

A FRAMEWORK FOR THE DETAILED FLOOD VULNERABILITY MODELLING OF BUILT CULTURAL HERITAGE

RUI FIGUEIREDO^{1*}, XAVIER ROMÃO¹ AND ESMERALDA PAUPÉRIO²

¹ CONSTRUCT-LESE, Faculty of Engineering, University of Porto
Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
e-mail: {ruifig, xnr}@fe.up.pt (*corresponding author)

² Construction Institute, Faculty of Engineering, University of Porto
Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
e-mail: pauperio@fe.up.pt

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Abstract. Flooding is the most common and damaging of natural hazards at global level, and in a context of climate change, flood risk is expected to increase. This has prompted governments and international agencies to adopt measures towards the reduction of flood risk in recent years. Among them is the development of flood risk assessments and flood risk management plans, with particular emphasis on cultural heritage, not only due to its significance for society, but also because of its particularly high vulnerability to natural hazards, including floods. In order to quantify risk and define prioritization and management plans for a given set of cultural heritage assets, vulnerability models that allow estimating and comparing the impacts of floods at an asset-by-asset level are required. However, there is currently a lack of approaches in the literature to achieve this. This study proposes a component-based synthetic modelling framework to perform detailed vulnerability analyses of cultural heritage assets. The framework is illustrated through an application to a Portuguese church.

1 INTRODUCTION

Flood risk is expected to increase worldwide in the coming decades due to various socio-economic and environmental factors, including climate change. Minimizing flood risk across any given region requires robust risk management decision-making, which must necessarily be supported by risk assessment studies. These combine flood hazard data for a region of interest with information on exposed assets and models of their vulnerability (i.e. the impact they are expected to undergo as a function of flood actions), and allow computing consistent risk metrics.

The socio-cultural importance of cultural heritage calls for particular attention to this asset type in any flood risk management plan. However, at present, there is a lack of methods in the literature to quantify the flood vulnerability of cultural heritage assets, which hampers the development of flood risk assessments, and consequently informed risk management prioritization and optimization of mitigation measures. This gap can be justified by various underlying difficulties. Firstly, cultural heritage assets tend to differ considerably among themselves, precluding the development and application of common vulnerability models to

portfolios of assets, except in large-scale risk assessments for preliminary screenings of risk. Secondly, empirical approaches commonly adopted for other asset types, such as common residential buildings, are not applicable, because they require datasets of observed damage and/or losses, which are not available for cultural heritage assets. Thirdly, there is no agreed upon method to quantify the value of cultural heritage assets and, consequently, their degree of damage or loss as a result of a disaster [1, 2].

This study aims to address the above issues by proposing a framework to model the flood vulnerability of cultural heritage assets, so that this information may be used within risk assessment studies where an asset-by-asset differentiation of risk is required. The proposed approach is based on a component-based synthetic modelling framework, whereby hypothetical flood scenarios are simulated and the corresponding potential overall damage is estimated as the combination of damage to each component of cultural value comprising an asset. The modelling framework is illustrated through an application to a church in Portugal.

2 METHODOLOGY

For each cultural heritage located in an area of interest, flood risk is defined as the probability that damage will occur as a result of flooding, and is commonly expressed as a function of hazard, vulnerability, and exposure. Within this conceptual framework, hazard represents the intensities and probabilities of occurrence of flood scenarios, exposure expresses the assets' overall values, and vulnerability links flood intensities to potential impacts. This paper specifically addresses the latter, presenting a methodology for the quantification of the vulnerability component of risk for cultural heritage assets. The approach is organized into three steps that are described in the following subsections.

2.1 Surveying and value assessment of exposed components

The specific nature of cultural heritage requires an asset-by-asset characterization of vulnerability when the objective is to develop risk management and prioritization plans with a high level of granularity. This can only be achieved through on-site collection of information. Therefore, the first step of the methodology involves the identification, documentation and value assessment of all the relevant exposed components that comprise a cultural heritage asset and contribute to its overall cultural value. The surveying process should allow collecting the most relevant information for characterizing the flood vulnerability of an asset. Simultaneously, it should also be a simple procedure that can be carried out efficiently without the need to involve significant resources and/or specific engineering skills (to allow surveys to be carried out by local non-technical stakeholders). In this regard, the two fundamental variables that need to be collected are the main material of each component and the height at which it is located.

In order to facilitate the surveying process of a given cultural heritage asset and help ensure that relevant components are not left out, it is useful to establish a taxonomy for such components beforehand. Because this classification scheme could vary significantly between different asset types, specific taxonomies should be defined for each type. For the case of churches, a taxonomy is proposed in Table 1, which was developed to support the application of the framework to the case study described in Section 3, a Portuguese church. The most common material types for each component are also identified to further support the surveying procedure.

Table 1: Proposed component taxonomy for churches, containing the most relevant components commonly found in Portuguese churches and their respective materials.

Group	Designation	Common main materials
1. Building	1.1. External walls	Stone, Concrete, Earth, Wood, Clay brick
	1.2. Internal walls	Stone, Concrete, Earth, Wood, Clay brick
	1.3. Basement walls	Stone, Concrete
	1.4. Wall paintings and coverings	Ceramic tilework, Gilded woodcarving, Murals, Decorative plaster
	1.5. Floors	Stone, Wood, Clay tiles
	1.6. Roofs	Concrete, Wood, Clay brick
	1.7. Doors	Wood, Metal
	1.8. Windows and stained glasses	Glass and Wood/Metal
2. Contents	2.1. Main retable and altar	Wood, Gilded woodcarving
	2.2. Other retables and altars	Wood, Gilded woodcarving
	2.3. Altar table	Stone, Wood, Earth
	2.4. Main altar pulpit	Stone, Wood, Metal
	2.5. Nave pulpit	Stone, Wood, Metal
	2.6. Baptismal font	Stone, Metal
	2.7. Statuary	Wood, Metal, Ceramic, Paper pulp
	2.8. Organ	Various
	2.9. Furniture	Wood
	2.10. Light fittings	Metal, Crystal
	2.11. Tombs	Wall, Stone
	2.12. Metal liturgical implements	Gold, Silver, Brass
	2.13. Textile liturgical paraments and implements	Textile
	2.14. Books	Book paper
	2.15. Candlesticks and lamps	Gold, Silver, Brass
	2.16. Porcelains	Porcelain

After the component survey, it is then necessary to estimate the value of each of the selected components. Given that such values cannot be expressed in absolute economic terms, within the proposed framework, indices of value for the different components of the cultural heritage asset are defined, which reflect their estimated relative value with respect to the other selected components. It is recommended that at least three levels of significance are adopted:

- a low level, for components that are not unique and that contribute in a limited manner to the overall cultural value of the asset;
- an intermediate level, for unique components that have significant cultural value;
- a high level, for unique components with exceptional cultural value, which are determinant for the overall cultural value of the asset.

In order to expedite the surveying procedure, particularly in situations with a large number of components, it is suggested that only components that can be affected by floods up to a certain return period are documented, and that the relative value of those components with respect to the whole set of components (i.e. floodable and non-floodable) is defined in aggregated terms, based on expert judgement.

2.2 Estimation of flood susceptibility for each component

The susceptibility of each component is defined as the level of impact it is expected to undergo as a result of the action of flooding. In order to estimate the susceptibility of different components, a literature review was carried out in order to characterize the effects of floodwater on certain commonly found materials [3–12], taking the taxonomy shown in Table 1 as a reference. A summary is presented in Table 2 for some materials. Based on this analysis, the susceptibility of each material was translated into a scale of indices, as represented in Figure 1. Note that for each material, besides a base level or range of susceptibility indices (represented by the hatched shapes), there are also higher levels of possible impact that are determined by amplifying factors related, for example, to the material condition, inadequate post-event drying or treatment, or the level of floodwater contamination, according to the descriptions presented in Table 2.

Table 2: Effects of exposure to flood water for some of the most commonly found materials in Portuguese churches.

Material	Description
Stone	<ul style="list-style-type: none"> - Different types of stone can behave differently under the actions of flooding, depending on their softening coefficient and hydric expansion. - The susceptibility of most common types of stone to flooding is generally low. - Negative impacts can increase if walls are not properly treated and dried after an event, if they are in poor state of conservation, or due to harsh weather conditions.
Concrete	<ul style="list-style-type: none"> - Concrete is not particularly vulnerable to flooding. - Concrete floors may take a long time to dry if appropriate actions are not taken.
Earth construction	<ul style="list-style-type: none"> - Unbaked earth-wall constructions are particularly vulnerable to water damage, especially if external plaster finishes that may exist are not well maintained.
Timber and woodwork	<ul style="list-style-type: none"> - Wood generally presents high values of hydric expansion and may swell and distort when wet. It is also vulnerable to fungal and insect infestations, causing rot. - Issues with wood may be minimized if appropriate action is taken following a flood event, and wood is properly ventilated and dried. This is especially true for sound structural timber. - Floorboards and other elements that can buckle require specific post-flood measures.
Metalwork	<ul style="list-style-type: none"> - Aluminium, bronze, copper and brass objects will not be damaged by immersion in water as long as they are allowed to dry quickly. Iron and steel may rust and expand, but damage can be limited through quick drying.
Wall paintings	<ul style="list-style-type: none"> - Historic wall paintings, including frescoes, may be damaged by salt crystallisation, paint flaking or mould growth, particularly if an inadequate drying procedure is adopted.
Book paper	<ul style="list-style-type: none"> - Paper is highly vulnerable to water and requires swift and appropriate post-event recovery actions to prevent destruction. Negative consequences can include rapid development of mould, physical damage, and bleeding of soluble inks and colorants. - Even if treated adequately (which requires expert knowledge), wet books and records generally cannot be fully restored to their pre-damage condition. - Contaminated water can exacerbate the negative impacts of floodwater on paper.

Table 2: Effects of exposure to flood water for some of the most commonly found materials in Portuguese churches (continued).

Paintings on canvas	<ul style="list-style-type: none"> - Exposure to water can cause immediate damage to most paintings, as well as make the artwork more susceptible to short or long-term damage. Appropriate drying is required to reduce negative impacts. - Water can lead to flaking and loss of image layers, as well as expansion, shrinkage and subsequent deformation of painting supports.
Textiles	<ul style="list-style-type: none"> - Textiles can present significant variations that determine if and how they can be salvaged after a flood. Damaged textiles can present colour change, bleeding of dyes, shrinkage, watermarks from migrating finishes, and mould. - Certain contaminants will require textiles to be discarded.

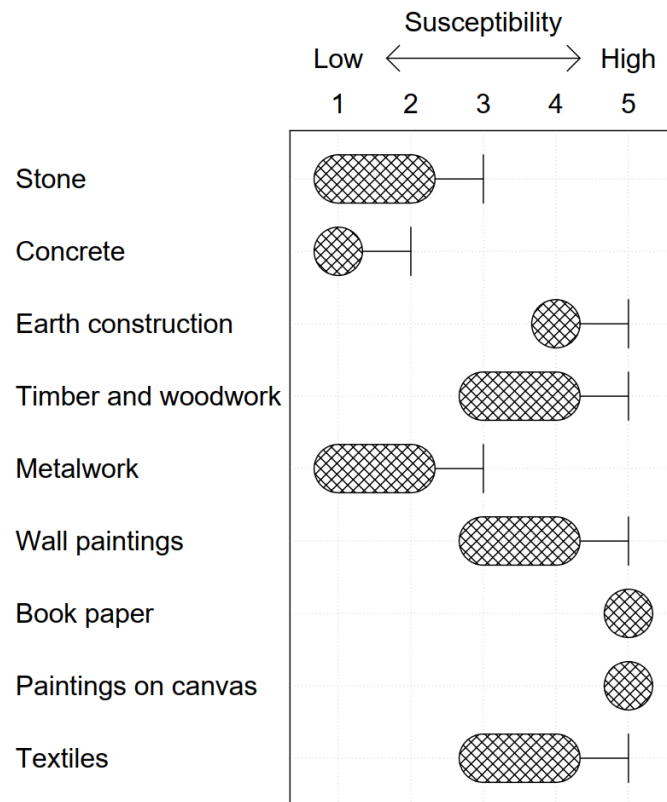


Figure 1: Examples of flood susceptibility indices considered for some materials.

2.3 Definition of the flood vulnerability function

The vulnerability function for a cultural heritage asset can then be defined as a function of the value, susceptibility, and elevation of its components. Given that values and impacts cannot be expressed in absolute terms, the vulnerability function should quantify impacts in relative terms, i.e. as a fraction of the overall cultural value of an asset (which should be defined independently of the quantification of vulnerability, based for example on its listed status). In order to achieve this, a normalization of the above indices is required. The value indices of the asset's components should be scaled such that they sum to one. In this way, the resulting values

will represent the fraction that each component is estimated to contribute to the overall value of the cultural heritage asset. The susceptibility indices should be scaled such that ‘no damage’ corresponds to 0, while ‘damage that is not fully repairable’ corresponds to 1. The vulnerability function is then obtained through a what-if analysis, based on a simulated step-by-step inundation of the asset, and in the evaluation of the corresponding damage based on the features described before. The level of damage at each step is given by

$$f(x) = \sum_i g(x) v_i s_i \quad (1)$$

with

$$g(x) = \begin{cases} 1 & \text{if } x \geq h_i \\ 0 & \text{if } x < h_i \end{cases} \quad (2)$$

where x is the water depth, i represents each component of the cultural heritage asset, h_i is the height at which the component is located above a reference level (typically the external ground floor level, from which the water depth is also measured), and v_i and h_i are their value and susceptibility indices, respectively.

3 CASE STUDY

3.1 Description

The case study adopted to illustrate the proposed framework is the Igreja da Misericórdia de Esposende (Figure 2), a church located in the municipality of Esposende, in northern Portugal. The church dates back to the end of the 16th century, having received a number of interventions over the centuries, and comprises mannerist, baroque and neoclassical architectural styles. Despite its relatively small size, it contains an extremely interesting and coherent set of works of art, and is listed as a building of public interest [13, 14].



Figure 2: Main façade of the church.

Based on the hazard maps developed for Portugal within the scope of the European Floods Directive [15], the church is located within the extents of high-probability flood scenarios, and the water depth associated with an extreme scenario of 1000-year return period (considered herein as the maximum achievable water depth) is 1.38m (Figure 3).

3.2 Vulnerability assessment results

The church was surveyed by the authors on 3 January 2020 following the general procedure described in Section 2. A detailed inventory was developed for the ground floor only (shown in Figure 4), given that the upper floors are above the maximum flood level. Still, the entire church was surveyed in order to establish the relative value of the floodable components.

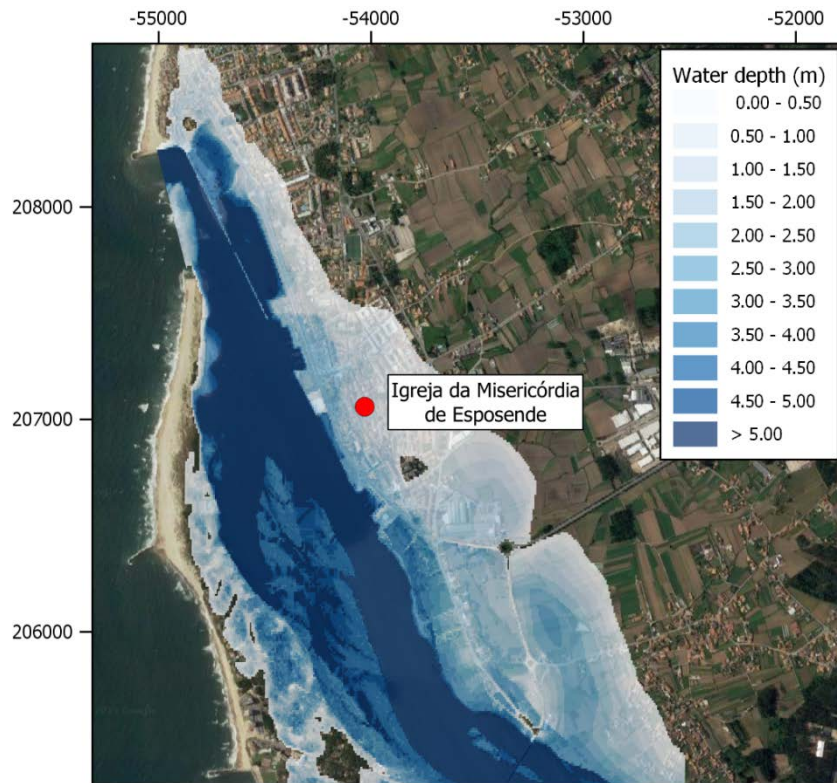


Figure 3: Location of the case study church (Igreja da Misericórdia de Esposende) and hazard map showing water depths for the 1000-year return period flood scenario (CRS: ETRS89 / Portugal TM06).

The inventory includes a total of 79 components and component assemblies, together with their materials, heights from the reference level, and information on whether they are moveable. The latter allows establishing two separate vulnerability functions that consider scenarios with and without the preventive evacuation of moveable items. Three indices of value (1, 3 and 10) were considered for assets with low, substantial, and exceptional significance, respectively. Table 3 presents the inventory referring to the contents of the main chapel, and a photograph of this part of the church is shown in Figure 5. For brevity, only this part of the inventory is presented herein. Finally, the obtained vulnerability function is presented in Figure 6.

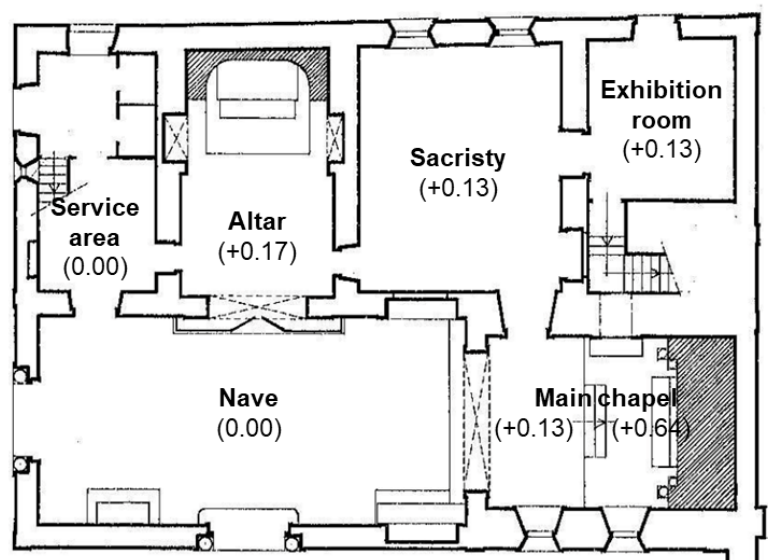


Figure 4: Ground floor plan.

Table 3: Inventory of contents of the main chapel.

Component	Move-able	Material family	Material	Height (m)	Value index	Impact index
Plinths (set of 2)		Stone	Granite	0.13	1	1
Statue	✓	Wood	Polychromed wood	1.02	3	4
Statue	✓	Wood	Polychromed wood	1.02	3	4
Kneeling benches (set of 2)	✓	Wood	Blackwood	0.13	1	4
Altar table		Wood	Gilded woodcarving	0.64	3	4
Pulpit	✓	Wood	Gilded woodcarving	0.69	3	4
Altar		Wood	Gilded woodcarving	1.29	3	4
Statue	✓	Wood	Polychromed wood	1.64	10	4
Main altar		Wood	Gilded woodcarving	0.64	10	4
Main retable		Wood	Gilded woodcarving	0.64	10	4
Painting		Canvas	Painting on canvas	2.49	10	5
Candlesticks (set of 2)	✓	Wood	Gilded woodcarving	1.84	1	4
Candlesticks (set of 2)	✓	Metal	Brass	1.84	1	2
Jugs (set of 2)	✓	Ceramic	Porcelain	1.84	1	5
Individual benches (set of 4)	✓	Wood	Blackwood	0.64	1	4
Altar side table	✓	Wood	Gilded woodcarving	0.64	3	4
Chair	✓	Wood	Upholstered blackwood	0.64	1	4



Figure 5: Photograph of the main chapel.

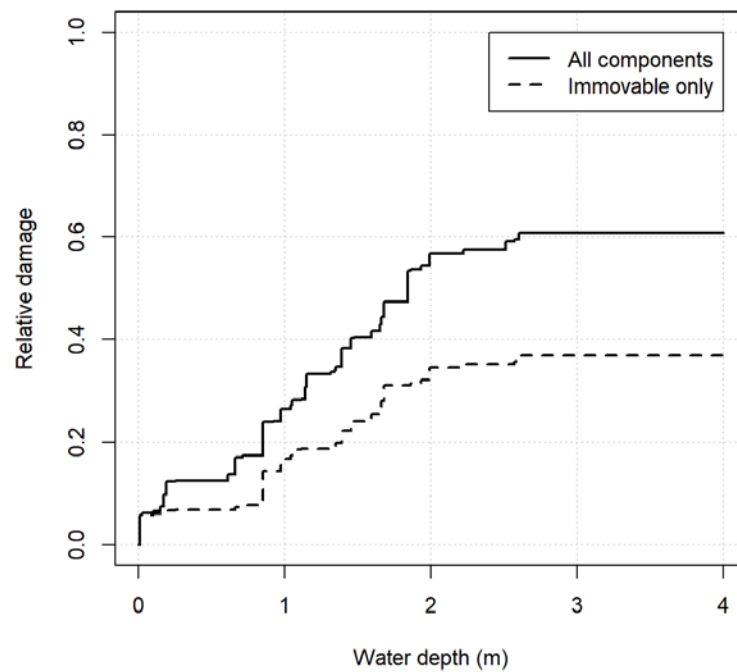


Figure 6: Vulnerability function for Igreja da Misericórdia de Esposende.

4 DISCUSSION

This paper has illustrated a new framework to model the flood vulnerability of cultural heritage assets based on a component-by-component analysis. The main objective of this framework is to provide a vulnerability analysis for risk assessment studies that aim to determine and compare levels of risk among cultural heritage assets, supporting the implementation of risk management plans at a detailed level. Although this inevitably requires site-specific surveying, the framework has been designed to achieve an adequate balance between simplicity and accuracy. Nevertheless, the framework may still be expanded to account for other flood properties besides water depth, such as flood duration and flow velocity, which may be relevant for certain building components.

In this study, the proposed vulnerability modelling framework was showcased for a church in northern Portugal, demonstrating its applicability. Further research will include applications to other churches in order to perform a comparative analysis of risk levels. In addition, developing vulnerability functions for different assets using a common approach can provide relevant insights about the extent to which asset-specific functions may be aggregated and used to extrapolate functions for asset types with similar characteristics, as well as to quantify their associated uncertainty.

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