




A simplified approach for flood vulnerability assessment of historic sites

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Abstract

In the last decades, floods have increased in frequency all over the world due to diverse phenomena such as climate change, extended urbanization, land use, etc. Their social, cultural, economic and environmental impacts have also grown significantly, highlighting the need for the development of further studies and improved methods to manage and mitigate flood risk, mainly in urban areas. Historic sites need particular attention in this field, not only because the high and irreplaceable cultural value of these areas, but also taking into account that the constructive typologies that they host are particularly vulnerable to natural hazards. In consequence of that, the analysis of the phenomena, the evaluation of their consequences and the adoption of adequate mitigation and preparedness measures are presently a fundamental societal challenge. Having this in mind, the present paper aims at proposing an innovative methodology focused on the assessment of flood vulnerability in historic sites through the evaluation of a set of exposure and sensitivity indicators. From the analysis of these indicators, it is possible to obtain a Flood Vulnerability Index capable of measuring the spread of flood vulnerability over an extended area. The historic centre of Guimarães, in Portugal, declared by UNESCO as a World Heritage Site in 2001, is used here as a pilot case study to apply and discusses the preliminary version of the approach. Although some improvements are still needed, this approach can be already used to provides preliminary vulnerability scenarios and to point the way to the definition of more efficient and customized strategies for managing and mitigating flood risk in historic sites. Moreover, with further improvements and calibrations resorting to larger and more diverse data, it will be possible to reduce some of the uncertainties currently involved in the assessment process and to make its application wider and more robust.

Keywords Flood vulnerability assessment · Exposure · Sensitivity · Historic sites · Historic centre of Guimarães

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1 Introduction

In the last decades, flood risk in urban areas has been increased due to several factors, among which land use and climate change are the two most driving ones (O'Brien et al. 2006). Moreover, as highlighted by Scott et al. (2013), despite the rise in knowledge concerning aspects such as flood forecasting, modelling and mapping, detrimental flooding events continue to occur making it one of the most frequent and widespread natural hazards (Ludy and Kondolf 2012; Kundzewicz et al. 2013; Hammond et al. 2015; Rana and Routray 2018).

According to several scientific literature (Ortiz et al. 2016; Wang 2015), flooding has had a particularly impact on cultural heritage and historic centres over the centuries. Examples of this impact include the floods that devastated cultural sites in 2002 and 2010 in Central Europe, several floods in South Asia in 2007 and 2008, and the New Orleans flood of 2005, caused by Hurricane Katrina. Marzeion and Levermann (2014) have investigated the number of cultural heritage sites throughout the world that might be affected by flooding events over the coming two millennia due to global warming. According to these authors, approximately 6% of UNESCO sites (about 40 sites) will be flooded, particularly in China and India. This hypothesis is also supported by the Intergovernmental Panel on Climate Change (IPCC), according to which it is expected that, as a result of climate change, there will be an increase in frequency and severity of natural hazards, including floods, in the near future (Field et al. 2012).

To face this global issue, a series of directives and regulations related to flood risk management have been developed to establish effective protection of cultural heritage sites. The UNISDR Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015) is an international agreement, striving to reduce disaster risk, as well as “economic, physical, social, cultural and environmental assets of persons, business, communities and countries” (Bedeaux et al. 2018). Further examples of guidelines specifically oriented to cultural heritage are the guides prepared by ICCROM (Stovel 1998; Michalski and Pedersoli Jr. 2016) or the publication “Before and After Disasters” by FEMA (2005). Also in the EU Floods Directive (2007/60/CE), an explicit reference is made to cultural heritage (European Parliament and Council 2007).

Against this backdrop, this work intends to contribute to systematize the current state of art on the assessment of flood risk in urban areas and to propose an original methodology to assess and manage flood vulnerability in historic sites. With the fundamental aim of mitigating damage and protecting human life and cultural heritage, such methodology is centred on the assessment of the flood vulnerability of the elements at risk through the evaluation of the features that contribute to this exposure and sensitivity. To this purpose, the historic centre of Guimarães in Portugal is used in this work as a pilot case-study to examine the applicability and limitations of the developed methodology.

2 A brief review on flood risk assessment

Since the definition of risk and their components is still an open discussion (Kaplan 1997), this section starts with a short conceptual framework of disaster risk in the context of flood risk assessment and mitigation, followed by a review of the most influential methodologies in recent research devoted to this topic. Moreover, considering that the methodology

proposed in this paper is a vulnerability assessment approach, particular attention is given to the vulnerability related concepts and approaches.

2.1 Conceptual framework of disaster risk

In disaster science, risk can be defined as “the potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or society over some specified time period” (UNISDR 2009). As previously discussed by Rana and Routray (2016), due to continuous change in vulnerabilities and varying hazard phenomenon, disaster risk is considered dynamic in nature (Birkmann et al. 2013). Risk was initially considered as an interaction between hazard and vulnerability (Wisner et al. 2004; Adger 2006). Exposure was added to explain elements at risk (Zhou et al. 2015; Crichton 1999), whereas capacity was incorporated for better understanding and countering risk (Bollin et al. 2003; UNOCHA 2013).

2.1.1 Hazard

If applied to natural phenomena, the hazard can be defined as the condition that expresses the probability of occurrence, within a specific period of time, and in a determinate area, of a potentially damaging/dangerous natural phenomenon (UNISDR 2009; Birkmann 2006). For an easy comprehension of the several parameters necessary to accurately describe the hazard, they are typically represented in the form of hazard maps for a certain geographical area. According to the European Flood Directive (EXCIMAP 2007), in the particular case of flooding, hazard maps should be prepared considering at least three scenarios associated with different probabilities of occurrence (low, medium and high). In addition, for each scenario, they have to include the flood extend and the water depth, and, if appropriate, the flow velocity.

2.1.2 Vulnerability related to exposure and sensitivity

Despite there is an array of definitions in the risk literature to describe the concept of vulnerability (Wisner et al. 2004; Birkmann 2006), it is usually referred as the intrinsic predisposition of an element to suffer damage from an event of a given intensity. According to Rana and Routray (2016), once a potential hazard is identified, the risk emerges due to presence of exposed elements. This exposure can be defined as “the presence of susceptible elements” (Field et al. 2012) or physical features of human society (infrastructure) and economic systems (livelihoods) which can be affected by the potential hazard (Birkmann et al. 2013). If an event occurs in an area with no exposure there is no risk. Inversely, in a hazard-prone area, different elements can be exposed to the same level of hazard, but they hardly have the same level of vulnerability. As highlighted by Rana and Routray (2016), sensitivity can be defined as the predisposition of elements at risk to suffer harm (Maiti et al. 2015) or “a tendency/degree of elements at risk” that can come to any harm as a result of the hazard (Birkmann et al. 2013), being that terms like fragility and susceptibility are also used as alternatives to sensitivity.

According to several past research, vulnerability is considered as a vital part of disaster risk reduction and climate change (Pelling 2003; Adger 2006) in the sense that it is the most eager element to be mitigated (Southgate et al. 2013). Vulnerability can express both direct and indirect effects, which, in turn, can be either tangible or intangible. According

to Adelekan (2011), vulnerability of individuals and human population to climate risks, in which flood hazard is included, is dependent on several factors including the geographical location, exposure of population and infrastructure, socio-economic and cultural conditions, political and institutional structures as well as coping and adaptive capacity that differentiate the impacts on people and human system (Wisner et al. 2004; Barroca et al. 2006). Furthermore, vulnerability depends on the type of study, the outputs required, the type of hazard and the spatial and temporal scale of the study. In this sense, one can say that the vulnerability concept is closely related to the analysis system used. It is also important to have a reference to a specific hazard at the moment when a vulnerability analysis is carried out because risk is different in each case. In fact, the correct analysis and the knowledge of the local vulnerabilities are of major importance to assess the risk. In order to synthesize and consider all the approaches and considerations associated with the vulnerability concept, Barroca et al. (2006) defined three levels of increasing complexity: vulnerability concerning the event itself; vulnerability concerning the various types of functions of the “element at risk” that could be affected by the hazard; and vulnerability concerning the risk associated with the object. From this classification one can conclude that the external complexity of vulnerability is related to the cause (or the hazard), the first inherent complexity is related both to the consequences of that hazard and the vulnerability of the element, and the second inherent complexity is related to the prevention and mitigation actions that can be taken when the different sources of vulnerability are identified and properly characterized.

2.1.3 Risk

Finally, risk can be defined as the combination of the probability of an event and its negative consequences. In other words, it can be simply put as the product of hazard and vulnerability (exposure and sensibility) and inversely related to coping/adaptive capacity (Rana and Routray 2016), which, in the light of disaster risk science, can be defined as “the ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters” (UNISDR 2009).

2.2 Flood risk assessment methodologies

Regarding flood risk assessment approaches, two fundamental currents of thought can be found in the literature: the approaches focused on the analysis of the hazard and the methods focused on the vulnerability assessment of the element at risk, see Sects. 2.2.1 and 2.2.2 respectively. It is worth noting that, regardless of the type and philosophy of the flood risk assessment approach, both physical and social dimensions should be considered in the analysis (Gain et al. 2015).

2.2.1 Approaches focused on flood hazard

According to Apel et al. (2009), in the case of the first group of approaches, basic data usually come from hydraulic models, which are considered as one of the most popular flood hazard assessment tools. With the worldwide increase of flood hazard (Zheng et al. 2013; Hammond et al. 2015; Rana and Routray 2018), the need to guaranty safety areas to new structures and to protect and mitigate the impact of flooding in the ones that are already built is also increasing. In urbanized areas, hydrological and hydraulic modelling is a

complex and very demanding task, not only due to their diverse and heterogenic condition, but also because the multiple interactions that exist between the urban structures and the water system at various temporal and spatial scales. It is important to highlight that, since the urban processes have more impact in the hydrological processes rather than the contrary, the hydrological modelling in urban areas should focus upon the evaluation of the urbanization effects on the natural water system, with the aim of assessing not only the impact of the flood over the city, but also the impact of the city on the flood probability.

2.2.2 Vulnerability-based approaches

As for the approaches focused on vulnerability, the data set required usually depends on several factors, namely the type of flood loss, the point of view of the analysis and the scale of the work site, but, in general, it should include: hazard data related to the events with potential to occur (inundation extent and depths); exposure data, i.e., building inventory and land cover data; sensitivity data, i.e., building characteristics and further data sets depending on the flood loss model; and flood loss data, i.e., the amount of damage expected to result from the flood event. This very incomplete list only includes the fundamental parameters to be considered when a flood risk assessment is carried out. For those situations where data is very incomplete or non-existent, the approach to be used must be adapted case by case. Following this line of thought, Stephenson and D’Ayala (2014) presented a holistic approach that aimed at bringing together data that characterizes the intrinsic properties of the buildings that contribute to their vulnerability to flood inundation. In this work, flood risk assessment is discussed on the basis of flood risk maps where building vulnerability is mapped within a deterministic flood hazard extent. A similar approach has already been proposed by Mebarki et al. (2012) to assess the failure risk for masonry structures to flood. As for the Stephenson and D’Ayala (2014) approach, in this method, vulnerability is evaluated from a set of parameters specifically formulated to characterize the intrinsic properties of the structures that condition their vulnerability to flood, however, in this case, with a more numerical and structural focus. Following the same concept but with a different purpose, Balica et al. (2012) developed a Coastal City Flood Vulnerability Index (CCFVI). The index gives a number from 0 to 1, indicating comparatively low or high coastal flood vulnerability, which shows which cities are most in need of further, more detailed investigation for decision-makers.

3 Description of the proposed methodology

As already referred, the main objective of this work is to propose an innovative methodology to assess flood vulnerability of historic urban areas. Thus, and considering not only the objective, but also the type and the amount of information available to achieve it, a simplified index-based flood vulnerability assessment approach was developed and applied in this work. Before moving forward, it is important to stress that, since the fundamental objective of the methodology is to assess flood vulnerability in historic sites, this approach was specifically designed to cope with their vulnerability on the basis of a multicriteria vulnerability analysis of their buildings. In accordance with the conceptual framework of disaster risk presented in Sect. 2.1, flood vulnerability is evaluated in this approach on the basis of two fundamental components: Exposure

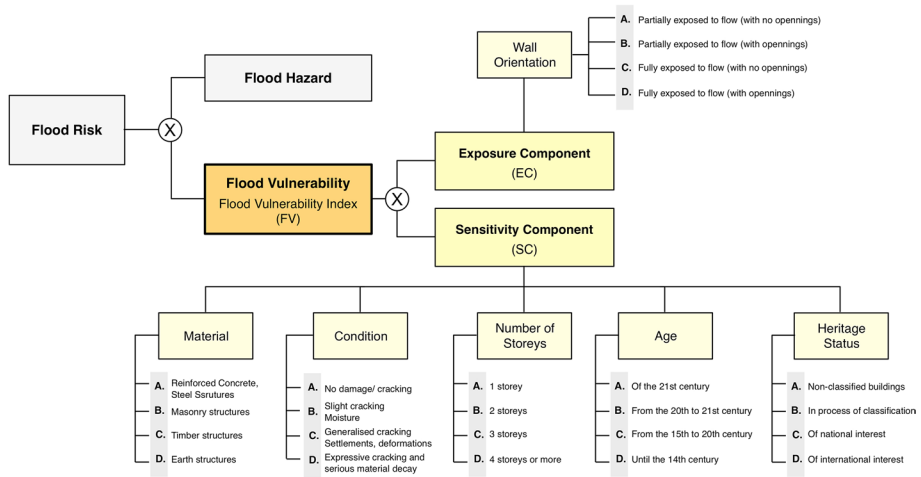


Fig. 1 Framework for simplified flood vulnerability assessment

and Sensitivity, see Fig. 1. From the analysis of these two components, it is possible to obtain a Flood Vulnerability Index (FV) capable of measuring the spread of flood vulnerability over an extended area.

Although the Flood Vulnerability Index could be complemented with further information about socio-economic and environmental aspects (Navia 2017), alone it was planned to provide a practical but still effective tool to measure flood vulnerability in historic sites.

As illustrated in Fig. 1, the Exposure (EC) and Sensitivity components (SC) are based on the calculation of an index for each building as the weighted sum of a set of parameters, which are individually evaluated through four classes of growing vulnerability: A (10), B (40), C (70) and D (100). The higher is the vulnerability class, the higher is the vulnerability of the building in relation to that particular aspect or feature. According to this approach, it is therefore possible to obtain two indices specifically designed to evaluate the Exposure (EC) and the Sensitivity (SC) of a certain historic building to flood.

Once the values of these two components are obtained, it is then possible to compute the Flood Vulnerability Index (FV) through Eq. (1).

$$FV = EC \times SC \quad (1)$$

For ease of use, the values of these three indices (EC, SC and FV), which range, respectively, between [10:100], [50:500] and [500:50000], are then normalized to fall within the range of [0:100], wherein the lower the value of the index, the lower the level of exposure, sensitivity or vulnerability of the building.

It is important to note that exposure and sensitivity components were defined in this work on the basis of similar indicators already available in the literature, developed for assessing analogous building typologies and structural characteristics under equivalent assessment conditions (see Table 1).

To better introduce the approach, exposure and sensitivity components are comprehensively described in the following paragraphs.

Table 1 Indicators selected for vulnerability assessment with respective sources

Indicator	Sources
<i>Exposure component</i>	
Wall orientation	Mebarki et al. (2012)
<i>Sensitivity component</i>	
Material	Schwarz and Maiwald (2008), Stephenson and D’Ayala (2014) and Mebarki et al. (2012)
Condition	Ferreira et al. (2014), Stephenson and D’Ayala (2014), Schwarz and Maiwald (2008) and Mebarki et al. (2012)
Number of storeys	Stephenson and D’Ayala (2014) and Mebarki et al. (2012)
Age	Stephenson and D’Ayala (2014), Santos et al. (2013) and Maio et al. (2017)
Heritage status	Stephenson and D’Ayala (2014)

3.1 Exposure component

As can be seen in Fig. 1, Exposure component is composed of one single parameter, “Wall Orientation”, which was established to evaluate the propensity of buildings to be affected by a flood event from the analysis of the orientation of its main façade wall with respect to the flow.

This parameter intends to bring together the multiple aspects that should be considered for the evaluation of this phenomenon, namely the location of the building, the orientation of its main façade wall and the existence of openings, knowing that buildings located in low-lying areas are theoretically more susceptible to inundation due to runoff. Like the other parameters, parameter “Wall Orientation” is classified in four vulnerability classes, being that: Class A corresponds to a building partially exposed without openings; Class B to a building partially exposed with openings; Class C to a building fully exposed without openings; and finally, Class D to a building that are fully exposed and present openings. In the case of a building located in low-lying areas, which is common in urban areas near to river banks, its vulnerability class should be increased to Class C or D, respectively, whether if it is a partially or a fully exposed building (regardless of the openings).

3.2 Sensitivity component

In what concerns the Sensitivity component (refer to Fig. 1), it is composed of five evaluation parameters specifically tailored to evaluate the physical characteristics of the buildings accounting for their material characteristics, condition (or conservation status), number of storeys, age and heritage status. As already noted, all of them were defined from the analysis of a vast literature review, see Table 1.

Parameter “Material” is based on the work of Schwarz and Maiwald (2008), who have delineated seven building types with different behaviour in face of flooding events. From this base and taking into account the most common constructive typologies in Europe, four main material/structural typologies were considered: reinforced concrete and steel structures (Class A); masonry structures (Class B); timber structures (Class C); and earth constructions (Class D). This hierarchy was defined considering the combination of two fundamental aspects: the lateral capacity of the wall structure; and the

absorption capacity of building materials. This parameter can be evaluated on the basis of in situ inspections and supported, or complemented, with architectural characterization obtained from literature. In a less accurate way, this information can be obtained only on the basis of a detailed investigation of constructive methods for each historical period.

The next parameter considered, “Condition”, was defined in this work on the basis of a methodology proposed by Ferreira et al. (2014) for assessing seismic vulnerability. In that work, the authors have identified some common structural damages resulting from seismic events, having qualified them in four grades of severity. A similar classification was adopted in this work, including in Class A the buildings whose walls are in good condition; in Class B those buildings that present cracking with less than 0.5 mm of opening and eventual coating decay; in Class C those that present more generalized and expressive cracking, with 2–3 mm, and that show signs of deformation; and in Class D those that evidence serious decay and present expressive cracking, even if not generalized. This classification is also in line with that proposed by Stephenson and D’Ayala (2014) for the flood vulnerability assessment of historic buildings, who stress that buildings in overall poorer condition, with less evidence of a continued programme of repair and maintenance, are necessarily more vulnerable to inundation due to pre-existing fatigue in the structure and fabric.

The third parameter is dedicated to evaluating the number of storeys, a feature that according to several authors, namely those cited in Table 1, can play a significant role in the increase of the flood vulnerability. This parameter is based on the proposal of Stephenson and D’Ayala (2014) who claim that, the greater the number of storeys, the higher is the vulnerability of the building to flood. According to them, in the presence of superficial foundations, a building with more storeys over the same footprint will be more susceptible to the stress differentials generated by saturation and drying of the foundation soil during and after a flood. It is important to note that this standpoint is discussed by some authors who defend the opposite. Nevertheless, and despite there is no consensus on this matter, the position of Stephenson and D’Ayala (2014) was followed in this work.

The two last parameters, “Age” and “Heritage Status”, are considered in this approach because most of the buildings located in historic sites present, at different levels, a potential value resulting from either their history or their constructive and material characteristics. Regarding parameter “Age”, it categorizes the buildings into four distinct historical periods ranging from the first century to our days. Assuming the thesis that the older the building the higher its propensity to suffer flood damage and its interest from the heritage preservation standpoint, vulnerability classes are arranged from the most recent to the older buildings (A to D). It is important to highlight that, to adapt to social, technological and comfort requirement, buildings changes over time, suffering modifications that can be potentially favourable or unfavourable in terms of vulnerability. In order to take this aspect into account, the last intervention should be considered for the qualification of the age. With this parameter, it is also possible to identify the predominant architectural style, a factor that could be very helpful at the moment to do the structural characterization, since the main structural lines that follow each style are usually well documented in the literature.

As for parameter “Heritage Status”, it is also arranged in four sensitivity classes, which evaluate the buildings according to their heritage status. Classes A and B are applicable, respectively, to buildings of international and national interest; Class C to building in process of classification; and Class D to non-classified buildings. It is worth referring here that this kind of information related to heritage classification is usually available for public consultation.

Finally, it is important to stress that despite this approach is primarily intended for assessing single buildings, it can be also used to evaluate the flood vulnerability of a block or even of an entire historic site, allowing for the assessment and analysis of the flood vulnerability at different scales and levels.

4 The historic Centre of Guimarães as a pilot case study

The city of Guimarães is located in the northern region of Portugal, in the Province of Minho, district of Braga ($41^{\circ}26'N$, $8^{\circ}19'W$). Its historical centre dates from the tenth century. It started as a two elements settlement: a monastery and a fort, one in the valley and the other in the hill, respectively. Over centuries these two focal points have continued to grow until they conformed the walled city in the thirteenth century. In the fifteenth and sixteenth centuries, a variety of activities have started to develop. Among others, the manufacture of cutlery, jewels and treatment of leather have become particularly prosperous. The eighteenth century marks a period of territorial expansion and intensive construction. It is by this time that the first urban master plan of the city appears, whose implementation, in the first half of the nineteenth century, led to the construction of new roads and to a decisive change in the mediaeval core of the city. In the twentieth century, the expansion process of the city ends, and the industrial development begins.

In 2001, the historic centre of Guimarães was declared as a World Heritage Site by UNESCO (2001). As depicted in Fig. 2, the declared area has a total area of approximately 16 ha and encompasses the thirteenth century mediaeval core, whereas the buffer area, with about 45 ha, corresponds to the urban core founded in the seventeenth century.

As the name suggests, the buffer area, whose limits were defined by government instances, surrounds the declared area, imposing the proper and necessary restrictions to

Fig. 2 Historic centre of Guimarães: declared core and buffer area





Fig. 3 Examples of floods in the Couros' basin between 2004 and 2007 (Source: Guimarães City Council)

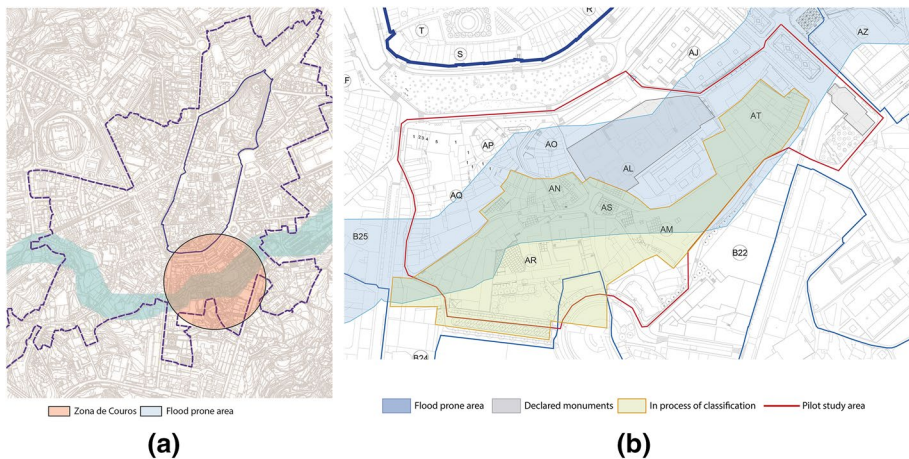


Fig. 4 Flood-prone area (a) and identification of the study area (b)

protect and value it. In accordance with the Article 44° of the Decree of law no. 309/2009 issued on October 23, 2009, by the Minister of Culture of the Portuguese Government (Portugal 2009), this buffer area should also ensure the landscape framing of the core area and the perspectives for its contemplation.

4.1 Characterization of the study area

During the last decades, the city of Guimarães has been subjected to strong anthropogenic pressure due to increasing urban and industrial occupation, giving rise to the deterioration of existing buildings and the environmental degradation of Couros river basin. This water body has been part of the population's life and a vital element for the development of the already mentioned leather industry (Ramísio et al. 2011). Throughout several decades, this watercourse has been subjected to severe pressure due to the urban growth and the intensive leather industry activity. As a result, the levels of pollution and contamination in the Couros creek, as well as the severity of flood events in the historic centre of Guimarães, have increased substantially, see Fig. 3. In an attempt to tackle these issues, in 2007, the Municipality of Guimarães and the University of Minho formalized a partnership to implement the Project Campurbis (Ramísio 2012). Among other direct and indirect outputs resulting from this project, the hydrological characteristics of the Couros river basin were

comprehensive analysed, and a flood-prone area of the historic city of Guimarães was geographically identified and mapped, see Fig. 4a.

According to the approach presented in this paper, the hazard component is treated in a deterministic way, namely by mean of the analysis of flood hazard maps or historical data related to flood events. In this case, the working area was defined from the confrontation between the flood-prone area, in Fig. 4a, and the exposure and sensitivity characteristic of the building that can be potentially affected.

Following this criterion, the urban area illustrated in Fig. 4b, known as “Zona de Couros”, was therefore selected as the pilot study area to apply the proposed methodology. Within the selected zone there are located two declared monuments of public interest, the Convent of St. Francisco and Santos Passos Church, and the industrial building complex of Couros, which is in process of heritage classification, as well as several buildings from the sixteenth to nineteenth century, which, despite not officially declared as heritage buildings, present significant cultural value conferred either by their singular architectural and constructive features or as elements of the built environment that compose this World Heritage Site.

4.2 Building appraisal: survey procedure and implementation of a GIS tool

The pilot study area is composed of nine blocks, labelled in Fig. 4b with the initials AL, AM, AN, AO, AP, AQ, AR, AS and AT. The assessment was based on an extensive field data survey supported by an inspection form specifically designed to collect the amount of data required to apply the above described flood vulnerability assessment approach.

116 buildings were inspected in the nine blocks and all the information gathered was digitalized and systematized into a Microsoft Excel spreadsheet where individual flood exposure, sensitivity and vulnerability components are automatically calculated. In order to improve the interpretation of the results, such individual flood vulnerability components, as well as other input information, were then integrated into a Geographical Information System (GIS) tool. The GIS software adopted in this study was the open-source suite QGIS (QGIS 2017) wherein geo-referenced graphical data (vectorized information and ortho-photo maps) was combined with building parameter information. In this specific case, each polygon (corresponding to a building) was associated with several features and attributes, allowing for their visualization, selection and search.

5 Flood vulnerability assessment

From the application of the flood vulnerability assessment approach to the 116 buildings located within the study area, it was obtained a distribution of the Flood Vulnerability Index (FV) values characterized by a mean value of 25.70 and a standard deviation of 16.01. Figure 5a shows the histogram along with the best fit normal curve for such distribution. From the analysis of the cumulative frequency curve presented in Fig. 5b, it is possible to observe that 25% of the buildings present a FV value ranging between 0 and 15 and about 35% between 15 and 30, which means that more than half of the buildings assessed (about 60%) have a Flood Vulnerability Index value comprised between 0 and 30.

It should be noted at this point that, although these Flood Vulnerability Index values cannot be directly correlated with flood damages, the distribution given in Fig. 5 seem to demonstrate that a considerable percentage of the buildings assessed in this work are

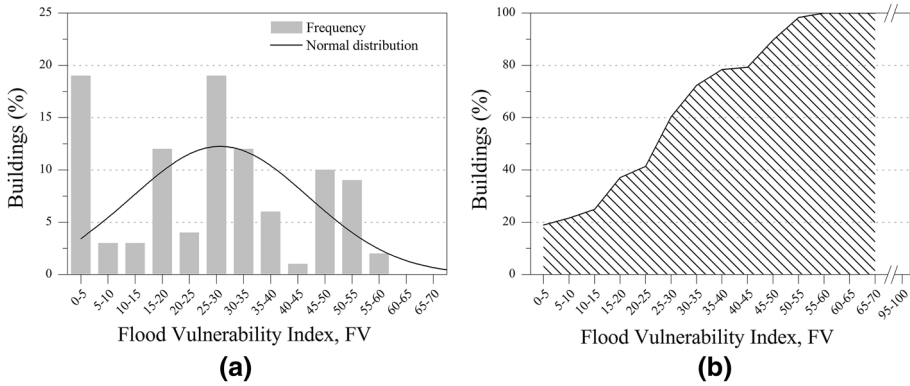


Fig. 5 Distribution of the Flood Vulnerability Index results: **a** histogram and best fit normal curve; and **b** cumulative frequency curve

vulnerable to flooding events. Thus, though not quantifiable, from the analysis of these preliminary vulnerability results, it is possible to admit that the impacts resulting from a flooding event in the study area are potentially important, both from the economic and the heritage preservation point of view.

5.1 Analysis of the parameters that compose the Flood Vulnerability Index

Before going into a more detailed individual analysis of the Exposure, Sensitivity and Vulnerability results, the investigation of the parameters that composes the Flood Vulnerability Index allows for characterizing and discussing some particular indicators that can help to better understand the overall flood vulnerability results. With this aim in view, their frequencies, as well as their spatial distributions over the study area, are illustrated in Figs. 6 and 7, respectively, and discussed on the following.

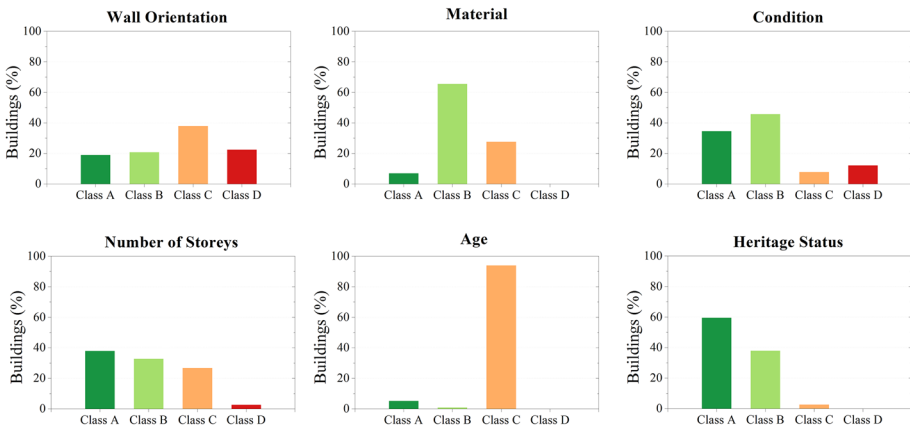


Fig. 6 Frequency distribution of the parameters that compose the Flood Vulnerability Index

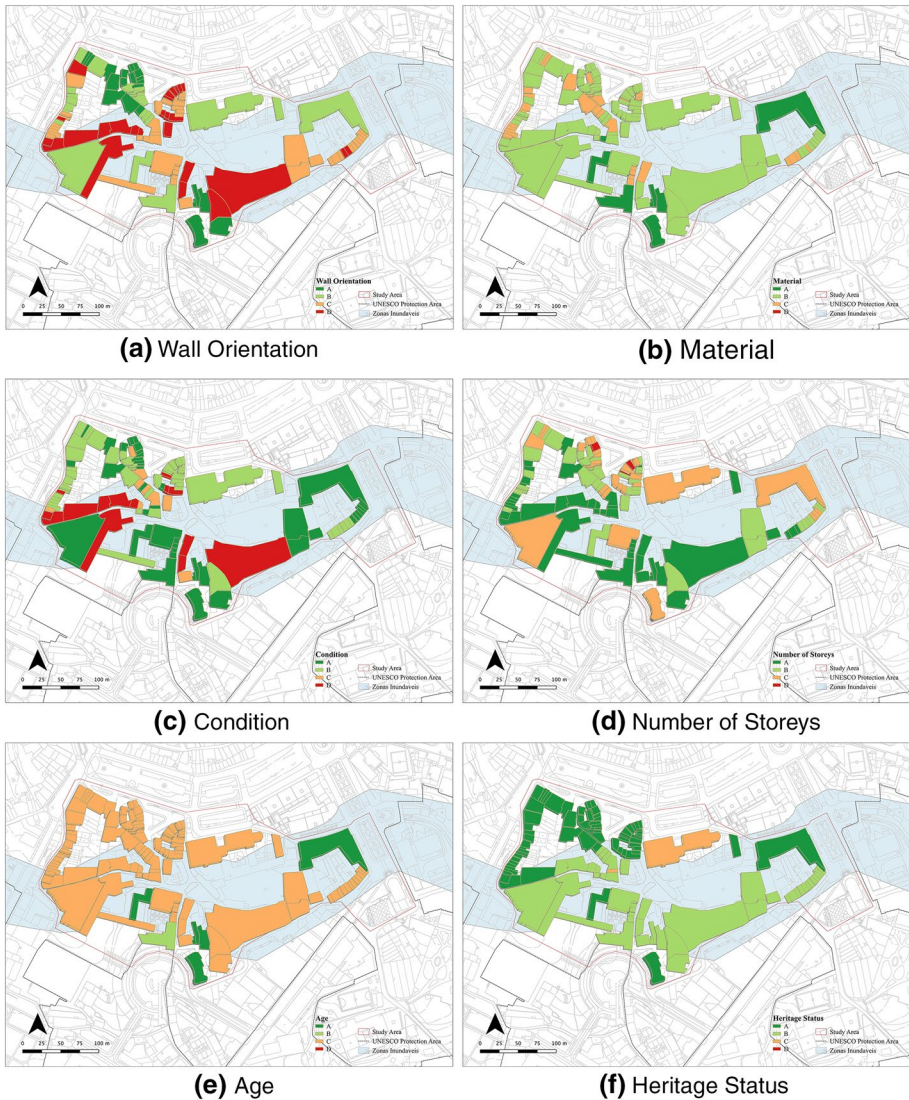


Fig. 7 Spatial distribution of the six parameters that compose the Flood Vulnerability Index

Regarding parameter “Wall Orientation”, the one that measures the level of exposure, about 19% of the buildings present a partially exposed situation with no openings in the water flow direction, 21% present a partially exposed situation with openings in the flow direction, 38% are fully exposed, without openings, and the remaining 22% are fully exposed, with openings in the water flow direction. From the analysis of Fig. 7a, it is possible to observe that this situation is further aggravated by the fact that most of the buildings that present higher levels of exposure (classes C and D) are located within the identified flood-prone area.

As for parameter “Material”, the first parameter of the Sensitivity component (see Sect. 3), there is a clear predominance of masonry buildings with a frequency of about 66%. The remaining 7% and 27% of the buildings are, respectively, reinforced concrete/steel and timber structures. In what concerns the buildings’ condition, it is possible to point out that almost 80% of the buildings assessed are either in good condition (about 34%) or present minor conservation issues, mainly related with small cracking and/or coating decay (in about 46% of the cases). Only about 20% of the buildings assessed are in poor conservation state, presenting moderate to large cracking and/or severe moisture issues. However, as for parameter “Wall Orientation”, the greater part of these buildings is located within the identified flood-prone area, which represents a potentially dangerous situation, see Fig. 7c.

In terms of “Number of Storeys”, as can be seen in Figs. 6 and 7d, the buildings are distributed between vulnerability classes A to C, with 38%, 33% and 27% of the buildings presenting 1, 2 and 3 storeys, respectively. Only two building have more than 3 storeys. As expected, parameter “Age” presents a major influence in the overall Flood Vulnerability Index results, since 94% of the buildings evaluated were built between the fifteenth and the twentieth centuries and therefore were classified with class C. Finally, in what concerns parameter “Heritage Status”, 59% of the buildings assessed are non-classified buildings, whereas 38% are currently in process of classification. Only 3% of the buildings are classified as heritage buildings.

5.2 Mapping of the exposure, sensitivity and vulnerability results

A more comprehensive understanding of the overall vulnerability results can be achieved by analysing their distribution over the study area. The use of the GIS tool (briefly described in Sect. 4.2) makes it possible to spatially represent the global distribution of the Exposure, Sensitivity and Flood Vulnerability Index results, enabling the identification of more vulnerable areas and buildings, which can be a very useful output for urban planning and management purposes.

Thus, the spatial distribution of the exposure and sensitivity components is presented, respectively, in Fig. 8a, b. From the analysis of Fig. 8, one can observe that despite there is a scatter distribution of the levels of exposure and sensitivity across the study area, some of the most exposed buildings are located in the south part of the site, exactly within the

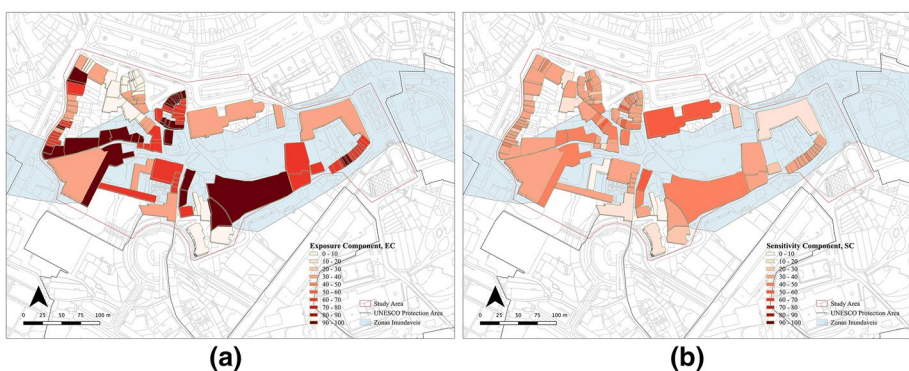


Fig. 8 Spatial distribution of the Exposure (a) and Sensitivity (b) components over the study area

identified flood-prone area, see Fig. 8a. This very same observation can be made regarding the spatial distribution of the Sensitivity component. In fact, as can be seen in Fig. 8b, the most relevant building from the point of view of their age and heritage value are located on this area.

As for the geographical distribution of the Flood Vulnerability Index, given in Fig. 9, it is possible to note that although there is a general dispersion of the vulnerability values over the study area, 10 out of the 14 most vulnerable buildings (with $VF \geq 50$) are scattered along the identified flood-prone area, Fig. 9b.

6 Conclusions

This paper addresses the issue of assessing and managing flood risk in historic sites, presenting a novel index-based approach by which the vulnerability of built cultural heritage to flood can be recorded, appraised, combined and quantified. The proposed methodology relates specifically to flood events and is drawn from specific definitions of exposure and sensitivity that are believed to be the most appropriate to historic buildings. It is based on a Flood Vulnerability Index (FV), which results from the combination of two different components. An exposure component, resulting from the analysis of the propensity of the buildings to be affect by a flood event, and a sensitivity component, which was specifically formulated to analyse the building characteristics that rule their physical sensitivity to flooding.

Despite the level of uncertainty associated with this kind of approaches, vulnerability assessment methods based on statistical approaches and damage observation can be seen as the most suitable tools for large-scale analysis, namely because they offer a very interesting compromise between the amount and the type of information required, the computational effort necessary to carry out the analysis and the reliability of the outputs produced. However, the definition of each parameter weight, the quality of exposure and sensitivity qualification data, as well as the eventual inclusion of some additional indicators, are issues that still require further study.

As a general conclusion on the results obtained for the historic centre of Guimarães, used herein as a pilot case study, it is important to highlight the need to take into particular

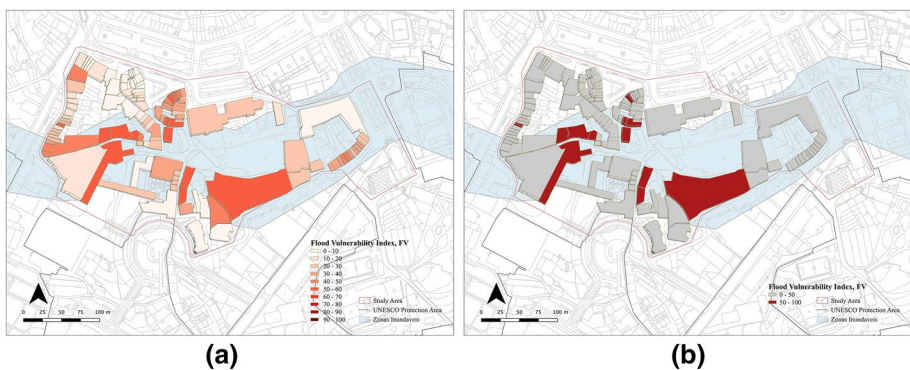


Fig. 9 Flood Vulnerability Index results: **a** distribution over the study area; and **b** identification of the most vulnerable buildings ($VF \geq 50$)

attention the buildings spread over the identified flood-prone area, namely those whose flood vulnerability index values are higher. Among those, special care has to be given to the abandoned buildings, which should be considered as priority for conservation and restoration efforts. It is worth noting that the actual overall conservation state of the evaluated buildings was poor, presenting fragilities that could compromise their good performance in the case of a flood event, even for low to moderate severity.

As discussed in Sect. 5, the analysis of the spatial outputs obtained with the GIS tool allows to better understand the spread of exposure, sensitivity and overall vulnerability over the study area, which is a fundamental prerequisite to propose more adequate intervention strategies based on realistic local conditions. In this sense, the methodology proposed can be used to provide preliminary vulnerability scenarios and to point the way to the definition of more efficient and customized strategies for managing and mitigating flood risk. With further improvements and calibrations resorting to larger and more diverse data, it will be possible to generalize the information in different areas with same characteristics and to reduce some of the uncertainties involved in the assessment. Still in this respect, it is important to note that the simplified flood vulnerability assessment approach proposed and applied in this work can be easily adapted to outline vulnerability scenarios for other historic/heritage sites around the world.

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