoma-Köhle, 2016), indicator-based methodologies have been gaining importance in vulnerability assessments, particularly regarding the building’s physical vulnerability in data-scarce regions (Fuchs, Keiler, Ortlepp, Schinke, & Papathoma-Köhle, 2019; Malgwi, Fuchs, & Keiler, 2020; Papathoma-Köhle, Cristofari, et al., 2019; Papathoma-Köhle, Schlägl, & Fuchs, 2019). These are common in the socioeconomic context, but have only recently been explored for physical vulnerability (e.g., Guillard-Gonçalves, Zézere, Pereira, & Garcia, 2016; Kappes et al., 2012; Müller, Reiter, & Weiland, 2011; Papathoma-Köhle, 2016; Silva & Pereira, 2014; Stephenson & D’Ayala, 2014). As a rule, vulnerability indicators look at vulnerability as an intrinsic predisposition, but not necessarily permanent or unchanging, for an element or a set of elements to be damaged when a natural hazard occurs (Cardona, 2003; de Bruijn, Green, Johnson, & McFadden, 2007; Winsemius, van Beek, Jongman, Ward, & Bouwman, 2013). This predisposition is dependent on the building properties (Beven et al., 2018; Merz, Kreibich, Schwarze, & Thieken, 2010). Structure, construction material, age, condition/conservation status, height, number of floors, and openings (existence, number, height, and dimension of doors and windows) are the most relevant (Douglas, 2007; Kappes et al., 2012; Kreibich, Seifert, Merz, & Thieken, 2010). However, indicator-based methodologies are often too focused on the characteristics of the exposed elements, forgetting that the intensity of the studied natural hazard plays a decisive role in vulnerability.

A physical vulnerability index (PhVI) combining intrinsic vulnerability (IV) and flash flood intensity (FFI) was proposed and applied to the exposed buildings in a small drainage basin in Portugal. The lack of a complete inventory of building damages caused by past flash flood events and the association with flow parameters justifies the use of an indicator-based methodology. The inclusion of flash flood parameters in an indicator-based methodology represents an innovative step in the assessment of this risk component. The interaction between floodwaters and buildings and the direct and indirect effects of flood extent, water depth and flow velocity can affect the level
of vulnerability of a building. The way each building is affected is different, resulting from the combination of its physical characteristics, its position in the flooded area, the flow parameters, and the intensity/magnitude of flash floods. The main goal of this work is to propose a method for assessing the physical vulnerability that assembles the IV and FFI, combining the characteristics of the exposed buildings and the potential of flash floods to cause damage. The results achieved can be useful for spatial planning and flood risk management, and the proposed method can be applied in other areas affected by flash floods and adapted to other natural hazards.

2 | STUDY AREA

Barcarena is a small, elongated drainage basin (area 34.2 km² and form factor 0.2, that is, the ratio of the basin area to the square of the basin length) included in the Sintra and Oeiras municipalities, close to Lisbon (Figure 1). Elevation ranges between 0 and 330 m. This is a low-permeability basin, in which the characteristics of bedrock (marls, limestones, and basalts), soil (mostly clayey) and land cover (almost half of its surface is occupied by built-up areas) favour overland flow. The time of concentration was estimated at 6 hr 20 min (according to the Temez method) and the lag time at 3 hr 48 min. The main watercourse, the Barcarena stream, is 19.4 km long with a torrential flow regime during heavy rainfall events. The average annual rainfall in this area is approximately 800 mm and is mainly concentrated between October and March. The maximum daily rainfall recorded was 181 mm. Flash flood events have caused 26 occurrences reported in newspapers and insurance claims during the 20th and 21st centuries in the Barcarena drainage basin (Figure 1). The most damaging event occurred in November 1967 (Trigo et al., 2016), causing eight fatalities.

The study area is in the middle section of the drainage basin (Figure 1), comprising a length of almost 1.5 km
and the confluence between the Barcarena stream and one of its main tributaries: the Massamá stream. There are retaining stone walls in some parts of this section to prevent lateral erosion and/or flooding. The study area contains housing, industrial, and education buildings with one or two floors with no basements. The same household or entity owns each building. Some of them are abandoned not only due to the closure of gunpowder, firearms, or ammunition factories but also because of flash floods. The housing buildings are old, in poor condition, and with structural problems in which mainly elderly and/or poor people remain. Currently, less than 10 people live in these precarious dwellings, after several families were relocated in recent years. However, the occupation of industrial and educational buildings during working days is substantially higher, increasing the number of people potentially exposed to flash floods. This is considered a critical point, as defined by the National Laboratory for Civil Engineering (LNEC), because flash floods are recurrent and even events with low return periods can cause damage. In the most recent damaging event, which occurred in November 2011, a pedestrian bridge and retaining walls near the confluence of the two streams were destroyed and floodwaters entered the houses. None of them was destroyed, and the costs were mainly associated with the content/goods in the houses.

3 | DATA AND METHODS

Figure 2 represents the methodological framework for assessing flood extent, flow parameters, exposed buildings, and the PhVI.

3.1 | Hydrologic and hydraulic modelling

Flood extent, water depths, and flow velocities in the study area were defined using hydrologic and hydraulic modelling. The lack of stream gauges in the drainage basin justified the use of a rainfall–runoff model in the HEC-HMS software to obtain peak discharges. A design hyetograph for a 100-year return period \( R_T \) was built from the intensity–duration–frequency curves of the São Julião do Tojal rain gauge, approximately 15 km NE of the study area, using a daily rainfall data series of 34 years (Brandão, Rodrigues, & Costa, 2001). The hyetograph was built using the alternating block method composed of 38 blocks of 10 min, equalling the time of concentration of the Barcarena drainage basin (6 hr 20 min). Furthermore, 119.5 mm is the cumulative rainfall during this period, and 19.5 mm is the maximum intensity in 10 min.

Hydraulic modelling was developed based on the interaction between HEC-RAS and Geographical Information Systems (GIS), using HEC-GeoRAS for ArcMap. The elevation data (1:2,000 scale) and the vectorised buildings were combined in a digital surface model (DSM). The input data pre-processed in ArcMap/HEC-GeoRAS and the peak discharges obtained from HEC-HMS were introduced in HEC-RAS to acquire water levels and flow velocities. Subsequently, the results were exported back to ArcMap, where the 100-year \( R_T \) flood was spatialised using HEC-GeoRAS. These results were validated by flood marks, testimonies from affected populations, newspapers’ information, television reports, and photographs of past flood events. Water depths and velocities were also spatialised using HEC-GeoRAS in a raster data structure with a 0.5 m cell resolution.

3.2 | Exposure

Exposure represents the elements (buildings) potentially affected by a natural hazard (Apel, Aronica, Kreibich, & Thieken, 2009; Merz, Thieken, & Gocht, 2007), in this case, by a 100-year \( R_T \) flood. Exposed buildings usually result from the intersection between flood extent and buildings in the study area. However, buildings were previously integrated in the DSM to achieve a correct terrain representation and estimate their influence on the extent, depths, and velocities of floodwaters. According to the results obtained from HEC-RAS/HEC-GeoRAS, buildings that are in contact with floodwaters are considered as exposed/affected.

This analysis allows the estimation of the potentially exposed perimeter (PEP), representing the portion of the building that can be affected by floodwaters and that, at most, will be equal to its perimeter. When PEP is smaller than the perimeter, it means that there are elements adjacent to that building (e.g., other buildings), not allowing it to be surrounded by floodwaters.

3.3 | Vulnerability

The physical vulnerability of the exposed buildings was assessed using an indicator-based methodology. The chosen indicators and their respective weights were selected based on scientific literature, the considered natural hazard (flash floods), and field knowledge. Equal weights were assigned when evidence was lacking that a given indicator was more important than another, as suggested by Rød, Opach, and Neset (2015) and Karagiorgos.
et al. (2016). A score from 0 (no vulnerability) to 1 (maximum vulnerability) was assigned to each building in each indicator, which is composed of a set of categories. Not all the categories presented in Figure 3 exist in the study area, but it was decided to include them for comparative purposes and understand the assigned weights, allowing this methodology to be used elsewhere. Only the exposed occupied buildings were included in the physical vulnerability assessment, excluding the abandoned ones. Most of them are currently in ruins since the gunpowder factory complex closed decades ago, while some of the residential buildings were abandoned due to the precarious housing conditions and their exposure to flash floods. These buildings will certainly not be reoccupied in the future.

3.3.1 | Intrinsic vulnerability

IV represents the propensity of exposed buildings to suffer damage, which are not equally susceptible to the impact and effects of a natural hazard (Papathoma-Köhle, Cristofari, et al., 2019). IV was assessed using five.
indicators with major influence on the resistance of buildings to flash floods (e.g., Fedeski & Gwilliam, 2007; Kappes et al., 2012; Karagiorgos et al., 2016; Papathoma-Köhle, Cristofari, et al., 2019; Silva & Pereira, 2014; Stephenson & D’Ayala, 2014), according to the built environment characteristics of the study area (Figure 3): material and structure (MS); condition/conservation status (CS); openings (OP); age (AG); and number of floors (FL). The properties of the exposed buildings were collected through fieldwork and census data.

MS has been considered the most important factor based on various physical vulnerability studies (e.g., Fuchs, Heiss, & Hübl, 2007; Guillard-Gonçalves et al., 2016; Karagiorgos et al., 2016; Müller et al., 2011; Silva & Pereira, 2014). This factor affects the physical fragility and resistance to the impact of floodwaters (Müller et al., 2011; Stephenson & D’Ayala, 2014). The degree of moisture absorption of the construction materials during flood events can influence long-term damage (D’Ayala & Aktas, 2016). Consequently, MS was weighted at 0.4. MS categories and the respective vulnerability scores are as follows (Figure 3): concrete (0.1), masonry walls with concrete (0.3), masonry walls without concrete (0.6), adobe (0.9), wood (1), and metal/zinc (1). These scores were based on the values assigned by Kappes et al. (2012), Silva and Pereira (2014), Stephenson and D’Ayala (2014), Guillard-Gonçalves et al. (2016) and Papathoma-Köhle (2016).

CS evaluates the building conditions and the degree of degradation, being frequently referred to as relevant in the resistance of structures when affected by a natural hazard (Blanco-Vogt & Schanze, 2014; Diakakis, Deligiannakis, Pallikarakis, & Skordoulis, 2017; Fedeski & Gwilliam, 2007; Kappes et al., 2012; Papathoma-Köhle, 2016; Silva & Pereira, 2014; Stephenson & D’Ayala, 2014). This indicator is highly relevant in the study area because of the characteristics of a set of precarious residential buildings. Their initial exterior metal/
zinc walls were replaced by brick masonry walls, although other components of the building preserve their precarious nature: deficient foundations or sheet metal roofs. These dwellings have structural weaknesses that make them more vulnerable to flash floods when compared to other buildings. CS was weighted at 0.2. CS categories and their respective vulnerability scores are as follows (Figure 3): good (0.1), medium (0.4), poor (0.7), and very poor (1). Score 1 identifies the above-mentioned dwellings. The exterior appearance, condition of the doors/windows, fissures/cracks (presence, amount, and thickness), and corrosion marks were verified for the other buildings to define their scores.

OP evaluates the existence of doors, windows, or other openings and their position. A building can be affected totally or partially by a flash flood, but IV increases if there are exposed entrances that favour the water inflow into the building (Federski & Gwilliam, 2007; Fuchs, 2009; Fuchs et al., 2007; Mazzorana et al., 2014; Papathoma-Köhle, 2016). The intake of water and debris can decisively contribute to the damage inside the building. OP was weighted at 0.2. The OP categories and the respective scores are as follows (Figure 3): stream side (1), slope side (0.4), and no exposed openings (0). Scores were assigned in an inverse logic as used by Papathoma-Köhle (2016) for debris flows, which is understandable according to the nature of flash floods. A score of 1 is assigned to buildings with exposed openings on the stream side. These buildings are subject to the effects of higher water depths and flow velocities. The score drops to 0.4 when floodwaters only affect the other facades. A score of 0 is assigned to buildings with no exposed openings or when these are above the estimated water level for the 100-year $R_T$.

AG is considered highly relevant in several studies. Nevertheless, there is redundancy involved, as it is often used to infer the degradation or type of construction (Federski & Gwilliam, 2007). Much of this information is already included in the first two IV indicators. AG was weighted at 0.1. The AG categories were defined by the Statistics Portugal and applied in the census (Figure 3): before 1946 (1), 1946–1960 (0.75), 1961–1980 (0.5), 1981–2000 (0.25), and after 2000 (0.1).

FL can influence vulnerability from different perspectives. The first considers the number of floors as exposure, in which the fewer the floors, the greater the affected fraction (Kappes et al., 2012; Papathoma-Köhle, 2016). Exposed single-story buildings are 100% affected because there are no unexposed floors. Double-story buildings are normally affected by 50%. This only does not happen when there are basements. Evacuation is another perspective, revealing an inverse logic when compared to exposure: the greater the number of floors, the more vulnerable the building will be (Stephenson & D’Ayala, 2014). Floodwaters can affect the access door, preventing or hindering the exit of inhabitants and the entry of rescue teams, unless people can evacuate or be rescued vertically. The exposure perspective was chosen because it is intended to assess only physical vulnerability. FL was weighted at 0.1. FL scores are as follows (Figure 3): one floor (1), two floors (0.5), and three or more floors (0.33). IV was calculated using the following equation:

$$IV = (0.4 \times MS) + (0.2 \times CS) + (0.2 \times OP) + (0.1 \times AG) + (0.1 \times FL)$$  \hspace{1cm} (1)$$

where MS is the material and structure, CS is the condition/conservation status, OP is the openings, AG is the age, and FL is the number of floors.

### 3.3.2 Flash flood intensity

The main factors that affect the degree of loss caused by flash floods are water depth, flow velocity, and solid charge (Merz et al., 2010). HEC-RAS and HEC-GeoRAS were used to determine flood extent, depths, and velocities around the exposed buildings. The integration of flow parameters for assessing physical vulnerability was done through FFI using three indicators (Figure 3): affected portion (AP), average depth (AD), and average velocity (AV).

AP is the fraction of the buildings' perimeter affected by a flash flood event with a given recurrence, in this case, by a 100-year $R_T$ event. These values were obtained in GIS by measuring the perimeter of the buildings affected by floodwaters. The AP of a building is at most equal to its PEP. AP represents what can potentially happen outside the building because floodwaters can prevent the opening of doors. In most situations, a building is not surrounded by floodwaters, either because all the facades are not affected or because there are adjacent buildings or walls. In some cases, buildings have facades that correspond simultaneously to a building's structural wall and a stream channel wall; hence, this portion should not be considered as AP because the streamside facade was built to withstand the effects of runoff and frequent contact with water. The following are the AP categories and scores (Figure 3): <25% (0.25), 25–50% (0.5), 51–75% (0.75), and >75% (1).

AD results from the average of the water depth values of the cells adjacent to the exposed buildings. The same
logic was applied to AV. AD categories and scores are as follows (Figure 3): <0.5 m (0.3), 0.5–1.99 m (0.7), and ≥2 m (1). The thresholds of water depth of 0.5 and 2 m are frequently referred to as critical values (Kreibich et al., 2009; Merz et al., 2007; Smith, 1991; Zimmermann, Pozzi, & Stoessel, 2005). The 50/60 cm can be considered a critical threshold for the stability of a person in a flood situation (Marco, 1994; Penning-Rowsell et al., 2005), 40 cm is the threshold for opening doors in flooded areas (Ishigaki et al., 2009), and 2 m represents the critical value for damage in buildings and infrastructure (Kreibich et al., 2009; Smith, 1991). AV categories and scores are as follows (Figure 3): <0.5 m/s (0.3), 0.5–1.99 m/s (0.7), and ≥2 m/s (1). The critical value for flow velocity is 2 m/s for buildings/infrastructure (Kreibich et al., 2009, Smith, 1991).

Defining the most important indicator carries a great deal of uncertainty. Therefore, it was decided that they should have the same weight. FFI was calculated using the following equation:
FFI = \left( \frac{1}{3} \cdot \text{AP} \right) + \left( \frac{1}{3} \cdot \text{AD} \right) + \left( \frac{1}{3} \cdot \text{AV} \right) \tag{2}

where \text{AP} is the affected portion, \text{AD} is the average depth, and \text{AV} is the average velocity.

3.3.3 Physical vulnerability index

PhVI combines IV and FFI (Figures 2 and 3). Equal weights were assigned (0.5) to IV and FFI because it is not possible to determine which one is more important for physical vulnerability. PhVI was calculated using the following equation:

\text{PhVI} = (0.5 \cdot \text{IV}) + (0.5 \cdot \text{FFI}) \tag{3}

where \text{PhVI} is the physical vulnerability index, \text{IV} is the intrinsic vulnerability, and \text{FFI} is the flash flood intensity.

4 RESULTS

4.1 Flood extent and exposed buildings

There are 26 exposed buildings, divided into four areas (Figure 4). Half of these buildings are already abandoned or in ruins. Area 1 corresponds to an industrial/logistics complex comprising seven occupied buildings (Figure 5a). Area 2 is composed of 12 housing buildings, 7 of which are abandoned (Figure 5b). Areas 3 and 4 integrated the gunpowder factory, the most important industrial complex of the study area, closed in 1988. The four exposed buildings in Area 3 are abandoned (Figure 5c). Area 4 has one exposed occupied building, a university administrative building (Figure 5d). Then, 7 of the 13 exposed occupied buildings have a PEP higher than 50%, and one of them (building No. 7) reaches 100%, meaning that it can be surrounded by floodwaters (Table 1).
4.2 | Vulnerability

4.2.1 | Intrinsic vulnerability

The building properties are presented in Table 2. The assigned scores and IV results are shown in Table 3 and Figure 6.

All the exposed buildings are made of masonry—stone or brick. Buildings Nos. 1–6 have a concrete structure (score 0.3), unlike building Nos. 7–24 (score 0.6).

CS levels range from good to very poor. The building Nos. 16–19 feature very poor levels (score 1, Figure 3) and a residential function. Most of the exposed buildings have a good and medium levels (scores 0.1 and 0.4, Table 2). Building No. 13 presents a poor level due to a lack of maintenance work. In the others, the very poor levels are due to the building type, the precarious conditions of the houses, and the lack of construction quality (Figure 7).

Building Nos. 13–19 have openings on the stream side (score 1), either to the Barcarena or the Massamá stream. Building Nos. 1–7 and No. 24 have openings on the slope side (score 0.4). In these cases, floodwaters can only enter the buildings from the opposite side of the stream, making it less likely to cause damage.

All the exposed buildings were built before 1980. The oldest buildings are Nos. 13 and 24, built prior to 1946 (score 1). The remaining buildings were built between 1946 and 1960 (score 0.75), except for No. 7 (1961–1980, score 0.5).

Most buildings have a single floor (score 1), except for building Nos. 1, 2, 4, 5, and 13, which have two floors (score 0.5).
IV range between 0.35 and 0.82 (Table 3 and Figure 6). The lowest value belongs to building No. 5 and the highest to building Nos. 16–19. The most vulnerable buildings are in Area 2 (Figure 6). The least vulnerable are building Nos. 1, 2, 4, 5, and 6 (Area 1) (Table 3). These results show the propensity of the buildings to suffer damage; however, their location in the floodplain and how they are affected by floodwaters will influence their physical vulnerability.

### 4.2.2 Flash flood intensity

The values and scores used to determine FFI are presented in Table 4.

The maximum AP reaches 100% in building No. 7, while the minimum is 6% in building No. 1. Building Nos. 2 and 7 have the highest AP values, exceeding 75% (score 1). Most of the buildings (7) reach values between 25 and 50% (score 0.5). The presence of adjacent buildings reduces PEP, preventing higher AP values. This happens with building No. 13, which has a PEP of 12%, resulting from a single exposed facade (Table 1 and Figure 8a). Flood protection walls can also reduce AP, as in building No. 24.

The water depths and flow velocities around the exposed buildings are far from those reached along the stream channel (Figure 8a,b). These values never reach 2 m (depth) or 2 m/s (velocity) next to the buildings—due to their location at higher positions, in the floodplain—preventing the assignment of maximum scores.

The AD values are less than 0.5 m (score 0.3) in seven buildings. Scores of 0.7 were assigned to the remaining buildings, with a maximum value of 1.17 m in building No. 6 (Table 4). Although they do not jeopardise the buildings’ structure, water depths above 0.5 m compromise people’s safety and can prevent the opening of doors. It is estimated that this critical threshold is exceeded in most buildings in Area 1 and in the only exposed occupied building in Area 4 (Table 4 and Figure 8a). The AD values obtained for the housing buildings (Area 2) are below this threshold, which is justified by: (a) the presence of flood protection walls next to...
These buildings (although the evidence of destruction in past high-magnitude events); (b) the high velocities of the Massamá stream near the confluence with the Barcarena stream (Figure 8b) during flash floods (valid for building No. 13); and (c) the width (about 15 m) of the Barcarena stream’s cross section immediately down-stream of the confluence (valid for building Nos. 16–19).

The AV values are even less substantial (Table 4). This can partly be explained by the flow friction caused by the buildings. Velocities next to the walls tend to be lower than that of in most of the flooded areas. The low slopes in the floodplains also explain the low velocities (Figure 8b). The buildings with the highest AD values are also those with the highest AV values. Scores of 0.7 were assigned to building Nos. 6 (0.54 m/s) and 24 (0.66 m/s) (Table 4).

FFI values range between 0.28 and 0.67 (Table 4 and Figure 8c). The highest values were obtained for building Nos. 6 and 7 (Area 1) and No. 24 (Area 4). The lowest values were obtained for building No. 1 (Area 1) and Nos. 13–19 (Area 2). These results show an almost inverse reality when compared to that demonstrated by IV, in which the most vulnerable buildings were in Area 2 (Table 3 and Figure 6).

### 4.2.3 Physical vulnerability index

The PhVI values range between 0.34 and 0.61 (Table 5 and Figure 9). Building No. 1 is the most vulnerable (PhVI value of 0.61), resulting from a medium IV (0.55) and the highest FFI (0.67). This is followed by building Nos. 16, 19, and 24 (0.59) and Nos. 17 and 18 (0.55). Despite their location at different points in the study area, building No. 24 has similar values of IV and FFI to that of No. 7. The same does not happen with the buildings in Area 2 (Nos. 16 to 19), in which the high values of PhVI are mainly due to their high IV. The lowest PhVI value was obtained for building No. 1 (0.34), concordantly with its low IV and FFI values. Considering that 0.61 is the highest PhVI value in the [0–1] range, there are no high values of PhVI in the study area because none of the buildings presents simultaneously high IV and FFI, leading to a low to moderate physical vulnerability to flash floods.

### 5 DISCUSSION

The physical vulnerability was obtained using an indicator-based methodology, which requires awareness of its limitations, uncertainties, and challenges. The following stand out and are further discussed: (a) selection of the most appropriate indicators to represent the sources of vulnerability in a specific area, (b) availability of data, (c) aggregation and combination of the indicators, (d) determination of the importance of each indicator and its standardisation, and (e) validation of the obtained results (Barnett et al., 2008; Müller et al., 2011).

The choice of indicators and the availability and/or capacity to collect data are the first steps towards creating a vulnerability index. Although the most relevant indicators are generically accepted by the scientific community, their relevance is dependent on the specificities of the affected site and the characteristics of the natural hazard (Kappes et al., 2012; Müller et al., 2011). Data collection must be carried out using fieldwork, compiling the properties of each building, being time-consuming.
The importance is assessed by assigning weights to the indicators (Fekete et al., 2010; Meyer, Scheuer, & Haase, 2009), the most sensitive step in the elaboration of the vulnerability index (Papathoma-Köhle, Cristofari, et al., 2019), which may imply greater subjectivity (Cutter, Burton, & Emrich, 2010; Jha et al., 2012; Stephenson & D’Ayala, 2014). The validation process can be used for analysing past flood consequences, allowing for subsequent calibration through the damage that may occur in the future (Papathoma-Köhle, Cristofari, et al., 2019), although conditioned by the lack of damage data, as in this study area. In most studies, the indicators are weighted empirically without validation regarding their selection and weighting (Malgwi et al., 2020; Papathoma-Köhle, 2016). Despite the uncertainty affecting the results, indicator-based methodologies are a simple, flexible tool applicable by several users, including decision makers and those responsible for spatial planning and management (Balica, Douben, & Wright, 2009; Barroca, Bernardara, Mouchel, & Hubert, 2006).

**TABLE 4** Values and scores used to determine FFI of the buildings exposed in the study area

| Building (No.) | AP Value (%) | Score | AD Value (m) | Score | AV Value (m/s) | Score | FFI |
|---------------|--------------|-------|--------------|-------|----------------|-------|-----|
| 1             | 6            | 0.25  | 0.13         | 0.3   | 0.01           | 0.3   | 0.28|
| 2             | 88           | 1     | 0.27         | 0.3   | 0.39           | 0.3   | 0.53|
| 3             | 28           | 0.5   | 0.55         | 0.7   | 0.01           | 0.3   | 0.50|
| 4             | 49           | 0.5   | 0.59         | 0.7   | 0.18           | 0.3   | 0.50|
| 5             | 33           | 0.5   | 0.62         | 0.7   | 0.12           | 0.3   | 0.50|
| 6             | 48           | 0.5   | 1.17         | 0.7   | 0.54           | 0.7   | 0.63|
| 7             | 100          | 1     | 0.53         | 0.7   | 0.31           | 0.3   | 0.67|
| 13            | 12           | 0.25  | 0.24         | 0.3   | 0.49           | 0.3   | 0.28|
| 16            | 36           | 0.5   | 0.23         | 0.3   | 0.27           | 0.3   | 0.37|
| 17            | 14           | 0.25  | 0.48         | 0.3   | 0.29           | 0.3   | 0.28|
| 18            | 15           | 0.25  | 0.44         | 0.3   | 0.20           | 0.3   | 0.28|
| 19            | 50           | 0.5   | 0.34         | 0.3   | 0.22           | 0.3   | 0.37|
| 24            | 32           | 0.5   | 1.06         | 0.7   | 0.66           | 0.7   | 0.63|

Abbreviations: AD, average depth; AP, affected portion; AV, average velocity; FFI, flash flood intensity.

Figure 7 Exposed buildings in Area 2

PhVI was applied to a set of 13 exposed buildings. The sample size can be considered a limitation of this study because it does not present a wide variety of spatial patterns of FFI and IV. The use of a larger set of buildings would be preferable; however, the main contribution of this work is the method for assessing physical vulnerability, which can be applied to other study areas and in a
larger number of buildings. The sample could increase with the addition of the abandoned exposed buildings, but most of them can be classified as ruins, with no roof, doors, or windows. However, these abandoned buildings were not included in the physical vulnerability assessment for two main reasons. First, their physical condition cannot be compared with the present occupied buildings, as they have been abandoned several cases decades ago. Second, we believe the physical vulnerability assessment is not necessary when a building has not structural conditions to be occupied with a specific function and people or goods to protect. Considering their current physical conditions, these buildings must be rebuilt if they will be occupied in the future. Additionally, those buildings are included in the National Ecological Reserve (REN), a biophysical structure including all the areas that, due to their ecological value and sensitivity or exposure and susceptibility to natural hazards, are subject to protection. Thus, the exposed buildings are located where new constructions are forbidden according to the areas threatened by floods.

**TABLE 5** Values of IV, FFI, and PhVI for the buildings exposed in the study area

| Building (No.) | IV   | FFI  | PhVI |
|---------------|------|------|------|
| 1             | 0.41 | 0.28 | 0.34 |
| 2             | 0.41 | 0.53 | 0.47 |
| 3             | 0.46 | 0.50 | 0.48 |
| 4             | 0.41 | 0.50 | 0.45 |
| 5             | 0.35 | 0.50 | 0.42 |
| 6             | 0.40 | 0.63 | 0.51 |
| 7             | 0.55 | 0.67 | 0.61 |
| 13            | 0.73 | 0.28 | 0.51 |
| 16            | 0.82 | 0.37 | 0.59 |
| 17            | 0.82 | 0.28 | 0.55 |
| 18            | 0.82 | 0.28 | 0.55 |
| 19            | 0.82 | 0.37 | 0.59 |
| 24            | 0.54 | 0.63 | 0.59 |

Abbreviations: FFI, flash flood intensity; IV, intrinsic vulnerability; PhVI, physical vulnerability index.
PhVI combines IV of the buildings and their positional relationship with the studied hazard, expressed by FFI. IV is constant and FFI can change with the severity of the natural hazard, which may increase the PhVI results with increasing return periods. Increments in water depth and velocity induce increases in erosion, pressure, turbulence, and other effects on buildings (Kelman & Spence, 2004; Papathoma-Köhle et al., 2011), affecting them differently depending on their resistance. Neglecting the intensity of the process is one of the main disadvantages of indicator-based methodologies, since buildings with high vulnerabilities “may experience low degree of loss because the intensity of the process happens to be low and vice versa” (Papathoma-Köhle et al., 2017).

Combining IV and FFI to determine PhVI can overcome this limitation. However, the determination of flow parameters requires specialised knowledge regarding hydraulic modelling and GIS; thus, it is not recommended for non-experts. On the other hand, more detailed results can be acquired regarding buildings’ physical vulnerability.

The FFI thresholds adopted for water depth and flow velocity may be debatable. A small increase in AD can induce an increase in the assigned score, generating a higher PhVI value. Nevertheless, small increases in water depth can represent larger water volumes. Such additional volume leads to higher hydrostatic pressure on the exposed openings and damage caused by the entrance of water and debris inside the buildings. It is worth mentioning that the thresholds used are based on critical values adopted by other researchers in similar built environment.

Buildings can be inherently fragile due to their construction materials or structure, but if flash floods are not able to cause significant damage because of their location/position on the floodplain, the presence of other buildings/infrastructure, or existing mitigation measures, then their vulnerability will never be high. The reverse can also occur: buildings can be surrounded by floodwaters, with high depths or velocities, but their resistance (construction material, structure, and foundations) reduces their vulnerability.

The previous highlights the importance of the buildings’ properties and the hazard intensity. These two theoretical considerations on the relationship between IV and the way the characteristics of the flood hazard impact buildings (FFI) can be directly applicable to spatial and urban planning. In addition, planning instruments that address flood risk should consider the reduction of exposure, which is also implicitly considered by the PhVI.

Despite the limited number of buildings located in this study area, this study contributes to practitioners from the civil protection, insurance companies and land use planning. The applications of PhVI are feasible at two main scales, both involving public and private sectors. At basin scale, in which spatial planning is conducted with municipal and intermunicipal planning instruments, this work provides a detailed physical vulnerability assessment of the buildings in flood-prone areas. From the spatial planning perspective, it can be applied the legislation of the REN to forbidden new constructions in this area, and for the existing constructions it can be applied specific technical corrections to avoid water accumulation on the buildings’ openings, when the potential water level is low. In this area, the medium to
long-term objectives should aim at: (a) reducing exposure through spatial zoning and regulations; and (b) reducing the hazard-related hydrodynamic stressors upon buildings, by decreasing velocities and solid charge, and by delaying the hydrograph peak to reduce flood depths, by promoting infiltration in upstream areas. This would preferably be achieved through blue and green infrastructure based on nature-based solutions. At the higher scale—floodplain, where the exposed buildings are located—, the results achieved can inform which buildings are more urgent to benefit from local flood defences, adaptation, and retrofitting interventions, where relocation is not an option. At this scale, vulnerability reduction strategies fall in the domain of structural engineering and urban design.

From the civil protection perspective, this work provides detailed information on the number and properties of affected buildings, water levels and flow velocities. It is also possible to estimate the number and characteristics of affected people (age, gender, mobility issues) and potential number of populations to evacuate in a hazardous situation. Additionally, this work contributes to manage and prepare the civil protection emergency response, providing detailed information to estimate the technical conditions to perform the evacuation during a flash flood event.

The replicability of this study to other locations is possible because the input data can be collected from fieldwork and hydraulic modelling. However, the applicability at other locations will have to consider their regulatory and institutional frameworks. The knowledge provided by PhVI supports decision-making in spatial and civil protection planning, allowing a more efficient allocation of resources.

6 | CONCLUSIONS

In this study, physical vulnerability to flash floods considers the propensity to suffer damage (building properties) and the potential to cause damage (flow parameters). The exposed buildings have different levels of physical vulnerability due to their distinct characteristics, location on the floodplain, and position in relation to the floodwaters. Vulnerability should be understood as a dynamic risk component, which can change when the intensity/magnitude of a flash flood event changes. The position of a building in a flooded area, its AP, and the water depths and flow velocities around this building, expressed by FFI, can modify its PhVI. Buildings with equal IV may have different PhVI due to distinct FFI. The same is also valid for buildings with equal FFI. A high IV does not necessarily mean a high PhVI because the physical vulnerability of a building should be measured not only by its properties, but also by its location on the floodplain and by its interaction with floodwaters.

The IV values revealed the least resistant buildings to the impact of flash floods in the study area. The FFI values showed that buildings can be affected by a high-intensity event, but it does not seem likely that flash floods can cause severe structural damage. Neither the water depths nor the flow velocities reach critical values to cause significant damage to infrastructures. There is almost an inversion between the results of IV and FFI. In general, the buildings with higher IV values are those in which flash floods have less destructive capacity, according to FFI values. This happens with the dwellings in Area 2. Notwithstanding their high IV, the AP, water depths, and flow velocities are of little relevance. Therefore, PhVI values of these buildings are not as high as would be expected if only the building properties were analysed. Simultaneously, PhVI values are also not as low as would be predictable if only AP and flow parameters were accounted for.

Understanding how floodwaters and flow parameters differently affect buildings with distinct physical characteristics is a key knowledge for spatial planning and risk management. PhVI combines building properties and flow parameters, which represents an advantage when compared to other indicator-based methodologies used in scientific research. This is a useful tool where damage records are rare or non-existent, allowing the prioritisation of resources and application of local protection measures. PhVI can be adapted to other study areas and natural hazards, according to their specificities, although testing PhVI on a larger set of exposed buildings and in other geographic contexts would help to improve the knowledge on the indicators and weights of IV and FFI.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.
DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

Apel, H., Aronica, G. T., Kreibich, H., & Thieken, A. H. (2009). Flood risk analyses—How detailed do we need to be? *Natural Hazards*, 49(1), 79–98. https://doi.org/10.1007/s11069-008-9277-8

Balica, S. F., Douben, N., & Wright, N. G. (2009). Flood vulnerability indices at varying spatial scales. *Water Science and Technology, 60*(10), 2571–2580. https://doi.org/10.2166/wst.2009.183

Barnett, J., Lambert, S., Fry, I., Barnett, J., Lambert, S., & Fry, I. (2008). The hazards of indicators: Insights from the environmental vulnerability index. *Annals of the Association of American Geographers*, 98(1), 102–119. https://doi.org/10.1080/00045600701734315

Barroca, B., Bernardara, P., Mouchel, J., & Hubert, G. (2006). Indicators for identification of urban flooding vulnerability. *Natural Hazards and Earth System Sciences, 6*(4), 553–561. https://doi.org/10.5194/nhess-6-553-2006

Beven, K. J., Almeida, S., Aspinall, W. P., Bates, P. D., Blazkova, S., Borgomeo, E., ... Smith, P. J. (2018). Epistemic uncertainties and natural hazard risk assessment—Part 1: A review of different natural hazard areas. *Natural Hazards and Earth System Sciences, 18*, 2741–2768. https://doi.org/10.5194/nhess-18-2741-2018

Birkmann, J. (2007). Risk and vulnerability indicators at different scales: Applicability, usefulness and policy implications. *Environmental Hazards, 7*(1), 20–31. https://doi.org/10.1016/j.envhaz.2007.04.002

Birkmann, J., Cardona, O. D., Carreño, M. L., Barbat, A. H., Pelling, M., Schneiderbauer, S., ... Welle, T. (2013). Framing vulnerability, risk and societal responses: The MOVE framework. *Natural Hazards, 67*(2), 193–211. https://doi.org/10.1007/s11069-013-0558-5

Blanco-Vogt, A., & Schanze, J. (2014). Assessment of the physical flood susceptibility of buildings on a large scale—Conceptual and methodological frameworks. *Natural Hazards and Earth System Sciences, 14*(8), 2105–2117. https://doi.org/10.5194/nhess-14-2105-2014

Botzen, W. J. W., van den Bergh, J. C. J. M., & Bouwer, L. M. (2010). Climate change and increased risk for the insurance sector: A global perspective and an assessment for the Netherlands. *Natural Hazards, 52*(3), 577–598. https://doi.org/10.1007/s11069-009-9404-1

Brandão, C., Rodrigues, R., & Costa, J. P. (2001). Análise de fenómenos extremos: Precipitações intensas em Portugal Continental. https://snrhr.apambiente.pt/snhr/download/relatorios/relatorio_prec_intensa.pdf

Büchele, B., Kreibich, H., Kron, A., Thieken, A., Ihringer, J., Oberle, P., ... Nestmann, F. (2006). Flood-risk mapping: Contributions towards an enhanced assessment of extreme events and associated risks. *Natural Hazards and Earth System Sciences, 6*(4), 483–503. https://doi.org/10.5194/nhess-6-485-2006

Camarasa-Belmonte, A. M., López-García, M. J., & Soriano-Garcia, J. (2011). Mapping temporarily-variable exposure to flooding in small Mediterranean basins using land-use indicators. *Applied Geography, 31*(1), 136–145. https://doi.org/10.1016/j.apgeog.2010.03.003

Cardona, O. D. (2003). The need for rethinking the concepts of vulnerability and risk from a holistic perspective. In G. Bankoff, G. Frerks, & D. Hilhorst (Eds.), *Mapping vulnerability: Disasters, development and people* (pp. 37–51). London: Earthscan Publishers. https://doi.org/10.4324/9781849771924

Cutter, S. L., Burton, C. G., & Emrich, C. T. (2010). Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management, 7*(1), 1–22. https://doi.org/10.2202/1547-7355.1732

D’Ayala, D., & Aktas, Y. D. (2016). Moisture dynamics in the masonry fabric of historic buildings subjected to wind-driven rain and flooding. *Building and Environment, 104*, 208–220. https://doi.org/10.1016/j.buildenv.2016.05.015

de Bruijn, K. M., Green, C., Johnson, C., & McFadden, L. (2007). Evolving concepts in flood risk management: Searching for a common language. In S. Begum, M. J. F. Stive, & J. W. Hall (Eds.), *Flood risk Management in Europe. Advances in natural and technological hazards research* (Vol. 25, pp. 61–75). Dordrecht: Springer. https://doi.org/10.1007/978-1-4020-4200-3_4

de Moel, H., Jongman, B., Kreibich, H., Merz, B., Penning-Rossell, E., & Ward, P. J. (2015). Flood risk assessments at different spatial scales. *Mitigation and Adaptation Strategies for Global Change, 20*(6), 865–890. https://doi.org/10.1007/s11027-015-9654-z

Diakakis, M., Deligiannakis, G., Pallikarakis, A., & Skordoulis, M. (2016). Factors controlling the spatial distribution of flash flooding in the complex environment of a metropolitan urban area. The case of Athens 2013 flash flood event. *International Journal of Disaster Risk Reduction, 18*, 171–180. https://doi.org/10.1016/j.ijdrr.2016.06.010

Diakakis, M., Deligiannakis, G., Pallikarakis, A., & Skordoulis, M. (2017). Identifying elements that affect the probability of buildings to suffer flooding in urban areas using Google Street View. A case study from Athens metropolitan area in Greece. *International Journal of Disaster Risk Reduction, 22*, 1–9. https://doi.org/10.1016/j.ijdrr.2017.02.002

Douglas, J. (2007). Physical vulnerability modelling in natural hazard risk assessment. *Natural Hazards and Earth System Sciences, 7*(2), 283–288. https://doi.org/10.5194/nhess-7-283-2007

Ettinger, S., Mounaud, L., Magill, C., Yao-Lafourcade, A. F., Thouret, J. C., Manville, V., ... Manrique Llerena, N. (2016). Contributions towards an enhanced assessment of extreme events and associated risks. *Natural Hazards and Earth System Sciences, 16*(4), 483–503. https://doi.org/10.5194/nhess-6-485-2006

Faccini, F., Luino, F., Paliaga, G., Sacchini, A., Turconi, L., & de Jong, C. (2018). Role of rainfall intensity and urban sprawl in
the 2014 flash flood in Genoa City, Bisagno catchment (Liguria, Italy). Applied Geography, 98, 224–241. https://doi.org/10.1016/j.apgeog.2018.07.022

Fedeski, M., & Gwilliam, J. (2007). Urban sustainability in the presence of flood and geological hazards: The development of a GIS-based vulnerability and risk assessment methodology. Landscape and Urban Planning, 83, 50–61. https://doi.org/10.1016/j.landurbplan.2007.05.012

Fekete, A. (2009). Validation of a social vulnerability index in context to river-floods in Germany. Natural Hazards and Earth System Sciences, 9(2), 393–403. https://doi.org/10.5194/nhess-9-393-2009

Fekete, A., Damm, M., & Birkmann, J. (2010). Scales as a challenge for vulnerability assessment. Natural Hazards, 55(3), 729–747. https://doi.org/10.1007/s11069-009-9445-5

Freni, G., La Loggia, G., & Notaro, V. (2010). Uncertainty in urban flood damage assessment due to urban drainage modelling and depth-damage curve estimation. Water Science and Technology, 61(12), 2979–2993. https://doi.org/10.2166/wst.2010.177

Fuchs, S. (2009). Susceptibility versus resilience to mountain hazards in Austria—Paradigms of vulnerability revisited. Natural Hazards and Earth System Sciences, 9(2), 337–352. https://doi.org/10.5194/nhess-9-337-2009

Fuchs, S., Heiss, K., & Hübll, J. (2007). Towards an empirical vulnerability function for use in debris flow risk assessment. Natural Hazards and Earth System Sciences, 7, 495–506. https://doi.org/10.5194/nhess-7-495-2007

Fuchs, S., Keiler, M., Ortlepp, R., Schinke, R., & Papathoma-Köhle, M. (2019). Recent advances in vulnerability assessment for the built environment exposed to torrential hazards: Challenges and the way forward. Journal of Hydrology, 575, 587–595. https://doi.org/10.1016/j.jhydrol.2019.05.067

Garrote, J., Diez-Herrero, A., Escudero, C., & García, I. (2020). A framework proposal for regional-scale flood-risk assessment of cultural heritage sites and application to the Castile and León region (Central Spain). Water (Switzerland), 12(2), 329. https://doi.org/10.3390/w12020329

Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., ... Viglione, A. (2009). A compilation of data on European flash floods. Journal of Hydrology, 367(1–2), 70–78. https://doi.org/10.1016/j.jhydrol.2008.12.028

Glade, T., & Crozier, M. J. (2012). The nature of landslide hazard impact. In T. Glade, M. Anderson, & M. J. Crozier (Eds.), Landslide hazard and risk (pp. 41–74). Chichester: John Wiley & Sons. https://doi.org/10.1002/9780470012659.ch2

Guillard-Gonçalves, C., Zézere, J. L., Pereira, S., & Garcia, R. A. C. (2016). Assessment of physical vulnerability of buildings and analysis of landslide risk at the municipal scale: Application to the Loures municipality, Portugal. Natural Hazards and Earth System Sciences, 16, 311–331. https://doi.org/10.5194/nhess-16-311-2016

Hammond, M. J., Chen, A. S., Djordjević, S., Butler, D., & Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. Urban Water Journal, 12(1), 14–29. https://doi.org/10.1080/1573062X.2013.857421

Hu, K. H., Cui, P., & Zhang, J. Q. (2012). Characteristics of damage to buildings by debris flows on 7 August 2010 in Zhouqu, Western China. Natural Hazards and Earth System Sciences, 12(7), 2209–2217. https://doi.org/10.5194/nhess-12-2209-2012

Ishigaki, T., Kawanaka, R., Onishi, Y., Shimada, H., Toda, K., & Baba, Y. (2009). Assessment of safety on evacuating route during underground flooding. In Advances in water resources and hydraulic engineering (pp. 141–146). Berlin: Springer. https://doi.org/10.1007/978-3-540-89465-0_27

Jha, A. K., Bloch, R., & Lamond, J. (2012). Cities and flooding: A guide to integrated urban flood risk management for the 21st century. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/2241

Kappes, M. S., Papathoma-Köhle, M., & Keiler, M. (2012). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. Applied Geography, 32(2), 577–590. https://doi.org/10.1016/j.apgeog.2011.07.002

Karagiorgos, K., Thaler, T., Heiser, M., Hübll, J., & Fuchs, S. (2016). Integrated flash flood vulnerability assessment: Insights from East Attica, Greece. Journal of Hydrology, 541, 553–562. https://doi.org/10.1016/j.jhydrol.2016.02.052

Kelman, I., & Spence, R. (2004). An overview of flood actions on buildings. Engineering Geology, 73, 297–309. https://doi.org/10.1016/j.enggeo.2004.01.010

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., ... Thieken, A. H. (2009). Is flow velocity a significant parameter in flood damage modelling? Natural Hazards and Earth System Sciences, 9, 1679–1692. https://doi.org/10.5194/nhess-9-1679-2009

Kreibich, H., Seifert, I., Merz, B., & Thieken, A. H. (2010). Development of FLEMOs—A new model for the estimation of flood losses in the commercial sector. Hydrological Sciences Journal, 55(8), 1302–1314. https://doi.org/10.1080/02626667.2010.529815

Leone, F., Asté, J.-P., & Lerol, E. (1996). Vulnerability assessment of elements exposed to mass-movement: Working toward a better risk perception. In K. Senneset (Ed.), Landslides-Glissements de Terrain (pp. 263–270). Rotterdam: Balkema

Malgwi, M. B., Fuchs, S., & Keiler, M. (2020). A generic physical vulnerability model for floods: Review and concept for data-scarce regions. Natural Hazards and Earth System Sciences, 20(7), 2067–2090. https://doi.org/10.5194/nhess-20-2067-2020

Marchi, L., Borga, M., Preciso, E., & Gaume, E. (2010). Characterisation of selected extreme flash floods in Europe and implications for flood risk management. Journal of Hydrology, 394(1–2), 118–133. https://doi.org/10.1016/j.jhydrol.2010.07.017

Marco, J. B. (1994). Flood risk mapping. In G. Rossi, N. Harmercangiolo, & V. Yevjevich (Eds.), Coping with floods. NATO ASI series (series E: Applied sciences) (Vol. 257, pp. 353–373). Dordrecht: Springer. https://doi.org/10.1007/978-94-011-1098-3_20

Mazzorana, B., Simoni, S., Scherer, C., Gems, B., Fuchs, S., & Keiler, M. (2014). A physical approach on flood risk vulnerability of buildings. Hydrology and Earth System Sciences, 18(9), 3817–3836. https://doi.org/10.5194/hess-18-3817-2014

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Review article “assessment of economic flood damage”. Natural Hazards and Earth System Sciences, 10(8), 1697–1724. https://doi.org/10.5194/nhess-10-1697-2010

Merz, B., Kreibich, H., Thieken, A., & Schmidtke, R. (2004). Estimation uncertainty of direct monetary flood damage to buildings. Natural Hazards and Earth System Sciences, 4, 153–163. https://doi.org/10.5194/nhess-4-153-2004
for municipal land use planning in Portugal. Science of the Total Environment, 735, 139463. https://doi.org/10.1016/j.scitotenv.2020.139463

Rod, J. K., Opach, T., & Neset, T.-S. (2015). Three core activities toward a relevant integrated vulnerability assessment: Validate, visualize, and negotiate. Journal of Risk Research, 18(7), 877–895. https://doi.org/10.1080/13698777.2014.923027

Rojas, O., Mardones, M., Rojas, C., Martínez, C., & Flores, L. (2017). Urban growth and flood disasters in the coastal river basin of South-Central Chile (1943–2011). Sustainability (Switzerland), 9(2), 1998–2008. https://doi.org/10.3390/su9020195

Silva, M., & Pereira, S. (2014). Assessment of physical vulnerability and potential losses of buildings due to shallow slides. Natural Hazards, 72, 1029–1050. https://doi.org/10.1007/s11069-014-1052-4

Smith, D. I. (1994). Flood damage estimation—A review of urban stage-damage curves and loss functions. Water SA, 20(3), 231–238. https://doi.org/10.1080/13669877.2014.923027

Smith, K. (1991). Environmental hazards: Assessing risk and reducing disaster. New York: Routledge. https://www.routledge.com/Environmental-Hazards-Assessing-Risk-and-Reducing-Disaster/Smith-Smith/p/book/9780415681063.

Spekkers, M. H., Clemens, F. H. L. R., & Ten Veldhuis, J. A. E. (2015). On the occurrence of rainstorm damage based on home insurance and weather data. Natural Hazards and Earth System Sciences, 15(2), 261–272. https://doi.org/10.5194/nhess-15-261-2015

Stephenson, V., & D’Ayala, D. (2014). A new approach to flood vulnerability assessment for historic buildings in England. Natural Hazards and Earth System Sciences, 14, 1035–1048. https://doi.org/10.5194/nhess-14-1035-2014

Trigo, R. M., Ramos, C., Pereira, S. S., Ramos, A. M., Zézere, J. L., & Liberato, M. L. R. (2016). The deadliest storm of the 20th century striking Portugal: Flood impacts and atmospheric circulation. Journal of Hydrology, 541(November 1967), 597–610. https://doi.org/10.1016/j.jhydrol.2015.10.036

Winsemius, H. C., van Beek, L. P. H., Jongman, B., Ward, P. J., & Bouwman, A. (2013). A framework for global river flood risk assessments. Hydrology and Earth System Sciences, 17(5), 1871–1892. https://doi.org/10.5194/hess-17-1871-2013

Zimmermann, M., Pozzi, A., & Stoessel, F. (2005). VADEMECUM. Hazard maps and related instruments. The Swiss system and its application abroad. Capitalisation of experience. Bern, Switzerland: Swiss Agency for Development and Cooperation (SDC). https://www.planat.ch/fileadmin/PLANAT/planat_pdf/alle_2012/2001-2005/PLANAT_2005_-_Vademecum.pdf

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