A Detailed Flood Vulnerability Assessment Model for Built Cultural Heritage

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Abstract: Flood risk assessments and management plans are increasingly important instruments to cope with and reduce flood risk. In this context, special attention should be given to cultural heritage, not only due to its significance for society but also because of its high vulnerability to floods. In order to quantify risk and define prioritization and management strategies for a group 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 and illustrates a modelling framework to perform detailed vulnerability analyses of cultural heritage assets.

Keywords: Cultural Heritage, Flood Vulnerability, Flood Risk, Risk Assessment

1. Introduction

Flood risk is expected to increase globally 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 that combine flood hazard data with information on exposed assets and models of their vulnerability.

The socio-cultural importance of cultural heritage calls for particular attention to this asset type in any risk management plan. However, at present, there is a lack of methods in the literature to quantify the flood vulnerability of cultural heritage assets (Figueiredo et al., 2019), which hampers the development of flood risk assessments. This study proposes 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 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 framework is illustrated through an application to a church in Portugal.

2. Methodology

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.

After the component survey, it is 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 are defined reflecting their estimated relative values. 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.

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 materials commonly found in Portuguese churches (e.g. Drdácký, 2010; English Heritage, 2015). 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 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.

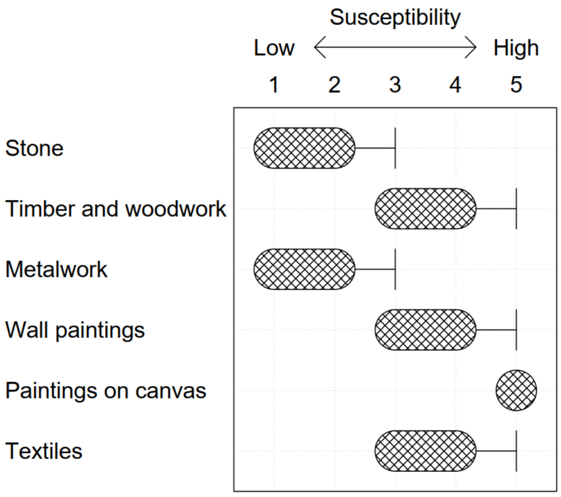

Figure 1 – Examples of flood susceptibility indices considered for some materials

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 (defined independently, 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, thus representing the fraction that each component is estimated to contribute to its overall value. 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 based on a simulated step-by-step inundation of the asset:

$$f(x) = \sum_i g(x) v_i s_i \tag{1}$$

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

where x is the water depth at each step, 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 s_i are their value and susceptibility indices, respectively.

3. Application and Results

The case study adopted to illustrate the proposed framework is the *Igreja da Misericórdia de Esposende*, a church located in northern Portugal that dates back to the 16th century. Despite its relatively small size, this church contains a very interesting and coherent set of works of art, and is listed as a building of public interest. Based on to the hazard maps developed for Portugal within the scope of the European Floods Directive (Brandão et al., 2014), the church is located within the extents of high-probability flood scenarios, and the water depth associated with an extreme scenario with a 1000-year return period is 1.38m.

Table 1 – Inventory of contents of the main chapel

Component	Move-able	Material family	Material	Height (m)	Value index	Suscept. 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

The church was surveyed following the procedure described before. A detailed inventory was developed for the ground floor only (shown in Figure 2), given that the uppers floors are above the maximum flood level. Still, the entire church was surveyed in order to establish the relative value of the floodable components in relation to the whole set of components (i.e. both floodable and non-floodable). The inventory includes a total of 79 components and component assemblies, together with their materials, heights above 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 1 presents the inventory referring to the contents of the main chapel, which is shown in Figure 3. For the sake of brevity, only this part of the inventory is presented herein. Finally, the obtained vulnerability function is presented in Figure 4. This modelling framework may be used to provide a vulnerability analysis for risk assessments that aim to determine and compare levels of risk among cultural heritage assets, supporting the implementation of risk management plans at a detailed level.

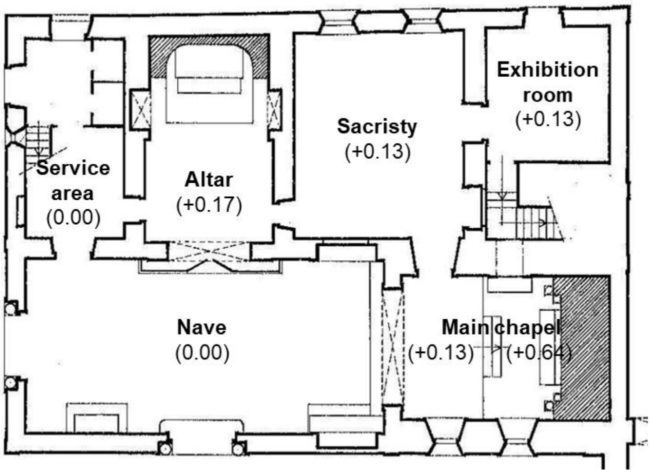

Figure 2 – Ground floor plan

Figure 3 – Photograph of the main chapel

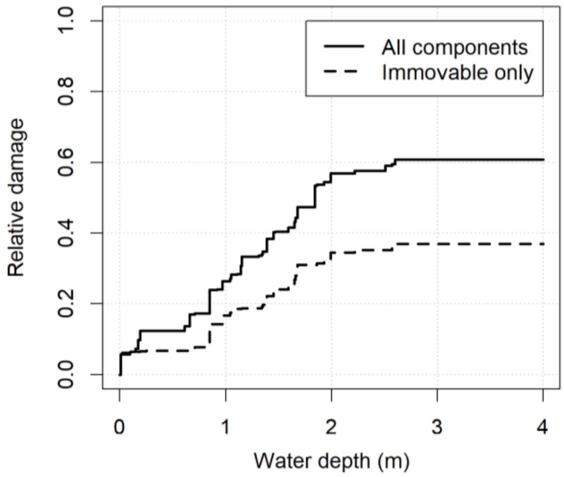

Figure 4 – Vulnerability function for *Igreja da Misericórdia de Esposende*

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