A hybrid approach for the assessment of flood vulnerability of historic constructions and their contents

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Abstract. Flooding is among the natural hazards that cause the most significant damage to immovable and movable cultural heritage assets worldwide. Simplified flood vulnerability assessment methodologies are practical tools that can support decision-making strategies to address potential flood damage in cultural heritage assets. However, existing flood vulnerability assessment approaches tailored for cultural heritage are scarce or tend to have significant limitations. Therefore, this paper proposes a new simplified framework for the flood vulnerability and risk assessment of historic buildings using a hybrid approach that combines a baseline vulnerability curve with an indicator-based method, which was defined through an in-depth literature review. The baseline vulnerability curve expresses the potential maximum damage of the historic building as a function of water depth, and accounts for flood vulnerability parameters that reflect the geometric properties of the historic building and the location of the cultural content (e.g., the height of the building, the height and location of the artwork, the existence of underground levels, the distance between the external ground level and the ground floor level). Subsequently, the vulnerability curve is adjusted using a vulnerability index, which has eighteen flood vulnerability indicators categorised into four groups, to establish the resulting vulnerability curve that provides a relative measure of the expected physical damage of the historic buildings due to floods of different intensities. The paper illustrates the methodology through an application to a historic Portuguese building exposed to floods.

Keywords: flood risk, cultural heritage, vulnerability analysis, indicator-based methods, vulnerability curves.

1 Introduction

The vulnerability and increasing exposure of cultural heritage assets to floods in the context of climate change [1,2] lead the interest towards the creation of flood risk assessment tools supporting the prevention of their physical damages, and thus the reduction of vulnerability through flood mitigation actions. However, existing approaches to assess the physical vulnerability of historic constructions to floods, i.e., to estimate the damage that they may undergo as a result of flood events, are sparse and tend to present limitations. For example, vulnerability assessment methods for application at large spatial scales (e.g., [3-5]) are unable to account for asset-specific characteristics and are therefore suited mostly for preliminary risk assessments. On the contrary, other existing methods focus on specific types of flood events (e.g., extreme precipitations [6]) or on a specific type of heritage considering materials for a certain region (e.g., [7,8]), and cannot be easily generalized. Thus, the purpose of this paper is to present a new, flexible and simplified vulnerability assessment framework developed considering the state of the art in flood vulnerability of buildings, which aims to characterise the expected physical damage due to flooding for different historic constructions and their contents.

The methodology can be framed within an intermediate level of a multilevel risk assessment framework (e.g., [9]) between a large spatial scale flood vulnerability analysis as developed in [3], and a component-based flood vulnerability modelling as proposed in [8]. Thereby, a hybrid method was created through the representation of a flood vulnerability curve ($FVC(\beta)$ in function of water depth (β) that combines a baseline vulnerability curve ($V_C(\beta)$) and the definition of an index based on eighteen flood vulnerability indicators (VI_{FL}). The paper illustrates the application of the methodology to a historic building exposed to floods located in Portugal, considering specific scenarios for river floods based on hazard maps developed in the scope of the Portuguese implementation of the European Floods Directive [3,10].

2 Flood vulnerability assessment method

The proposed methodology combines two types of measurable components, namely parameters and indicators, which were investigated in [11] for flood vulnerability assessment in cultural heritage. The parameters, associated with the geometric properties of the historic building and the height where the cultural content is located, support the characterisation of a baseline flood vulnerability curve, whereas the indicators are used to estimate an index that reflects other features that

influence the flood vulnerability of the building. Fig. 1 depicts a summary of the literature used to identify and select the parameters and indicators for the development of this method.

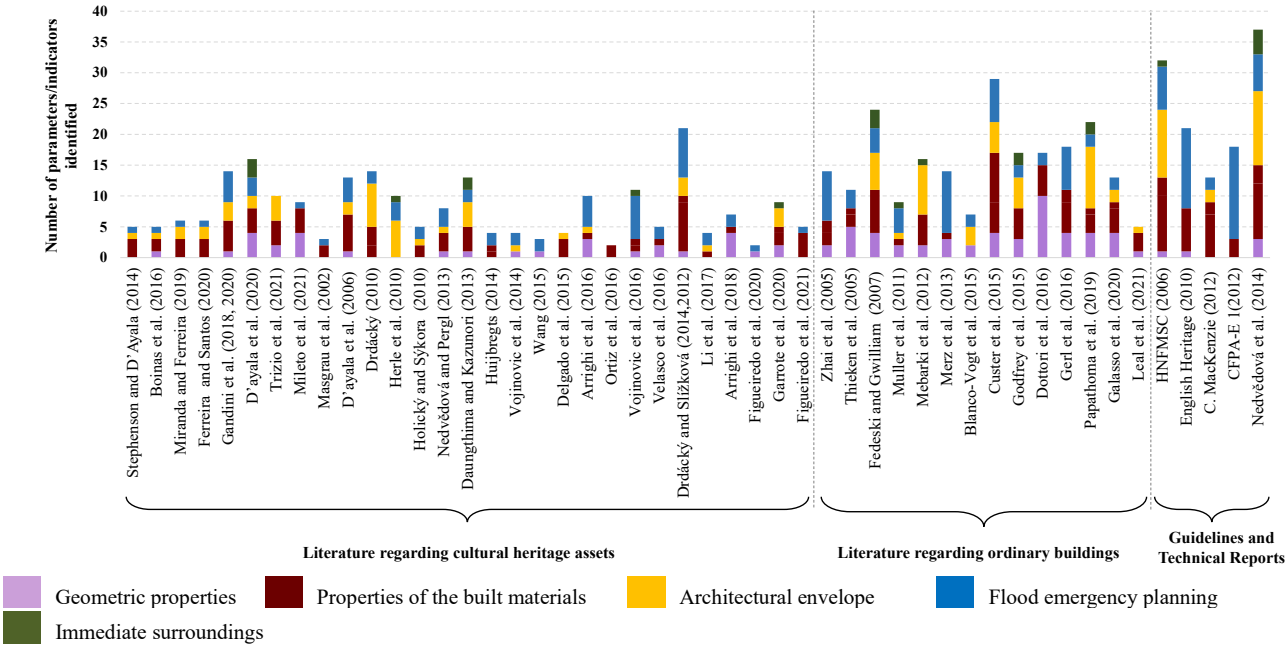


Fig. 1. Literature used (48 references) to define the geometric parameters and the flood vulnerability indicators of the hybrid flood vulnerability assessment divided into literature involving flood vulnerability methods tailored for cultural heritage, flood vulnerability literature of ordinary buildings, and complementary literature involving technical guidelines and reports (HNFMSC stands for Hawkesbury-Nepean Floodplain Management Steering Committee; CFPA-E stands for Confederation of Fire Protection Association Europe).

Within the proposed framework, the parameters and indicators are applied, respectively, in two phases. In the first phase, a baseline vulnerability curve ($V_C(\beta)$) is defined through the geometric parameters obtained from the historic building under assessment, based on its architectural configuration and the expected location of its contents of value. This baseline vulnerability curve will express the distribution of potential damage in the levels of the building considered to be floodable (i.e., ground floor and basement), expressed in relative terms, as a function of height, in a range between 0 and 100, where 0 corresponds to no damage and 100 corresponds to complete damage. This represents a hypothetical worst-case scenario whereby the water is considered to cause complete damage to all the components that it reaches.

In the second phase, the baseline vulnerability curve is adjusted through the definition of a vulnerability index VI_{FL} based on eighteen Flood Vulnerability Indicators (I_{FLi}) grouped into four categories: 1) properties of the immovable and movable cultural materials (C_M), 2) the architectural envelope (C_{AE}), 3) the flood emergency planning (C_{FP}), and 4) the immediate surroundings (C_{IS}). The calculation of the VI_{FL} index will be determined according to the average value for each category (i.e., $\overline{C_M}, \overline{C_{AE}}, \overline{C_{FP}}, and\ \overline{C_{IS}}$), obtained through the classification scores presented in subsections 2.2 and 3.2 for each I_{FLi}, and multiplied by weights proposed by the authors. The assignment of weights was determined after the characterisation of the flood vulnerability indicators, taking into account that not all the indicators contribute in the same way to the damaging flood effects. The categories with indicators regarding the properties of the materials (C_M) and the architectural configuration (C_{AE}) were considered to contribute more to the impact than the groups with indicators linked to the surrounding (C_{IS}) and flood preventive measures (C_{FP}). Therefore, to reflect this difference, the assigned weights to each of these four groups were 30%, 30%, 20%, and 20%, respectively, as presented in Eq. (1):

$$VI_{FL} = \left(\overline{C_M}_{[1:7]} \times 0.30\right) + \left(\overline{C_{AE}}_{[8:10]} \times 0.30\right) + \left(\overline{C_{FP}}_{[11:14]} \times 0.20\right) + \left(\overline{C_{IS}}_{[15:18]} \times 0.20\right) \quad (1)$$

where, $\overline{C}_{\iota[j:k]}$ is the mean score of indicators j to k from the categories C_M, C_{AE}, C_{FP} and C_{IS}. The following sections explain how the baseline vulnerability curve (i.e., $V_C(\beta)$) and the eighteen flood vulnerability indicators were developed to create the hybrid method. Note that some indicators ($I_{FLi}(\beta)$) can be influenced by the water depth, as will be referred in subsections 2.2 and 3.2. Each flood vulnerability indicator represents a different feature of the building that can affect its flood vulnerability and will be scored between 0 and 100, where 0 reflects a very low contribution to the occurrence of potential flood damage and 100 reflects a very high contribution. These quantities will be weighted by groups to estimate a Flood

Vulnerability Index VI_{FL}, which is subsequently combined (i.e., multiplied) with the baseline vulnerability curve, as shown in Eq. (2).

$$FVC(\beta) = V_C(\beta) \times \left(\frac{VI_{FL}}{100}\right) \quad (2)$$

where $FVC(\beta)$ is the final vulnerability curve for the historic building under assessment, which depends on the hypothetical water depth measured from the external ground level (β), $V_C(\beta)$ is the baseline vulnerability curve, and VI_{FL} is the flood vulnerability index accounting for the 18 flood vulnerability indicators. The final vulnerability curve $FVC(\beta)$ can provide a relative measure of the expected physical damage for a historic building and its valuable content due to potential floods of different intensities.

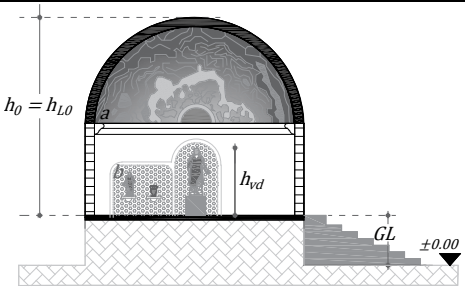
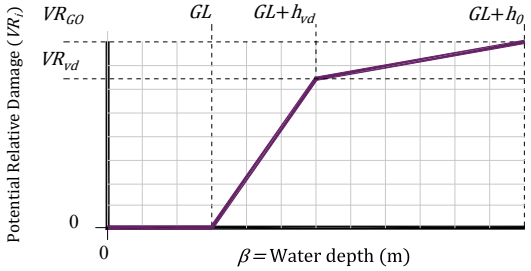
2.1 Baseline Vulnerability Curve ($V_C(\beta)$)

The definition of $V_C(\beta)$ is based on the geometric parameters of the building and certain assumptions regarding the vertical distribution of components with cultural value, including contents, within the floodable parts of the building. This baseline vulnerability curve will represent the maximum potential flood damage as a function of the water depth (β), assumed as the worst-case scenario, as previously mentioned. Depending on the specifics of each building, the baseline curve can take various forms. For brevity, this paper focuses on a building typology with no basement and with the ground flood level located above the external ground level. In this case, $V_C(\beta)$ is given by:

$$V_c(\beta) = \begin{cases} 0, & 0 < \beta \leq GL \\ \frac{VR_{vd}}{h_{vd}} \cdot (\beta - GL), & GL < \beta \leq (GL + h_{vd}) \\ VR_{G0} - \frac{(VR_{G0} - VR_{vd})}{(h_0 - h_{vd})} \cdot (GL + h_0 - \beta), & (GL + h_{vd}) < \beta \leq (GL + h_0) \end{cases} \quad (3)$$

where GL is the distance from the external ground level to the ground floor level located above; h_0 is the height of the ground floor level; h_{L0} is the height up to which cultural movable or immovable assets on the ground floor level exist that should be considered by the surveyor for possible cultural loss; and VR_{G0} is the maximum potential relative damage in the ground floor. In this formulation, the cultural value within the building is assumed to be linearly distributed in height. However, the contents of value tend to be concentrated at the lower levels of a building, meaning that the assumption of a single slope in the vulnerability curve will generally be unrealistic. To account for this, an additional parameter h_{vd} and a corresponding value of potential relative damage VR_{vd} are considered in order to enable a differentiation in the slope of the vulnerability curve. For the sake of illustration, one could assume that on the ground floor of a 12-meter-high church, at 3 metres height (i.e., h_{vd}=3m), components of the building representing 80% of its cultural value, which could include for example floors, wall paintings, artwork, statues, or others, may be touched by water (i.e., VR_{vd}=80), whereas the remaining 20% of the value would be located between 3m and 12m. Table 1 depicts the baseline vulnerability curve and a schematic representation corresponding to a building typology with no basement and with the ground flood level located above the external ground level. The illustrative cross section in Table 1 represents a historic construction with fixed and movable cultural assets (e.g., vault paintings (a), and altarpieces with pottery and sculptures (b)).

Table 1. Conditions, schematic representation, and baseline vulnerability curve of a selected illustrative case for this framework.

Conditions	Illustrative Cross Section	Baseline Vulnerability Curve
$GL > 0$ *(Ground floor above external ground level)*		
$h_0 = h_{L0}$ *(Contents of value along the entire height)*		

2.2 Flood vulnerability indicators

As previously mentioned, the eighteen flood vulnerability indicators were organised into four categories. The category related to the properties of the immovable and movable cultural materials (C_M) is summarised and classified in Table 2,

which involves indicators that consider some of the susceptible chemical or physical reactions of cultural heritage materials of the structure and its contents due to water contact. The classifications of I_{FL1} to I_{FL5} are based on Eq. (4), which includes the susceptibility indices (SI_i) and the number (n) of the different materials that may be found in the vertical structural supports (I_{FL1}), horizontal structural supports $I_{FL2}(\beta)$, finishings and linings (I_{FL3}), movable heritage content (I_{FL4}) and attached artwork (I_{FL5}). The susceptibility indices (SI_i) can take one of five values (i.e., 0, 25, 50, 75, 100), reflecting the susceptibility of different materials when in contact with water, based on the methodology presented in [8]. $I_{FL2}(\beta)$ will influence the vulnerability assessment only when the height of the hypothetical water depth (β) reaches the structural horizontal supports. $I_{FL6}(\beta)$ measures the level of damage due to possible water entry by considering the type of window and opening protection, the worst-case ratio between the façade and the openings (i.e., windows and doors) and the hypothetical water depth (β) that reaches the level of the openings. I_{FL7} measures the global conservation state of the historic building.

Table 2. Vulnerability indicators for the category properties of the immovable and movable cultural materials (C_M).

Indicator (I_{FLi})	Summarised description for each classification	Value
I_{FL1} – Vertical supports	$I_{FL_{[1:5]}} = \frac{\sum_{i=1}^{n} SI_i}{n}$ (4)	0…100
$I_{FL2}(\beta)$ – Floors		0…100
I_{FL3} – Finishings		0…100
I_{FL4} – Movable heritage		0…100
I_{FL5} – Attached artwork		0…100
$I_{FL6}(\beta)$ – Openings	It does not present openings with glass, or the water depth (β) does not reach the openings	0
	It presents openings with adequate protection (e.g., window locks/catches, hinges)	25
	β reaches the bottom of the openings, there is no protection, and the ratio is less than 25%.	50
	β reaches the bottom of the openings, there is no protection, and the ratio is between 25% and 50%	75
	β reaches the bottom of the openings, there is no protection, and the ratio is more than 50%	100
I_{FL7} – Conservation state	Excellent: The floodwater will not produce adverse effects	0
	Good: It presents only superficial damage (e.g., efflorescence) of the construction materials.	25
	Medium: It presents material degradation (e.g., spalling) that does not affect the stability of a structure	50
	Bad: It presents damages that can trigger the instability of the structure in the medium term	75
	Very bad: It denotes a visible deterioration that can trigger partial/total collapse in a flood	100

The category related to architectural configuration (C_{AE}) is summarised and classified in Table 3. $I_{FL8}(\beta)$ measures the capacity of the vertical structure envelope prone to water pressure, by employing the graphs published in [12]. This approach considers four types of walls depending on their supports classified into P1, P2, P3 and P4 (see Fig. 2). P1 is the wall simply supported at the foundation level (one-edge support). P2 is the wall simply supported at the top and the foundation level (two-edge supports). P3 is the wall simply supported on the cross walls and at the foundation level, but without constraints at the top (three-edge supports). Lastly, P4 (four-edges support) is the wall simply supported along its perimeter by the cross walls, at the top and the foundation level [12]. Furthermore, $I_{FL8}(\beta)$ accounts for the slenderness ratio of the faced walls (i.e., thickness over height, X_2), a representative curve given by [12] of the ratio X_3 (see Fig. 3) that represents the load over the wall and the wall weight (i.e., only the self-weight of the wall $\therefore X_3 = 0$; one floor above the ground floor $\therefore X_3 = 1$, and two floors (or more) above the ground floor $\therefore X_3 = 2$), and the water depth(s) referred as X_4 in [12].

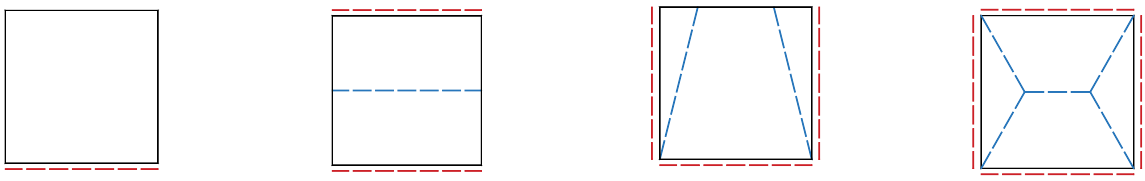


Fig. 2. Four types of walls depending on their supports, taken from [12].

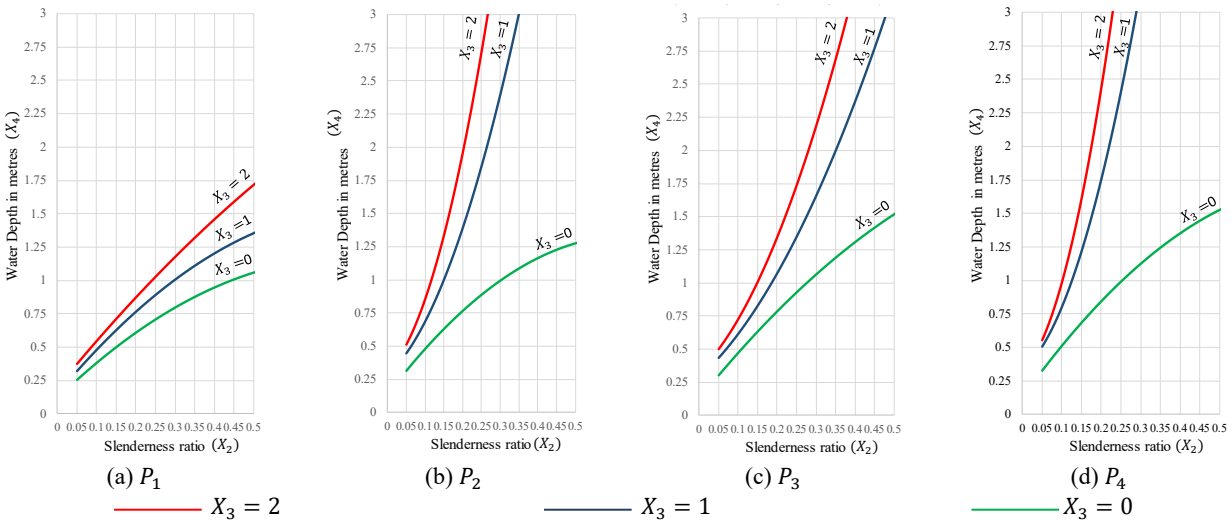


Fig. 3. Vulnerability thresholds for the reference walls: (a) P_1, (b) P_2, (c) P_3, and (d) P_4, as a function of the slenderness ratio of the wall (X_2) and the hypothetical water depths (X_4). The graphs, taken from [12], which are up to 2 metres, were replicated by using WebPlotDigitizer [13], extrapolating the data up to 3 metres from the source using Polynomial trend line in Excel.

The 'Roof' indicator (I_{FL9}) measures the state of conservation of the roof and the propensity to accumulate water due to the shape of the roof. The 'Foundation and soil' indicator (I_{FL10}) assesses the expected damage due to scouring, by considering the type of soil and the exposition of the foundation considering its surrounding material.

Table 3. Vulnerability indicators for the category architectural configuration (C_{AE}).

Indicator (I_{FLi})	Summarised description for each classification	Value
$I_{FL8}(\beta)$ – Vertical structure envelope	The point between the relation X_4 and X_2 of the worst-case wall is located below the curve selected for X_3 assuming that the capacity of the wall is high against the static pressure of the water in a flood.	0
	The point between the relation X_4 and X_2 of the worst-case wall is located above the curve selected for X_3 assuming that the capacity of the wall is low against the static pressure of the water in a flood.	100
I_{FL9} – Roof	No probability of infiltration from the top, and the roof shape avoids accumulation of rainwater (*rw*)	0
	No probability of infiltration from the top, but the roof shape allows accumulation of *rw*	20
	Likely infiltrations from the top if repairs are not carried out, but the roof shape avoids accumulation of *rw*	40
	Likely infiltrations from the top if repairs are not carried out, and the roof shape allows accumulation of *rw*	60
	It allows water infiltrations from the top, but the roof shape avoids accumulation of *rw*	80
	It allows water infiltrations from the top, and the roof shape allows accumulation of *rw*	100
I_{FL10} – Foundation and soil	The soil is mostly fine-grained, and the foundations are not exposed to the scouring effect (e.g., sidewalks)	0
	The soil is mostly coarse-grained, and the foundations are not exposed to the scouring effect (e.g., sidewalks)	35
	The soil is mostly fine-grained, and the foundations are exposed to the scouring effect (e.g., bare soil)	70
	The soil is mostly coarse-grained, and the foundations are exposed to the scouring effect (e.g., bare soil)	100

The category related to the flood emergency plan (C_{FP}) is summarised and classified in Table 4. The 'Flood preparedness plan' indicator (I_{FL11}) considers the existence of a flood emergency plan, if the location where the cultural asset has experienced a flood event in the last 20 years and if there are fixed visible components (e.g., rails or supports for floodgates) that support the integration of protective measures when there is a forecast of, for instance, heavy rains that may cause a flood. In the case of the 'drainage system' indicator, the classification of I_{FL12} assesses the existence and functionality of a drainage system that can be used after a flood if the floodwater flows inside of the heritage asset. For I_{FL13} (drying systems), the classification considers the existence and type of drying systems (i.e., active, passive or both), as well as their functionality after a flood, that might reduce the humidity of the construction systems in the architectural asset. For $I_{FL14}(\beta)$ (utilities and appliances), the classification measures the location of the electrical utilities and appliances that can be affected by the flood with respect to the water depth (β) and if these utilities present or not flood-adapted systems.

The category related to the immediate surroundings (C_{IS}) is summarised and classified in Table 5. I_{FL15} (vegetation) aims to characterise the susceptibility of the asset by considering the surrounding vegetation that can influence water flow to reduce damaging effects, by slowing its speed, as well as prevent the impact of debris. In the case of the 'Inclination and type of ground surface' indicator (I_{FL16}), it measures the susceptibility of the area surrounding the built cultural heritage asset, namely regarding its propensity to accumulate water due to its flatness. I_{FL17} (permeability of the surface) considers the susceptibility of the area to accumulate water on the surface by measuring the permeability of the soil, based on the

coefficients of soil permeability (cp) (i.e., clean gravel, coarse and fine sand, silty and clay soils), as cited in [14], and if the surrounding artificial pavement material of the built cultural heritage asset is highly permeable (e.g., paving bricks) or low/non-permeable (e.g., asphalt, stamped concrete). Finally, based on the criteria adopted by [15], I_{FL18} (closeness to a slope) measures the vulnerability of the built cultural heritage asset due to its closeness to a slope, either on the low or up end of a slopped terrain.

Table 4. Vulnerability indicators for the category flood emergency plan (C_{FP}).

Indicator (I_{FLi})	Summarised description for each classification	Value
I_{FL11} – Flood preparedness plan	There is a flood emergency plan that considers the protection of cultural heritage assets; or No flood emergency plan; no flood events in the last 20 years; and there are visible components (e.g., rails or supports for floodgates) that support the integration of protective measures in the case of a flood	0
	No flood emergency plan; flood events in the last 20 years; and there are visible components	35
	No flood emergency plan, no flood events in the last 20 years; but there are no visible components	70
	No flood emergency plan; flood events in the last 20 years; and there are no visible components	100
I_{FL12} – Drainage system	Existence of a system (e.g., sump pumps with black flow valves) that assures its functionality after a flood	0
	No drainage system	100
I_{FL13} – Drying systems	There are dual/hybrid drying systems (i.e., passive and active systems, e.g., wall-ventilation systems)	0
	It considers only active (e.g., dehumidifiers) or passive (e.g., vents, weep holes, or airbricks) drying systems	35
	It considers only active/passive drying systems that are expected to suffer damages after the flood	70
	There is no drying measure system	100
$I_{FL14}(\beta)$ – Utilities and appliances	The fixed electrical utilities are located above the hypothetical water depth(s)	0
	The fixed electrical utilities are located below the hypothetical water depth(s) but they are prevented to suffer damages due to the flood-adapted systems	50
	The electrical utilities are below the hypothetical water depth(s) and they do not present flood-adapted systems	100

Table 5. Vulnerability indicators for the category immediate surrounding (C_{IS}).

Indicator (I_{FLi})	Summarised description for each classification	Value
I_{FL15} – Vegetation	There is high-density vegetation surrounding the built cultural heritage asset.	0
	There is low-density vegetation surrounding the built cultural heritage asset.	50
	There is no vegetation surrounding the built cultural heritage asset.	100
I_{FL16} – Inclination and type of ground surface	The built cultural heritage asset lies on a convex or steep ground surface.	0
	The built cultural heritage asset lies on a flat ground surface.	50
	The built cultural heritage asset lies on a concave ground surface.	100
I_{FL17}– Permeability of the surface	1 cm/s ≤ cp < 100 cm/s (e.g., gravels) and the existing pavement is highly permeable	0
	0.001 cm/s ≤ cp < 1 cm/s (e.g., coarse/fine sands) and the pavement is highly permeable	15
	cp < 0.001 cm/s (e.g., clays) and the existing pavement is highly permeable	30
	1 cm/s ≤ cp < 100 cm/s (e.g., gravels) and the existing pavement is low or non-permeable	45
	0.001 cm/s ≤ cp < 1 cm/s (e.g., coarse/fine sands) and the pavement is low/non-permeable	60
	cp < 0.001 cm/s (e.g., clays) and the existing pavement is low or non-permeable	75
	The artificial pavement presents a layer of low or non-permeable material (asphalt, stamped concrete)	100
I_{FL18}– Closeness to a slope	The built cultural heritage assets are not close to or on a sloping terrain.	0
	The built cultural heritage assets are close to or on a sloping terrain	100

It should be noted that the vulnerability index (VI_{FL}) that will be used to adjust the baseline vulnerability curve ($V_C(\beta)$) will not be constant due to the contribution of the four flood vulnerability indicators (i.e., $I_{FL2}(\beta)$, $I_{FL6}(\beta)$, $I_{FL8}(\beta)$, $I_{FL14}(\beta)$), that depend on the water depth (β).

3 Application of the method

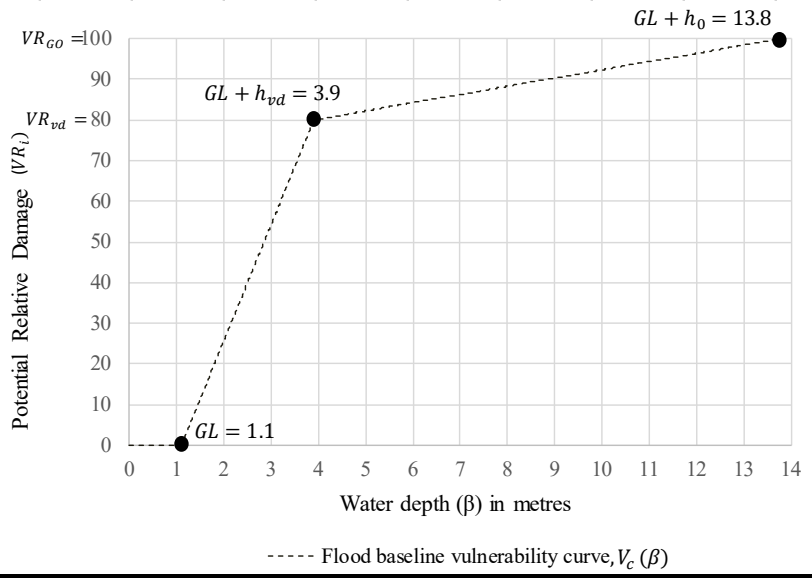
To demonstrate the feasibility of the proposed flood vulnerability assessment method, the 17th century baroque church of Misericórdia located in the municipality of Ponte de Lima, Portugal (41°46'4.17"N, 8°35'4.27"W) will be presented to estimate the expected damage in case of river flooding, using data taken from an on-site survey carried out in 2020. The reason for selecting this case is due to the high-probability flood scenarios that might occur based on the hazard analysis carried out in the context of the implementation of the European Floods Directive for Portugal [3,10].

3.1 Estimation of the flood baseline vulnerability curve ($V_C(\beta)$)

Initially, a baseline vulnerability curve is determined using Eq. (3) with the consideration of the geometric parameters of the historic construction under assessment (i.e., $GL, h_0\ h_{L0},\ and\ h_{vd}$) and the potential relative damage values (i.e., VR_{GO}, VR_{vd}). Thus, Table 6 shows the flood baseline vulnerability curve for the Misericórdia church located in Ponte de Lima.

Table 6. Parameters of the Misericórdia Church in Ponte de Lima to define the baseline vulnerability curve.

Parameters	Values	Flood baseline vulnerability curve
GL	1.1 m	
h_0	12.7 m	
h_{L0}	12.7 m	
h_{vd}	2.8 m	
$GL + h_{vd}$	3.9 m	
VR_{G0}	100	
VR_{vd}	80	



3.2 Calculation of the flood vulnerability index (VI_{FL})

This subsection explains how the indicators were classified for the illustrative case of the church of Misericórdia of Ponte de Lima. The value of the I_{FL1} indicator is 33.33 because the vertical support (and its coatings) present granite stone (*SI* =0), lime-based mortar (*SI* =25) and white painting (*SI* =75). I_{FL2} takes a value of 37.50 because the materials present in the horizontal supports that can be in contact with floodwater are timber (*SI* =75) and stone (*SI* =0), which in this case correspond to the high-choir at 4.35 metres. The value for I_{FL3} is 37.50 due to the materials present in the finishings and linings, which are timber in the ceiling vault and the floors (*SI* =75) and granite stone in some areas of the ground floor (*SI* =0). I_{FL4} is equal to 66.67 as a result of the movable heritage contents, considering timber sculptures and candlesticks (*SI* =75), textiles found in the religious furniture (*SI* =50), and the paintings (*SI* =75) found in the main nave of the church. The value for I_{FL5} is 41.67 due to the artwork materials attached to the structure considering the wood found in the vaults, walls, altarpieces and heritage doors (*SI* =75), the stonework found in some sculptures and the marble centre table (*SI* =0), and textiles used in the curtains of some altarpieces (*SI* =50). The value for I_{FL6} is 50, influencing the vulnerability assessment above 1.37 metres. Therefore, this class (i.e., 50) for I_{FL6} signifies that there is no evident protection at the openings to avoid water entry, and the ratio between the area of the worst-case façade and the openings is less than 25% (i.e., approx. 12%). For I_{FL7}, the value is 50, considering a medium conservation state because some walls present erosion, efflorescence and some columns are seen to exhibit some stone degradation.

The value for I_{FL8} is 100 from 1.54 metres. The estimation of the class and the proposed height is considered from the worst case where $X_3 = 0$, because only the self-weight of the wall is considered, the type of support identified in the worst case of the church is P3 (i.e., three-edge supports: cross walls and at the foundation level), and the slenderness ratio is equal to 0.95m/10.15 m = 0.093. Therefore, using the criteria explained previously by considering the ref. [12] and performing the analysis in Microsoft Excel, the expected damage of the worst-case wall is expected after 0.44 metres (i.e., 1.54m from terrain level by considering $GL = 1.1$). The value for I_{FL9} is 0 because there is a gable roof, which does not produce accumulation of the water and is in good conservation state. The value for I_{FL10} is considered 35 because the foundation does not present any signs of deterioration that can produce a scouring effect in case of a flood (i.e., good condition, surrounded by sidewalks), and because, according to the database of soils in Portugal [16,17], the soil samples close to the case study are fluvisol, which, is mostly a soil with coarse-grained soils.

The value for I_{FL11} is 100 because there is no flood emergency plan that considers the protection of the cultural heritage assets, and historic records reflect the occurrence of previous flood events in the last 20 years (i.e., 2016 [18]), which means

that the inhabitants are aware that it could happen again. The values for I_{FL12}, and I_{FL13} are 100 because there is no drainage or any type of drying system. In terms of I_{FL14}, the value is considered 100 from 1.25m, where the electrical plugs are located from ground level, without flood-adapted systems.

The value for I_{FL15} is 100 due to the low density of vegetation. I_{FL16} corresponds to a value of 0 because the historic construction is located on a steeped ground surface. The value for I_{FL17} is 15 based on the information taken from [16,17], which denotes a FLUVISOL soil around the case under study, which presents a high content of sands (i.e., high permeability), as well as considering the surrounding pavements with a material that allows the permeability of water (handmade Portuguese technique of black and white stone basalts with limestone). Finally, for I_{FL18}, the value is 0 because the historic construction under assessment is not positioned close to a steeper slope. Table 7 shows the VI_{FL} at characteristic water depths that may influence the flood damage for the church in Ponte de Lima, depicting the classification results for each indicator, the values at different water depths (β), and the outcomes using Eq. (1) through the mean values per category (i.e., $\overline{C_M}$, $\overline{C_{AE}}$, $\overline{C_{FP}}$, and $\overline{C_{IS}}$) and the attributed weights by category (i.e., $W_M = 0.30$, $W_{AE} = 0.30$, $W_{FP} = 0.20$, and $W_{IS} = 0.20$).

Table 7: Flood vulnerability index (VI_{FL}) for the 17th century baroque church of Misericórdia in Ponte de Lima

Indicator (I_{FLi})	Values at different β in m.					$\overline{C_i}$*W_i, at different β in m.				
	1.0	1.25	1.37	1.54	4.35	1.0	1.25	1.37	1.54	4.35
I_{FL1}	33.33	33.33	33.33	33.33	33..33					
$I_{FL2}(\beta = 4.35)$*	0.00	0.00	0.00	0.00	37.50					
I_{FL3}	37.50	37.50	37.50	37.50	37.50					
I_{FL4}	66.67	66.67	66.67	66.67	66.67	9.82	9.82	11.96	11.96	14.17
I_{FL5}	41.67	41.67	41.67	41.67	41.67					
$I_{FL6}(\beta = 1.37)$*	0.00	0.00	50.00	50.00	50.00					
I_{FL7}	50.00	50.00	50.00	50.00	50.00					
$I_{FL8}(\beta = 1.54)$*	0.00	0.00	0.00	100.00	100.00					
I_{FL9}	0.00	0.00	0.00	0.00	0.00	3.50	3.50	3.50	13.50	13.50
I_{FL10}	35.00	35.00	35.00	35.00	35.00					
I_{FL11}	100.00	100.00	100.00	100.00	100.00					
I_{FL12}	100.00	100.00	100.00	100.00	100.00	15.00	20.00	20.00	20.00	20.00
I_{FL13}	100.00	100.00	100.00	100.00	100.00					
$I_{FL14}(\beta = 1.25)$*	0.00	100.00	100.00	100.00	100.00					
I_{FL15}	100.00	100.00	100.00	100.00	100.00					
I_{FL16}	0.00	0.00	0.00	0.00	0.00	5.75	5.75	5.75	5.75	5.75
I_{FL17}	15.00	15.00	15.00	15.00	15.00					
I_{FL18}	0.00	0.00	0.00	0.00	0.00					
TOTAL (VI_{FL})						34.07	39.07	41.21	51.21	53.42

*These indicators consider the β that may influence the damaging impact at a specific height, referred in brackets "()", in metres.

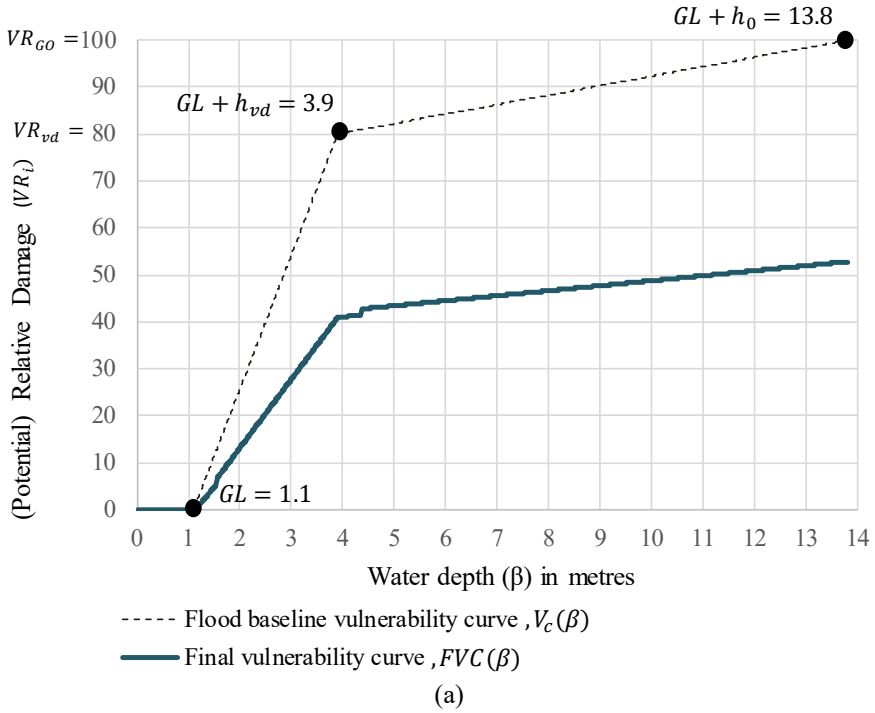
According to Table 7, the category C_M considers the multiplication of the indicator average by a factor of 0.30 (as explained in Section 2) resulting in 9.82, 9.82, 11.96, 11.96, and 14.17 at different heights (i.e., 1.0, 1.25, 1.37, 1.54, 4.35 metres, respectively) that demonstrate the variation influence of $I_{FL6}(\beta)$ and $I_{FL2}(\beta)$, at 1.37 and 4.35 metres. The category C_{AE} considers the multiplication of the indicator average by a factor of 0.30 resulting in 3.50, 3.50, 3.50, 13.50, and 13.50 at different heights (i.e., 1.0, 1.25, 1.37, 1.54, 4.35 metres, respectively) indicating the varying influence of $I_{FL8}(\beta)$ at 1.54 metres. For the category C_{FP}, the indicator average was multiplied by a factor of 0.20 resulting in 15, 20, 20, 20, and 20 at different heights (i.e., 1.0, 1.25, 1.37, 1.54, 4.35 metres, respectively) justifying the varying influence of $I_{FL14}(\beta)$ at 1.25 metres. In other words, as commented in Section 2.2, $I_{FL2}(\beta)$, $I_{FL6}(\beta)$, $I_{FL8}(\beta)$ and $I_{FL14}(\beta)$ are indicators activated when the water depth (β) reaches the height of the historic building that influence those indicators. For the last category C_{IS}, the indicator average was multiplied by a factor of 0.20 resulting in a constant value of 5.75 since it does not depend on indicators that vary with the height of the historic building or as a function of β.

3.3 Combination of the baseline vulnerability curve with the vulnerability index

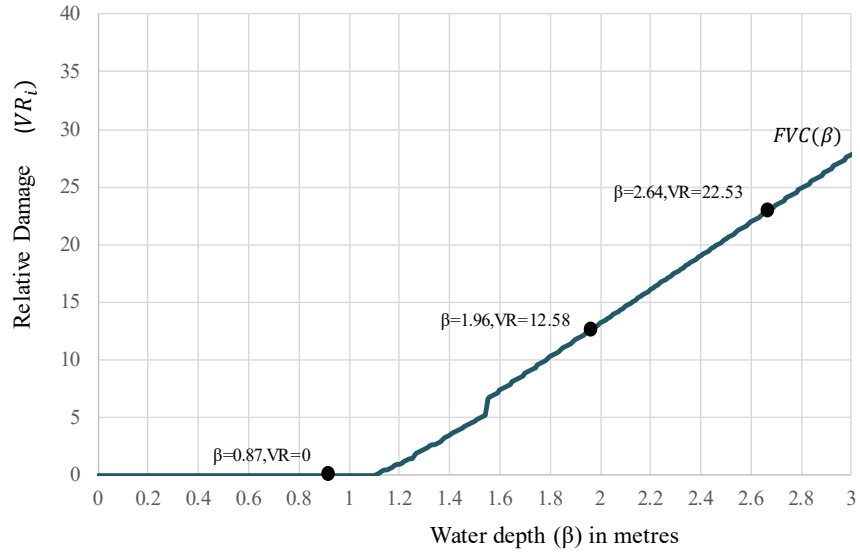
Once the baseline vulnerability curve $V_c(\beta)$ is determined (see Table 6) and vulnerability index is calculated at different heights (as presented in Table 7), $V_c(\beta)$ is adjusted by using Eq. (2) to obtain the final vulnerability curve $FVC(\beta)$, as depicted in Fig. 4a for the Misericórdia church in Ponte de Lima. The black dashed line indicates the baseline vulnerability

curve ($V_C(\beta)$), whereas the blue continuous line indicates the final flood vulnerability curve ($FVC(\beta)$). $FVC(\beta)$ represents the relative damage (VR_i) in a flood across the total floodable height of the building for various water depths (β).

These graphical representations can support decision-making and flood mitigation by using probabilistic scenarios. Therefore, considering the return periods of 20, 100, and 1000 years based on the data taken from [3,10], the water depths associated with the location of the church in Ponte de Lima are 0.87, 1.96 and 2.64 metres. Therefore, Fig. 4b shows the points for the chosen probabilistic scenarios and their corresponding relative damage (VR_i), i.e., for β = 0.87m, $VR = 0$; for β =1.96m, $VR = 12.58$; and for β =2.64m, $VR = 22.53$.



(a)



(b)

Fig. 4. (a) Flood baseline vulnerability curve, $V_C(\beta)$ (black dashed line) and Final Flood Vulnerability Curves $FVC(\beta)$ (blue continuous line) adjusted by VI_{FL} at different β for the Misericórdia church in Ponte de Lima; (b) Zoom in of the $FVC(\beta)$ (continuous blue line) indicating the relative damage values with respect to the probabilistic water depths associated with the three chosen return periods (20, 100 and 1000 years) for the Misericórdia church in Ponte de Lima.

4 Conclusion

A new method for physical flood vulnerability assessment in historic constructions that may host movable heritage assets was created. The proposed method is a hybrid approach that combines a vulnerability curve with a vulnerability index based on 18 flood vulnerability indicators that were established based on a literature review. The vulnerability index is used to adjust a baseline vulnerability curve, which is based on geometric properties and the potential relative damage that is likely to occur over the expected floodable height of the building. The adjusted vulnerability curve can then be used to compare the expected level of relative damage for specific flood scenarios. The proposed methodology aims to fill a research gap between the use of large-scale flood vulnerability assessment methods (i.e., that allow assessing several immovable cultural assets with little distinction between them) and the use of detailed asset-specific methods that require a larger amount of detailed data. The results obtained from the proposed methodology can support the development of mitigation strategies to reduce the expected damage due to flooding across different flood hazard scenarios. In particular, analysing the individual vulnerability indicators that are seen to have larger contributions to the overall level of expected damage can provide a more detailed understanding of the flood vulnerability drivers in a given historic construction, and help develop more targeted measures for flood vulnerability reduction.

5 Acknowledgements

The authors acknowledge the financial support of the BD scholarship funded by FCT (Fundação para a Ciência e Tecnologia), reference PD/BD/150405/2019 (1st author), the financial support of the Base Funding - UIDB/04708/2020 of CONSTRUCT - Instituto de I&D em Estruturas e Construções, funded by national funds through FCT/MCTES (PIDDAC) (2nd author), and the financial support of FCT through the Scientific Employment Stimulus program (2022.03980.CEECIND) (3rd author).

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