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Flood risk assessment of cultural heritage across countries and spatial scales

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ABSTRACT

Floods are a threatening natural hazard for cultural heritage, making flood risk assessments fundamental to develop effective mitigation strategies. The increased accessibility of global and regional flood hazard maps raises the question of whether these maps can accurately assess the flood risk to assets like cultural heritage, represented as discrete points in georeferenced databases with attributes varying by country. This study aims to investigate the feasibility of using large-scale hazard maps to assess flood risk to cultural heritage, evaluating how different spatial resolutions influence the risk assessment, while also developing a standardized methodology for estimating flood risk that can be effectively applied across different countries. To achieve these objectives, the current study conducts a comparative flood risk assessment for cultural heritage in Portugal and in the Po River Basin in Italy. Cultural heritage and hazard maps were integrated in a GIS environment to produce exposure and hazard maps, assessing vulnerability with a vulnerability index and flood risk using a semi-quantitative index-based method. The findings reveal that: (1) global hazard maps have strong limitations to accurately assess risk; (2) continental hazard maps have a better agreement with Floods Directive maps but are sensitive to the area considered; (3) the comparison of risk rankings from various hazard sources shows a low degree of agreement, with notable discrepancies in Po River Basin. This study could support decision-makers in prioritizing cultural heritage that require further investigation and highlights the importance of considering their spatial distribution when producing high-resolution hazard maps.

1. Introduction

Floods are among the most frequent and costliest natural hazards worldwide. In many regions, the magnitude and frequency of extreme flood events and associated economic and non-economic losses are expected to increase due to climate change, urbanization, and population growth [1–3]. Although Asia is the most severely impacted continent, Europe is not immune to such events. From 2001 to 2020, 6.6 million people in Europe have been affected by catastrophic floods, such as the August 2002 flood, which led to

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devastating damages on the historical cities of Prague and Dresden and $ 20 billions of material losses across Europe, or the more recent 2021 European floods, which caused economic losses of $ 40 billion in Germany [4,5].

In this context, flood risk assessment studies have become a crucial tool to support decision-makers to develop effective and prompt mitigation strategies [6,7]. In fact, in recent years several international organizations have centered their attention on disaster risk reduction, including the United Nations with the Sendai Framework for Disaster Risk Reduction [8], and the European Union with Directive 2007/60/EC [9] on the assessment and management of flood risks. Both texts specifically underline the need to include cultural heritage in risk assessments and the need to protect it, in line with global trends, reflecting its importance for economic well-being and its socio-cultural value [10–12]. It is well-known that cultural heritage is particularly vulnerable to floods, not only because of the damage to the structures caused by the direct contact with floodwaters, but also due to the damage to the base and the subsoil [13–15]. Furthermore, given its intrinsic physical properties, such as building materials, aging structures and artistic contents, a damaged cultural heritage monument or site may not return to its pre-disaster state, leading to considerable indirect impacts, for example, to local communities and to tourism [16,17].

Despite significant scientific attention being given to cultural heritage preservation, there is still a notable lack of emphasis on its integration into disaster risk management planning. While numerous studies in the literature address the preservation of individual monuments or sites, the broader incorporation of cultural heritage in such planning remains insufficient [18–20]. Several studies have attempted to map cultural heritage sites susceptible to natural hazards at different scales [21–24], but there is a scarcity of literature focusing on comprehensive risk assessment and mapping beyond individual monuments or sites [25]. In fact, existing research primarily concentrates on identifying potentially exposed assets, with only a limited number of studies taking the crucial next step of applying the complete risk chain and quantifying the associated risks for large sets of assets, e.g., at the national, continental or global level, even if using various simplifying assumptions [26–29].

Large-scale flood risk assessment studies, for example at the national level, can be used to identify hotspots of flood risk, estimate annual expected losses on a macro-scale, and support the development and prioritization of flood mitigation strategies, among others [30–32]. Therefore, they are a crucial tool to support disaster risk management activities. This is particularly useful when assessing the risk for cultural heritage, given the interdependence of economic, social and cultural systems, and the importance of cultural heritage for local and national economies [33]. Furthermore, cultural heritage sites hold intrinsic value not only for local communities but are part of the world's heritage, emphasizing the importance of addressing flooding risks at a large scale transcending local boundaries with a broader community of stakeholders involved [34,35]. However, regional- and/or national-level high-resolution flood hazard maps are not present in many areas, and risk assessments for cultural heritage have often resorted to existing open-access datasets developed at larger spatial scales, such as the widely-used European Commission's Joint Research Centre (JRC) flood hazard maps (e.g., [27,29]). Although this type of datasets provides invaluable insights into the spatial distribution of flood hazard at the large scale, they have lower spatial resolutions and are inevitably associated with uncertainty in the estimation of water depths at local levels, which can be problematic when considering cultural heritage. In this case, risk must be estimated on an asset-by-asset basis, and therefore it is desirable that water depth estimates at the location of each asset are as accurate as possible. This contrasts with other types of assets, such as residential buildings, where interest lies mainly in aggregate loss estimates and therefore some error compensation among loss estimates for different assets can occur. Previous studies have attempted to understand the influence of different sources of uncertainty, including flood hazard estimates, in the assessment of flood risk [36–38]. However, given the specificities of cultural heritage, particularly their representation as discrete points in georeferenced databases rather than polygons or continuous areas, it is still to be understood at which level the spatial resolution of hazard maps influences the risk estimation and whether large-scale hazard maps can be reliably employed to perform a national scale risk assessment for cultural heritage. In this context, this study addresses two significant gaps in the current knowledge and practice of flood risk assessment for cultural heritage. First, as highlighted by the challenges of using large-scale hazard maps, the impact of the hazard maps' spatial resolution on cultural heritage flood risk assessment remains poorly understood. Second, there is a scarcity of comprehensive studies evaluating flood risk to immovable cultural heritage at large scales (country or watershed level). To address these gaps and contribute to the existing scientific literature, this study applies a semi-quantitative risk index-based approach, namely the Heritage Flood Risk (*HFR*) index developed by Figueiredo et al. [29]. This method is applied using different resolution hazard maps (i.e., global, continental and national), conducting a comparative analysis between two European countries: mainland Portugal and the Po River Basin in Italy. This comparison allows to assess both the applicability of the *HFR* index at large scales and the sensitivity of risk assessment to the spatial resolution of hazard maps in different study areas, providing insights for future cultural heritage flood risk assessments.

2. Literature review

There are very few existing approaches in the scientific literature for the flood risk assessment of cultural heritage at a large scale, and in most cases risk has been addressed in a qualitative way, underlining the lack of quantitative applications [21,27,39–41]. Quantitative or semi-quantitative approaches have only been developed more recently for cultural heritage, allowing a more analytical and precise representation of flood risk [42–46]. This lack of applications can be attributed, in part, to difficulties in modeling flood vulnerability for cultural heritage assets, i.e., estimating losses to cultural heritage caused by flooding as a function of its intensity. While traditional large-scale flood risk assessment studies typically use depth-damage functions to describe damage ratios and economic losses to groups of assets sharing similar characteristics [47,48], doing so for cultural heritage is not a trivial task for several reasons. These include the different characteristics of each asset, which make it challenging to group them into standard depth-damage functions, as well as their intangible nature and their connections to the urban environment [49–52]. This can be attributed also to a lack of data on past flood events, which make it more difficult to produce depth-damage functions. Moreover, it is very challenging to assign an economic value to cultural heritage, given the complexity to monetize the different historic, social and spiritual components of their value. For this reason, given the multidimensionality of the problem, specific methodologies for the assessment of disaster losses for cultural heritage have been scarce [17].

One of the earliest attempts to evaluate flood risk for cultural heritage beyond the scale of a single asset was conducted by Lanza [39] for the town of Genoa, Italy. However, vulnerability models were not implemented, nor were hydrological or hydraulic simulations. Vojinovic et al. [46] implemented a framework for flood risk assessment in areas with a high density of cultural heritage applied to the city of Ayutthaya (Thailand) using a holistic approach. This approach consisted in coupling qualitative and quantitative data from public sources, surveys, expertise interviews and the perceived risk of local residents, resulting in two different risk maps that were then combined together. By combining the traditional risk methodology, applying a quantitative or analytical method, with the perceived risk, the approach emphasizes the social, cultural and ethical aspects of cultural heritage in local communities. Arrighi et al. [42] developed one of the most comprehensive frameworks for assessing flood risk in an art city, including cultural heritage sites, for the city of Florence. This was one of the first attempts to apply the full risk chain for cultural heritage at a municipality level, by analyzing the historical data to assess the percentage of losses for different artworks as well as their vulnerability. Figueiredo et al. [29] developed a novel framework for flood risk assessment for mainland Portugal for immovable cultural heritage. Their methodology follows a semi-quantitative approach with expert-based support where the vulnerability is represented by a depth-damage function. In the work carried out by Arrighi et al. [16], the reopening time of cultural heritage sites was used as a proxy for the indirect damage, in order to derive a new vulnerability function for the historical city of Florence which connects this reopening time to a flood depth value. This was one of the first attempts to link cultural heritage sites with the urban context in which they are located by evaluating the associated indirect impacts on tourism; therefore, the exposure is defined by the number of visitors. Jia et al. [45] adopted a GIS-based Soil Conservation Service-Curve Number (SCS–CN) method to assess flood-prone areas in Shanxi province, in China, considering climate change impacts. More recently, Arrighi et al. [44] developed a new flood damage index for cultural heritage within the Po River District Authority in the context of a project dedicated to the flood damage analysis of all cultural heritage sites in flood-prone areas.

3. Objectives

The first objective of this work is to investigate the feasibility of using large-scale hazard maps to assess flood exposure and flood risk of cultural heritage. Specifically, this study evaluates how hazard maps of varying spatial resolutions influence the assessment cultural heritage flood risk. This is achieved by analyzing and comparing the results obtained in terms of risk values using different hazard maps with three spatial resolutions (global, continental, national).

The second objective of this study addresses a crucial gap in current practice: the scarcity of large-scale flood risk assessment studies for cultural heritage, which highlights the need for a standardized approach to cultural heritage flood risk assessment that can be applied across different countries and regions. Since quantifying flood risk for cultural heritage assets requires consistent estimation of potential flood impacts, this work aims to establish a common procedure that transcends national boundaries. This involves developing and combining existing methods into a generalized methodology for assessing flood risk on cultural heritage at a large-scale by incorporating a vulnerability model that does not depend on the region specificity. To achieve this, the present work implements a vulnerability model that accounts for the distinct physical and cultural characteristics of each asset, building upon existing methodologies developed by Figueiredo et al. [29] and Arrighi et al. [44]. This comprehensive vulnerability model represents a significant advancement over existing methodologies, as it can be applied consistently across different geographical and cultural contexts while maintaining sensitivity to local heritage values.

To achieve both objectives, this work presents a comparative assessment in two different European countries: mainland Portugal and the Po River Basin in Italy. These two areas, although comparable in terms of extension, are characterized by different morphologies and different densities of cultural heritage monuments and sites. Therefore, this comparison is of great interest, because the two study cases share similarities but also differences that might be reflected in the results obtained. This multi-country approach underscores the site-independent nature of this study and emphasizes the wider applicability of the methodology.

4. Methods

To perform a flood risk assessment, it is fundamental to define and evaluate hazard, exposure and vulnerability. In the context of this study, hazard is expressed as a potential flood event and its probability of occurrence, exposure is the location and value of cultural heritage in flood-prone areas, and vulnerability is the potential degree of harm that a flood event can cause to cultural heritage [53].

Cultural heritage includes “artifacts, monuments, groups of buildings and sites, museums that have a diversity of values including symbolic, historic, artistic, aesthetic, ethnological or anthropological, scientific and social significance” [54]. Even though intangible cultural heritage is also considered to be fundamental part of a national identity and the collective memory, in the context of this study only tangible and immovable cultural heritage is considered, which is defined as monuments, groups of buildings or sites [55]. Here, a semi-quantitative approach, adapted from the one proposed by Figueiredo et al. [29], is implemented to assess flood risk on immovable cultural heritage.

This section describes the datasets used for the two different study cases and the methodology adopted to assess the risk and to quantify the degree of agreement between different resolution hazard maps.

4.1. Data

4.1.1. Hazard

Over the last decade, several large-scale flood hazard maps have been developed, such as the ECMWF [56], GLOFRIS [57], Aqueduct Floods [58,59] and JRC maps [60,61]. For the purpose of this study, the JRC global and JRC European flood hazard maps were adopted. These maps are based on streamflow data from the European and Global Flood Awareness System (EFAS and GloFAS) and are computed using two-dimensional hydrodynamic models. JRC European maps have a resolution of 100 × 100 m, while that of JRC global maps is 1 × 1 km. The versions of the maps used herein are the ones described in Dottori et al. [60]and Dottori et al. [62].

The adopted country-specific maps for Portugal and Italy are the ones produced in the framework of the European Floods Directive 2007/60/EC for the geographical areas for which potential significant flood risk exists or might occur (APSFR). In fact, following the implementation of the European Floods Directive, all Member States have to produce flood hazard maps for low, medium and high probability of occurrence, providing flood extent, water depth, and flow velocity where possible. There are different flow characteristics that influence the occurrence of flood damage, but inundation depth is usually considered as the determining parameter [6,7,63]; therefore, in this study focus is given to flood extent and water depth, while flow velocity is not included, also due to the lack of data for large-scale maps.

In the case of Portugal, the maps adopted in this study were developed by Agência Portuguesa do Ambiente [64] within the second cycle of the Floods Directive. These maps are the most recent open-access available ones, they have been published in 2023 within a web GIS interface, and more recently also through a Web Service Feature (WFS). The maps cover 62 critical areas in Portugal that were defined based on historical records, using as criteria that at least one person having died or gone missing and at least 15 people having been affected as a result of flooding. These maps have a spatial resolution which ranges from 50 × 50 m to 2 × 2 m depending on the critical zone considered. They are available on this website: https://snig.dgterritorio.gov.pt/

For the Po River Basin, the maps adopted were developed by Autorità del Bacino del Fiume Po (AdBPo) within the second cycle of the Floods Directive. These maps were derived only for those areas that are at a potentially significant flood risk (APSFR), and, in particular, for the purpose of this study, only the district areas were considered, which are defined as: "areas with strategic importance on a district scale which need complex mitigation measures among different regions" [65]. AdBPo defined the extents of APSFR during the redaction of Flood Risk Management Plan in 2015, updated afterwards in 2018. The selected hazard maps are those developed for the district areas identified in 2018. Due to the extensive area and the diverse flood process across the Po River Basin, the hazard maps developed by AdBPo adopted different methodological approaches tailored to the specific areas, a more detailed explanation of the hydrological and hydraulic modelling employed can be found on AdBPo website: https://pianoalluvioni.adbpo.it/mappe-della-pericolosita-e-del-rischio-di-alluvione/. They have a spatial resolution that ranges from 20 × 20 m to 1 × 1 m depending on the extension of the APSFR considered and since they are produced by different entities, they are developed considering different return periods (e.g., the medium probability scenario is modeled considering a return period of 100 years or 200 years) and different spatial resolutions. These maps are the most recent open-access available for the Po River Basin, and they are available as well through a WFS. They have been published by Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) and on Geoportale Nazionale. However, the available maps do not have discrete water depth values for each polygon, but rather they are characterized by different water depth intervals. This is a limitation of the maps produced in the framework of the European Floods Directive especially for end-users or decision-makers that they must rely on those maps.

They are available on this website: https://gn.mase.gov.it/portale/wfs.

4.1.2. Exposure

In Portugal, the Directorate-General for Cultural Heritage (DGPC) is responsible for managing cultural heritage sites. There are three different open access databases: one for "classified heritage and heritage in process of classification", one for "archaeological heritage" and one for "architectural heritage". The dataset used in this study is SIPA (Information System for Architectural Heritage), which is the most comprehensive inventory of cultural heritage sites in Portugal. This dataset contains information about the geographic location and some characteristics (i.e. type of asset), which are necessary to define vulnerability and exposure. The geospatial data are available as GIS shapefiles with point features which contain, besides the geographical location of each asset, the following information:

- Designation,
- Category,
- Protection,
- URL.

The SIPA GIS database contains 24,656 entries (4201 protected and 20,455 unprotected heritage assets); for the purpose of this study, only the protected sites were considered.

The dataset is available on the SIPA website: http://www.monumentos.gov.pt/

This dataset was complemented with information regarding vulnerability classes and exposure values by Figueiredo et al. [29] which are necessary to assess flood risk.

In the framework of the EU Floods Directive, the Po River Basin Authority has previously identified, as potentially exposed elements, cultural heritage assets located in flood-prone areas that are protected by MiBACT (Ministero per i Beni e le Attività Culturali e per il Turismo) within the catalog "Vincoli in Rete".This dataset was updated in the framework of the redaction of PGRA 2021 (Piano di

Gestione del Rischio Alluvioni), for the second cycle of the EU Floods Directive, in order to have a more precise representation of the exposed assets. In this context, Arrighi et al. [44] developed a more comprehensive database to include regional cartographic datasets by overcoming the issue of multiple elements spread among several institutional databases. This updated database is the one used for the purpose of this study and was derived by merging the cartographic data with cultural heritage assets protected by MiBACT and by UNESCO, resulting in 124,974 elements. These elements were classified according to their level of protection and, in particular, the three following levels were identified: world significance (UNESCO World Heritage sites), national significance, and local significance. Furthermore, the elements were grouped into 10 categories based on common features that are assumed to be relevant when assessing flood risk. The categories are:

- Religious architecture,
- Residential and tertiary architecture,
- Fortified architecture,
- Rural architecture,
- Museum
- Open space
- Monument
- Infrastructure and plant,
- Industrial and productive architecture,
- Archaeological site.

This dataset is available as a GIS shape file as point features.

4.2. Risk assessment

4.2.1. Hazard analysis

One of the requirements for performing a flood risk assessment study is a set of flood hazard maps covering the entire study area. Flood hazard is defined as "the exceedance probability of potentially damaging flood" [66] and therefore, flood hazard maps describe the intensity of floods and their associated probability of occurrence. The complexity of the models adopted to define the flood hazard can vary a lot, depending on the scale and on the scope of the analysis [36]. All of these models are characterized by many uncertainties and the calibration and validation of the results obtained is often not trivial due to scarcity of data on inundation extents and water depths [36,67]. While detailed flood maps would be preferable for risk assessment, the selection of data and models should align with the analysis objectives, whether for management purposes or cost-benefit analysis of flood mitigation measures [36]. This study investigates the feasibility of using large-scale hazard maps for cultural heritage risk assessment at country or watershed scales. The analysis examines flood hazard maps developed by the Joint Research Center of the European Commission and local authorities under the European Floods Directive, which are characterized by three different spatial scales: global, continental, and national. Rather than comparing the underlying models and data used to derive these hazard maps, this study adopts a socio-economic perspective to evaluate how various factors, including hazard map characteristics (e.g., resolution, scale, data sources), vulnerability, and exposure, influence the risk evaluation process. This approach is helping to bridge the gap between large-scale flood hazard assessment and national-scale risk management needs, particularly for cultural heritage assets where detailed information is often limited.

While many flood maps exist, each with distinct characteristics, flood extent and water depth consistently emerge as the primary parameters in flood hazard mapping. Although other variables, including water velocity, flood duration, flood wave propagation, and the rate at which water levels increase, can play crucial roles depending on the specific context, this analysis focuses exclusively on flood extent and water depth. The study uses JRC and Floods Directive hazard maps for three different scenarios: high probability (i.e., 20-years return period), medium probability (i.e., 100–200 years return period) and low probability (i.e., 500–1000 years return period). The low probability scenario available for JRC global, European and AdBPo maps has a return period of 500 years, while for Portuguese maps the return period is 1000 years. This discrepancy is considered irrelevant for the purpose of this study because large-scale maps don't consider flood defenses in their hydraulic model, meaning that flood extents for a hypothetical 1000-year return period map would likely have only a marginally larger flood footprint. Therefore, it is assumed that the low probability scenarios of the different set maps are comparable.

Due to the importance of water depth in damage estimation and its availability across all datasets, this parameter was used to characterize hazard, while flood extent determined potentially exposed assets. Water depth values were extracted at each asset's location within a GIS environment for all hazard maps and return periods. For the Po River Basin, where water depths were provided in intervals rather than discrete values, a uniform distribution was applied, using JRC European maps' highest value as the upper limit for intervals exceeding 2m. In the available shapefile representing hydraulic information of flooded areas in the case of Po River Basin, water depth values are described in intervals rather than discrete values.

4.2.2. Vulnerability modeling

To establish a common representation of the two study cases, this study adapts the flood vulnerability model developed by Figueiredo et al. [29] for different types of cultural heritage. In fact, applying and adapting a vulnerability model that accurately describes the diverse cultural and architectural characteristics of the heritage sites in both countries is not a trivial task. Each cultural heritage has unique characteristics that may vary between countries, making it challenging to create generalizable classes across different cultural contexts. The vulnerability model groups cultural heritage into different vulnerability classes based on common features that are assumed to be relevant when assessing flood risk. This model is chosen for this comparative analysis because it depicts the various characteristics represented in each class with sufficient accuracy. In Table 1, the eight different categories are described in detail. Bridges were not included in the classification due to data limitations, despite their cultural value. In particular, it is impossible to straightforwardly establish which portion of the bridge is actually flooded, because it would require information on the topographic elevation of the base level of the bridge and the topographic elevation of the water. Such detailed analysis is beyond the scope of this large-scale risk assessment study.

An expert-based approach was implemented to adapt the existing vulnerability model developed by Figueiredo et al. [29] to the Italian context. Notably, class H was not part of the original classification, but was included due to the large number of elements, specific to the Po River Basin database. Portuguese cultural heritage sites have already been grouped using this approach, as previously mentioned, while for Italian heritage it was necessary to modify the already existing classification in order to align them with these vulnerability classes. As previously mentioned, cultural heritage may have different and distinctive characteristics across various countries. In particular, in the case of the Po River Basin, certain sites originally categorized as castles were reassigned to vulnerability class B and not vulnerability class C to account for the importance of their artistic and cultural contents. These vulnerability classes allow to group assets that share specific construction characteristics and/or types of contents with the assumption that they would experience similar degree of damage under comparable flood conditions. On top of these vulnerability classes, the vulnerability modelling approach adopted in this work utilizes a vulnerability function, commonly known as depth-damage function, developed by Figueiredo et al. [29], which can be used to estimate the relation between flood intensity and flood impact to cultural heritage assets. In this case, the flood intensity is defined in terms of water depth (m) while flood impact is expressed through the *HFI* (Heritage Flood Impact) index. *HFI* is assumed to increase linearly with water depth up to a certain threshold, at which no additional damage of relevance is assumed to occur. The vulnerability function is given by

$$HFI = \begin{cases} ax/b, x < b \\ a, x \geq b \end{cases} \tag{1}$$

where x is the water depth, a is the maximum flood impact index, and b is the corresponding water depth. The a and b parameters depend on the vulnerability class of the asset, as shown in Fig. 1.

The model assumes that for each cultural heritage asset there is a maximum degree of possible flood impact corresponding to a certain water depth threshold. The parameter a can assume values from 1 to 5, depending on the vulnerability class. This should reflect the susceptibility to flooding of different assets typologies. This *HFI* index is a semi-quantitative index which expresses the potential flood impact on cultural heritage as a function of water depth, making it a useful indicator that can support the identification of assets at risk and subsequently set risk prioritization levels on the national scale.

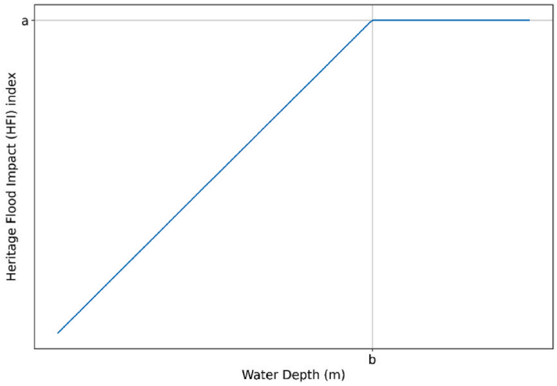
4.2.3. Exposure modeling

Following the definition of exposure provided by the IPCC, which states that exposure is “the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected”, many risk assessment studies have assessed exposure to flood risk for different types of assets in an area, including the number of residents [68] and the economic value of assets [69]. Following these approaches, this study aims to identify both the locations of cultural heritage sites in flood-prone areas and their value. Both components play a key role when defining risk. In particular, being able to identify whether a cultural heritage site is located in a flood-prone area is fundamental to determining whether an asset is at risk

Table 1
Vulnerability classes and their corresponding type of assets, adapted from Figueiredo et al. [29].

Vuln. class	Designation	Description
A	Buildings with flood-susceptible contents of significant value	Buildings containing elements susceptible to flood damage that have significant cultural value and may not be fully repairable or replaceable because of that damage (due to their material characteristics or uniqueness).
B	Buildings with flood-susceptible contents of limited value	Buildings containing elements susceptible to flood damage that have a limited cultural value or may be fully repairable or replaceable because of that damage.
C	Castles and walls	Defensive structures taller than most common constructions, usually built with thick masonry walls and that do not house valuable contents or collections. In cases where these constructions house valuable contents, vulnerability class A or B should be considered instead.
D	Isolated vertical constructions	Slender and often monolithic constructions made of stone or masonry. In some cases, these constructions are built on top of a plinth and are often located in urban squares.
E	Other constructions and buildings	Constructions or buildings that do not house contents of cultural value and do not belong to vulnerability classes A to D. This class includes constructions or buildings that are abandoned or in ruins, but whose configuration can still be almost fully identified.
F	Archaeological sites, remains and ruins	Human-made elements or constructions providing evidence of past activity, such as ruins of constructions whose configuration cannot be fully identified. These elements or constructions are often in stone or masonry, and usually have a low height.
G	Rock art	Artwork done over natural stone found in cave walls or on large blocks in the open air, using painting or engraving techniques. They are assumed to be marginally vulnerable to the actions of flooding.
H	Open spaces	Elements that are less susceptible to flood damage and their extension is mainly set at open air.

(a)



(b)

Vulnerability Class	a	b
A	5	2.0
B	4	2.0
C	3	5.0
D	3	2.5
E	3	3.0
F	3	0.5
G	2	1.5
H	1	0.5

Fig. 1. Vulnerability model adopted in this study, adapted from Figueiredo et al. [29]: (a) Generic plot of the function; (b) Vulnerability classes and corresponding function parameters.

or not. This is a crucial point of this study, which has the objective of understanding the feasibility of using large-scale hazard maps, characterized by a coarser resolution, for assessing risk on cultural heritage. Moreover, defining the exact location of cultural heritage sites is challenging due to data limitations, as also further highlighted in this work. For this reason, this study adopts a simple approach that involves determining the number of assets exposed to flooding using a geographical information system (GIS), which is used to overlay the cultural heritage locations with flood hazard maps.

Moreover, the influence of cultural heritage in the socio-economic context in which they are located, as previously mentioned, it is not straightforward to assign a monetary value to these peculiar assets [70], unlike other type of assets for which the value can be uniquely determined in monetary terms. To address this, and to assign a value to cultural heritage, this study adopts a methodology proposed by the National Trust of Australia [71] and adopted by Figueiredo et al. [29]. A qualitative Value Index was assigned to each cultural heritage, using the value scale presented in Table 2. The listed status (i.e. level of protection) was divided into three main categories reflecting the global, national or local importance of each asset. A Value Index was then assigned to each listed status: World Heritage sites have a value of 20, National Interest sites a value of 10 and Municipal Interest of 5. This index should be able to reflect the relative degrees of importance between the assets, highlighting the key role of world heritage for a country. Indeed, it does not represent a direct monetary value but rather serves as a proxy for relative importance and, by extension, differing economic value. The elements for which the listed status was under assessment were considered as municipal interest given their limited significance. On the other hand, the elements for which no legal protection was granted were not considered in this study. Thus, by combining the spatial analysis of cultural heritage sites along with their associated value, it was possible to quantify cultural heritage potentially exposed to flooding, which could then be used, in combination with hazard and vulnerability assessments, to assess risk [72].

4.2.4. *Risk index*

The final step in the flood risk assessment chain is the quantification of the risk, which is defined as a function of hazard, vulnerability and exposure and is typically estimated using a loss exceedance probability curve, or simply risk curve. In this study, for risk assessment, the approach developed by Figueiredo et al. [29] is adopted, which is based on the computation of the Heritage Flood Risk index *HFR*. This index is calculated for each asset as a trapezoidal approximation of the area under the risk curve, given by the equation:

$$HFR = V\sum_{i=1}^{n-1}(P_{i+1} - P_i)\frac{HFI_{i+1} + HFI_i}{2} \tag{2}$$

where n is the number of adopted hazard scenarios, P_i is the annual probability of occurrence of the ith hazard scenario (with $P_{i+1} > P_i$), HFI_i is the Heritage Flood Impact index given by Eq. (1), and V is the value index of the cultural heritage asset, according to Table 2.

This semi-quantitative index-based approach is particularly useful given the difficulty in assigning an economic value or any monetary expression for cultural heritage. Moreover, this approach facilitates the establishment of prioritization levels by providing a

Table 2
Cultural heritage value index as a function of its listed status, adapted from National Trust of Australia [71] and Figueiredo et al. [29].

Status	Value Index	Description
World Heritage	20	Listed asset with features of exceptional/international significance or that contains elements with a significance beyond national boundaries
National Interest	10	Listed asset with features of considerable national significance reflected by its national monument status
Municipal Interest	5	Listed asset with features of limited/local significance

comprehensive overview of the varying degrees of risk associated with each cultural heritage asset.

4.3. Degree of agreement

The feasibility of using large-scale hazard maps to assess flood risk on cultural heritage is assessed by performing a comparative analysis of the potentially flooded assets and their corresponding risk values. This is achieved by comparing the results obtained using as hazard maps, three different resolution maps, namely JRC global, JRC European, and Floods Directive maps both for Portugal and the Po River Basin. The degree of agreement is therefore assessed considering the exposed assets, using Venn diagrams and exposure maps (Figss. 4–5) and by analyzing rank correlation matrix (Fig. 6) of the risk values obtained from the analysis.

The study area is defined by merging the flood footprints for the low probability scenario of all three maps. It is important to note that this study area does not encompass all flood-prone areas in the two regions, but only those modeled by JRC and Floods Directive maps. The degree of agreement is evaluated by comparing risk values for potentially flooded assets identified within the entire study area, as well as within the area where all three maps intersect. Furthermore, the agreement is assessed by identifying exposed assets in a medium probability scenario across all three hazard maps, considering both the entire study area and the intersection area.

All analyses were carried out using QGIS, an open-source geographic information system (GIS) software. During this analysis, the official hazard maps produced in the framework of the Floods Directive were used as a benchmark, because they are considered to model the expected flood extents with a good accuracy, i.e., with high resolution ad flood defenses, even though they have been produced only for areas where there is a potentially significant flood risk. However, this definition does not consider the spatial distribution of cultural heritage, and this is a significant limitation when assessing flood risk for cultural heritage at national scale. This is because some flood-prone areas might not be covered by those maps and some important cultural heritage sites could be left out from the risk evaluation. This consideration is crucial for managing and preserving cultural heritage at risk of flooding, given that cultural heritage often includes assets of national importance. Consequently, decision-makers should be able to derive mitigation and adaptation measures at a national scale. A more detailed discussion of this limitation will be presented in the discussion section.

5. Results

5.1. Study area identification

Fig. 2 illustrates the critical areas considered in this study. These areas were derived by merging the flood footprints from the lowest return period hazard maps developed under the Directive 2007/60/EC and those available from the Joint Research Centre of the European Commission. The areas highlighted in green represent the intersection of Floods Directive and JRC hazard maps, while the orange areas correspond to those modeled only by Floods Directive maps and the red areas by JRC maps only. The risk assessment for cultural heritage assets was conducted for all the sites located in this study area. Specifically, 292 sites in Portugal and 31232 in the Po River Basin are included in this analysis. However, other cultural heritage sites at risk of flooding may exist outside these areas,

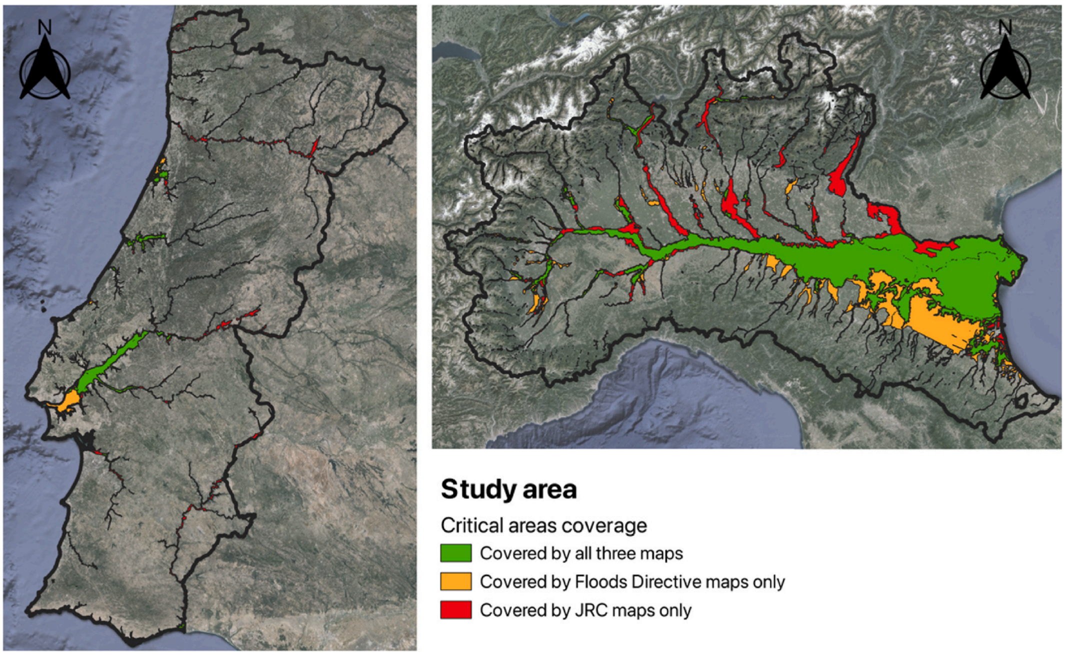


Fig. 2. Map of the study area and spatial distribution of the critical areas.

potentially identifiable using alternative hazard maps for risk assessment.

This initial analysis highlights one of the primary limitations of large-scale risk assessment studies: the lack of coverage by global and continental hazard maps for some areas identified as areas at a higher flood risk. Conversely, some areas predicted to be flooded by JRC maps are not covered by the Floods Directive maps, especially for Portugal, but also for the Po River Basin.

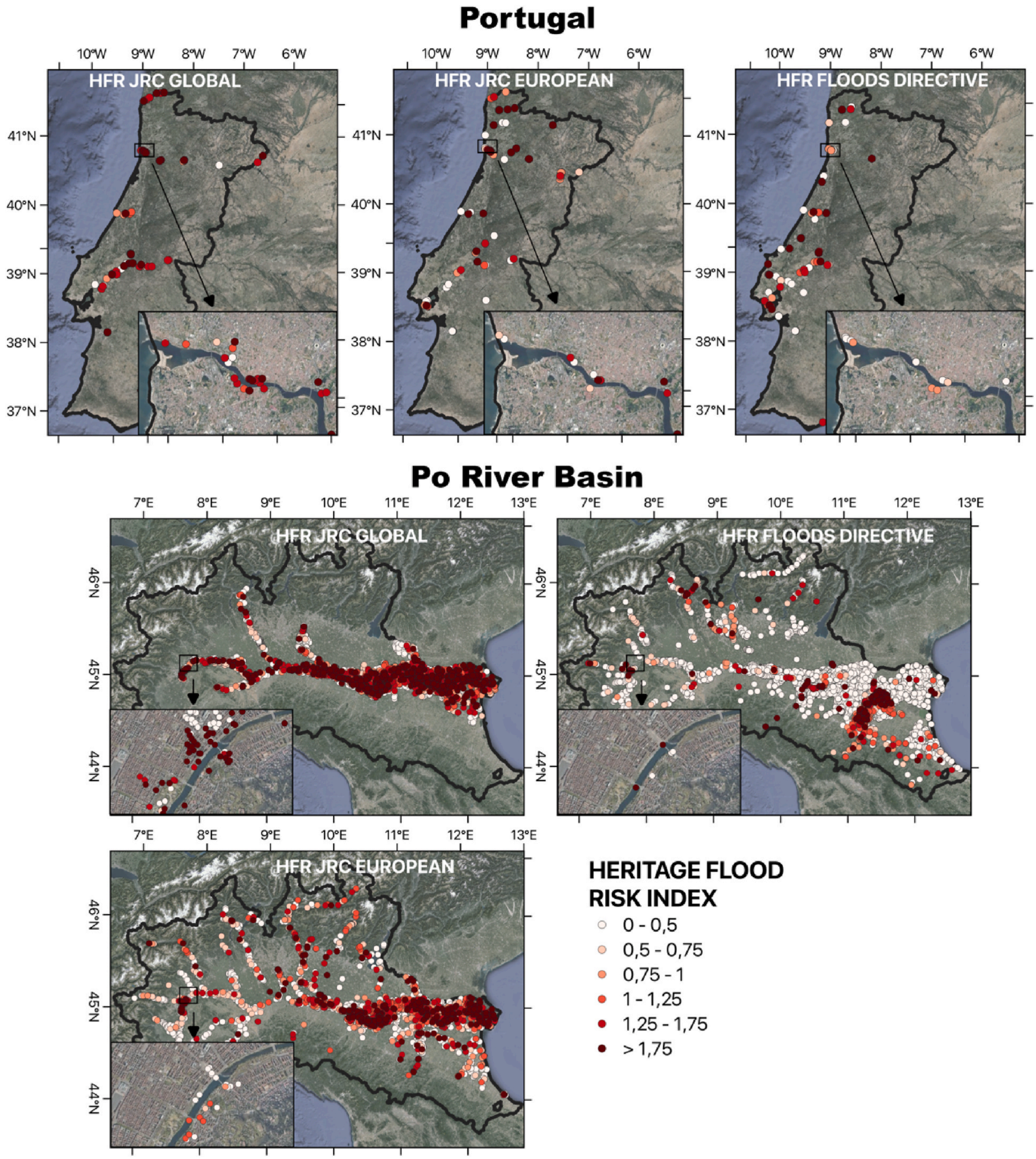


Fig. 3. Map of the spatial distribution of cultural heritage exposed to flooding and their corresponding HFR indices for Portugal and for Po River Basin.

5.2. Risk assessment

The spatial distribution of exposed assets in Portugal and in the Po River Basin, along with their corresponding HFR indices calculated using Equation (2), is illustrated in Fig. 3. Fig. 3 reveals crucial differences in the spatial distribution of HFR values in the countries. In particular, although in Portugal JRC maps tends to yield higher HFR values in many areas, in the Po River Basin there is a evident discrepancy between JRC's maps and Floods Directive maps. However, despite this observed trend on a large-scale, it is plausible that all three maps correctly identify cultural heritage at a higher risk. To explore this possibility, Tables 3 and 4 provide a list of the ten cultural heritage assets with the highest risk values considering Floods Directive hazard maps. It is important to clarify that these values do not express a monetary value; rather, they indicate a risk index, which enables the rapid identification of assets that may be at potentially higher risk. The results suggest significant discrepancies for both Portugal and the Po River Basin. Not only the values differ substantially between the maps, but also a considerable number of assets deemed high risk are not considered at risk of flooding by others. In both regions, the highest HFR value is 2.4 although theoretically these values could range up to 5. This suggest that the sites with the highest level of protection and the most vulnerable ones, are characterized by low water depth levels in all flooding scenarios. A striking similarity between the two regions is the prevalence of religious sites, particularly churches, among the assets with the highest risk values. This finding highlights the vulnerability of religious heritage to flood risk in both countries, possibly due to their historical locations or architectural characteristics. In each region there are four cultural heritage sites identified as being at high risk of flooding in Floods Directive maps, not considered to be flooded at all in the others and, in addition, many cultural heritage sites show considerably lower risk values. This discrepancy underscores the variability in flood risk assessment depending on the hazard map used. This could be attributed to various characteristics of large-scale hazard maps, such as differences in spatial resolution compared to Floods Directive maps. These limitations and their implications will be addressed in more detail in the discussion section. The analysis underscores the challenges in using large-scale hazard maps for accurate risk assessment of cultural heritage sites and highlights the need for careful interpretation of the results derived from different mapping methodologies.

5.3. Degree of agreement

Fig. 4 presents four Venn diagrams describing the proportion of potentially flooded cultural heritage assets based on the three different hazard maps, considering the differences in exposure, for a medium probability scenario. The green diagram corresponds to the Floods Directive, the blue diagram to JRC European and the red one to JRC Global. It is worth pointing out that the number of potentially flooded cultural heritage assets differs significantly between the two countries considered in this study. In Portugal, the analysis covers 68 cultural heritage assets, while in the Po River Basin, a considerably larger number of 10490 assets were considered. This variation stems from the substantial difference in cultural heritage density between the two countries, despite their relatively comparable geographical extents. These diagrams are derived considering two scenarios: the study area as a whole, and a smaller portion consisting of the area where all three maps intersect. It is crucial to note that this area is identified using the extension of the

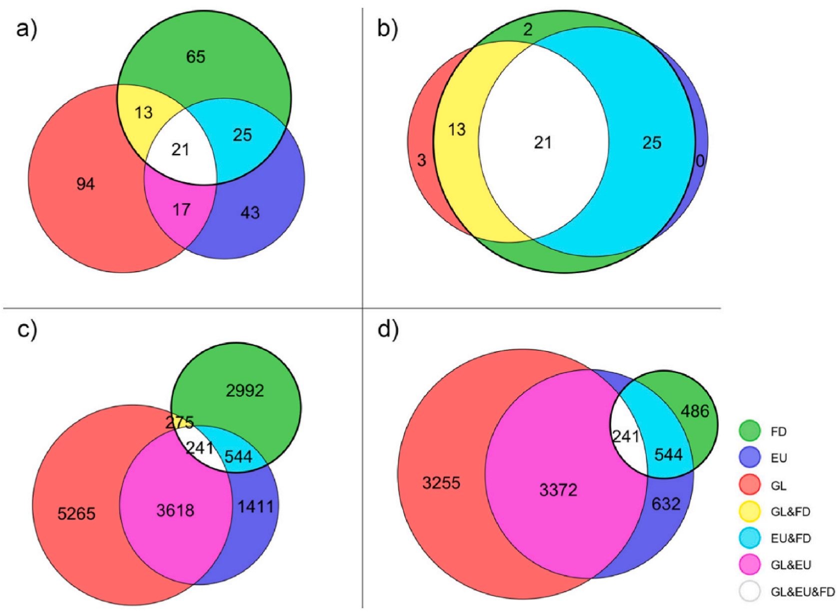


Fig. 4. Venn diagrams representing the exposed assets for each different hazard map in the medium probability of occurrence scenario. Specifically, 'FD' is used to denote the Floods Directive, 'EU' for JRC European, 'GL' for JRC Global hazard maps. The diagrams in the upper part (a, b) correspond to Portugal while in the lower part they correspond to Italy (c, d). Specifically (a) and (c) represents the exposed assets over the whole study area (i.e. union area). On the other hand, (b) and (d) represents the exposed assets over a portion of the study area (i.e. intersection area).

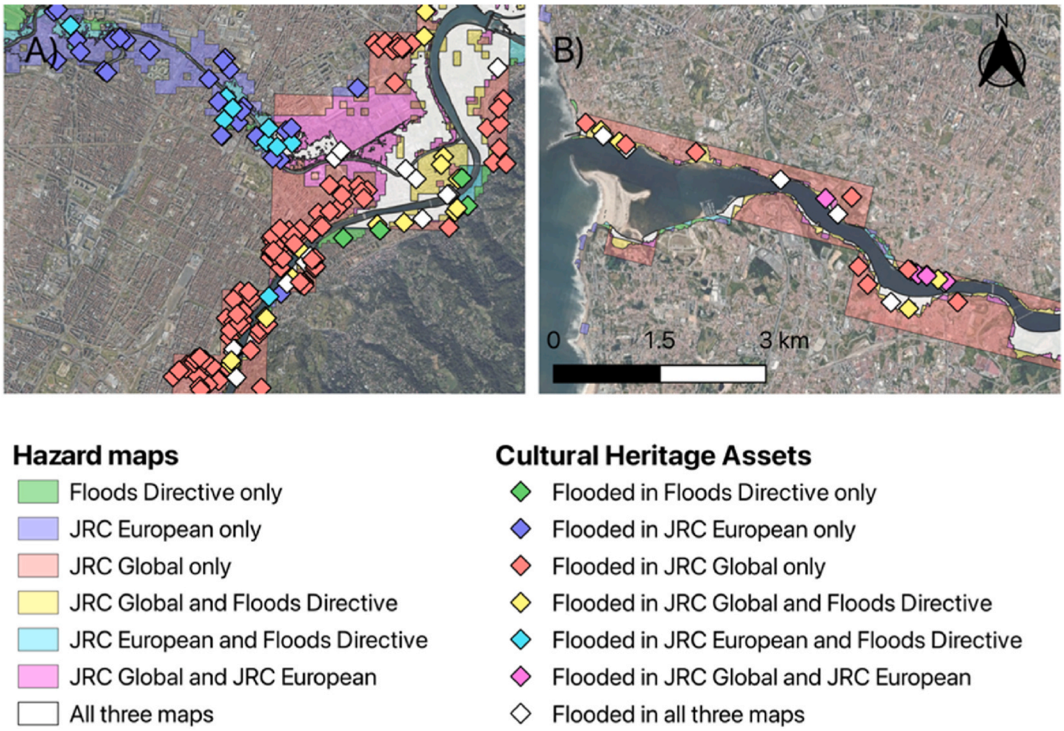


Fig. 5. Multiple comparison of the three maps considered in this study and the cultural heritage located in the corresponding inundated area for a medium probability scenario: a) Torino (fiume Po), b) Porto/Vila Nova de Gaia (Douro).

flooded area in the low probability scenario for all three maps. In both countries, as expected, the number of exposed assets identified only by the Floods Directive maps decreases when considering only the intersection area. However, an interesting observation emerges for the Po River Basin: although the number of potentially flooded assets identified only by JRC maps reduces (i.e. red and blue diagrams), many assets are still flooded according to these maps alone. This points out that, in general, the global hazard map tends to overestimate the number of exposed cultural heritage sites. However, it is important to note that this is not entirely the case for the continental hazard maps. The number of cultural heritage sites identified as flooded by all three maps is considerably small for both countries (i.e. white diagram). In particular, the proportion of cultural heritage assets that are modeled to be flooded according to all three maps differs significantly between Portugal and the Po River Basin. Fig. 5 provides a comparison of the exposed cultural heritage with the corresponding hazard map, with the illustrative example of two cities: Porto in Portugal, and Torino in Italy. This analysis highlighted that the results obtained on the large-scale are very sensitive depending on the area considered and its characteristics. In particular, these two representative study cases depict some of the limitations of the hazard models considered. In particular, from the map, it is evident that in Porto (Fig. 4a), due to the lower spatial resolution of the global hazard map (1 × 1 km), there are many sites wrongly indicated as exposed to flooding, which are likely located at higher elevations from the riverbanks. On the other hand, in Torino (Fig. 5b), the JRC hazard maps model some areas with flood defenses as prone to flooding, showing that large-scale models might not account for existing flood protection infrastructures. Additionally, Fig. 6 presents the rank correlation matrices of HFR indices obtained from the three different hazard maps for both case studies. These matrices illustrate the level of agreement between the different flood maps, revealing some patterns and discrepancies. A key observation is that there is no substantial overall agreement between the three maps. However, some correlations emerge. In Portugal, when considering the Intersection Area, JRC European shows a reasonably good agreement with the Floods Directive maps, with a correlation coefficient of 0.40. This suggests that these two mapping systems have some level of consistency in their risk assessments for cultural heritage sites in Portugal, at least within the areas where their coverage overlaps. A negative correlation is found between JRC global and Floods Directive maps for both Portugal and the Po River Basin. This result suggests that these maps often provide contradictory risk assessments for the same cultural heritage sites. Surprisingly the analysis shows that there is a low correlation between JRC global and JRC European in Portugal. This unexpected result could be attributed to several factors, including the tendency of global hazard maps to yield considerably higher water depth levels. These results could be influenced by various factors, stemming from the distinct characteristics of the two countries. The morphological differences between Portugal and the Po River Basin likely play a role in how flood risks are modeled and assessed. The varying densities of cultural heritage sites in each region may also impact the outcomes, as areas with higher densities of sites might be more sensitive to small variations in flood modeling. Furthermore, differences in the spatial resolution of the maps play a crucial role in risk assessment accuracy. A more detailed analysis of these factors and their implications will be addressed in the following sections, providing deeper insights into the challenges and potential solutions for accurate flood risk assessment of cultural heritage sites.

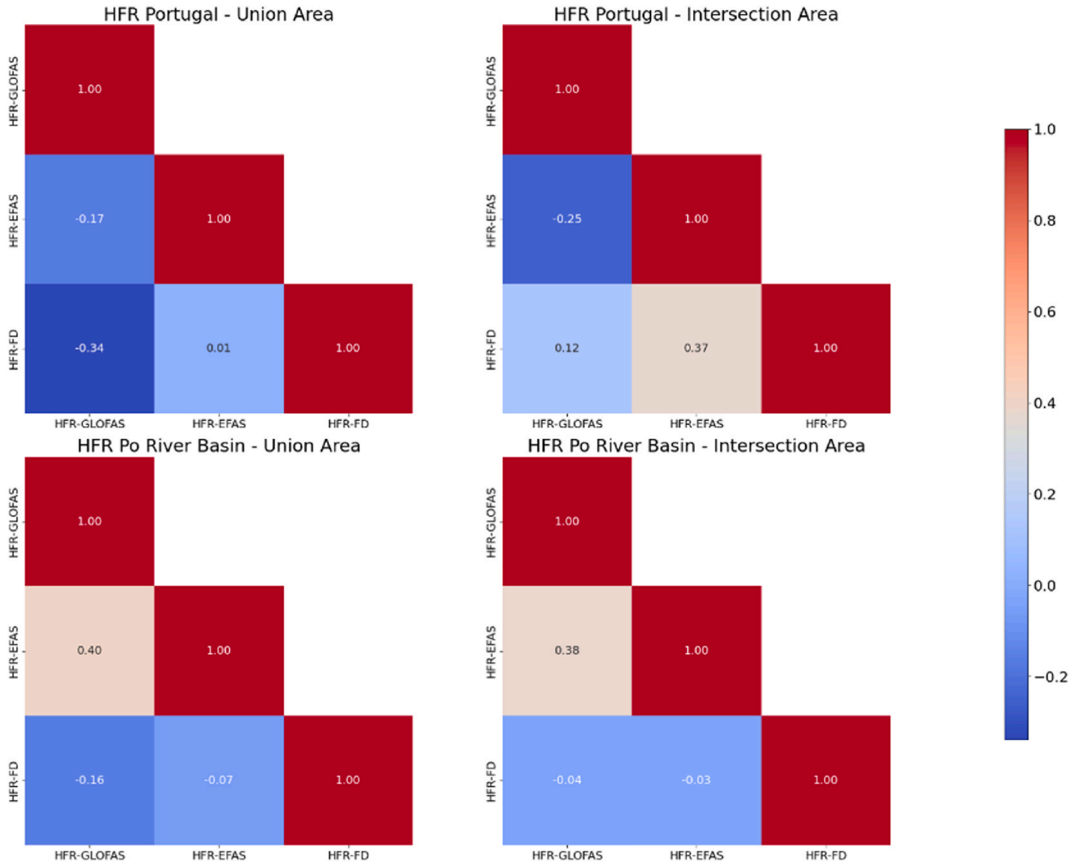


Fig. 6. Correlation matrix of the HFR indices considering the three hazard maps for Portugal and Po River Basin for both the “Union” area and the “Intersection” area.

Table 3
List of the 10 cultural heritage assets within Portugal with the highest risk values adopting Floods Directive hazard maps.

Portugal						
Name	Category	Vuln. class	Value index	HFR JRC-GL	HFR JRC-EU	HFR FD
Capela de São Lourenço	Edifício e Estrutura	A	10	2.40	0.15	2.40
Mosteiro de Santa Clara-a-Velha	Edifício e Estrutura	A	10	0.00	2.40	2.40
Convento e Igreja de Santa Iria	Edifício e Estrutura	A	10	0.21	0.00	2.40
Igreja e Hospital da Misericórdia de Leiria	Edifício e Estrutura	A	10	0.00	0.00	2.40
Capela de Nossa Senhora da Conceição	Edifício e Estrutura	A	10	0.00	0.00	2.26
Capela da Misericórdia de Montemor-o-Velho	Edifício e Estrutura	A	10	2.40	0.01	2.17
Convento de Santo António da Lourinhã	Edifício e Estrutura	A	10	0.00	0.00	2.13
Edifício da Capitania do Porto de Aveiro	Edifício e Estrutura	B	10	0.00	0.00	1.92
Edifício da Geradora	Edifício e Estrutura	B	10	0.17	0.94	1.92
Capela do Anjo da Guarda	Edifício e Estrutura	B	10	0.00	1.92	1.92

6. Discussion

The results of this comparative study provide significant insights into the assessment of flood risk for cultural heritage assets across different European contexts. First, the results demonstrate the critical role of hazard sources in flood risk assessments, particularly given that cultural heritage assets are represented as discrete points in space. As hypothesized, in fact, the risk estimation for cultural heritage is very sensitive to the adopted hazard model. Specifically, the JRC global hazard maps tend to overestimate the exposure of cultural heritage, while the JRC European hazard maps result in a more limited overestimation, though this variation largely depends on the area considered. Moreover, the correlation analysis between different hazard maps reveals varying levels of agreement between the JRC maps and the Floods Directive in the two study areas. These findings directly address the first objective by quantifying how spatial resolution influences risk assessment outcomes. However, the differences obtained in the two study cases can be attributed to several factors, including the morphology of the areas as hypothesized before. The overall low correlation values obtained emphasize

Table 4
List of the 10 cultural heritage assets within the Po River Basin with the highest risk values adopting Floods Directive hazard maps.

Po River Basin						
Name	Category	Vuln. class	Value index	HFR JRC-GL	HFR JRC-EU	HFR-FD
Chiesa di S. Salvatore, detta "Monastero"	Architettura Religiosa e Rituale	A	10	0.00	0.00	2.41
Chiesa di S. Benedetto e Canonica	Architettura Religiosa e Rituale	A	10	2.45	2.29	2.39
Chiesa della B. V. Annunciata e S. Giovanni Battista	Architettura Religiosa e Rituale	A	10	2.10	1.49	2.39
Vecchio Campanile	Architettura Religiosa e Rituale	A	10	2.45	2.45	2.39
Dogmania del Battistero	Architettura Religiosa e Rituale	A	10	0.00	0.00	2.34
Complesso San Benedetto - Liceo e palestra	Architettura Religiosa e Rituale	A	10	0.00	0.00	2.34
Chiesa di S. Siro	Architettura Religiosa e Rituale	A	10	0.00	0.00	2.34
Chiesa di S. Maria Assunta dell'Abbazia (ex)	Architettura Religiosa e Rituale	A	10	2.36	0.74	2.28
Oratorio di San Giovanni Battista	Architettura Religiosa e Rituale	A	10	0.15	0.00	2.23
Chiesa di S. Giovanni Evangelista e pertinenze	Architettura Religiosa e Rituale	A	10	0.00	0.00	2.23

the pivotal role of the hazard source when assessing flood risk for cultural heritage, specifically because these particular assets are represented as discrete points in space and cannot be aggregated.

The comparison of results obtained by adopting the same vulnerability framework, built using the semi-quantitative index-based approach developed by Figueiredo et al. [29] and the GIS-based Flood Damage Index methodology proposed by Arrighi et al. [44], underscores the substantial uncertainty inherent in the flood risk analysis process. Furthermore, this large-scale analysis demonstrates that the developed framework is particularly effective for cultural heritage assessment, as it establishes relative importance scores, thus addressing the inherent difficulty of assigning a monetary value to cultural heritage assets.

These findings contribute to the existing literature on large-scale hazard mapping in several ways. Previous studies have demonstrated a considerably high level of agreement between modeled flooded areas of large-scale maps and higher-resolution hazard maps [60,62]. Others have examined differences in modelling exposed assets, such as population, GDP or various land use classes [57,73]. Although cultural heritage was not included in these analyses, Dottori et al. [62] highlighted that in some lowland areas, JRC European hazard maps have large overestimations for maps for a high and medium probability of flooding. While the current study does not compare directly the flood extents of the different maps, the results obtained for the exposure and risk assessment for cultural heritage are coherent with the ones obtained by Dottori et al. [62], finding an overestimation pattern. Furthermore, through the analysis of specific sites, Arrighi [27] highlighted limitations of global hazard maps that can only be addressed using flood models typically adopted for site-scale analysis, which are therefore not suitable for large-scale analysis. The reliability of the vulnerability assessment approach is further validated by recent post-flood damage analyses in the Marche Region [74], which confirms the high vulnerability of religious buildings identified in both study areas. While more complex and comprehensive frameworks incorporating landscape and socio-economic aspects exist [75], the results demonstrate that the proposed approach effectively addresses the primary challenge of hazard data source suitability in large-scale assessments. In fact, underestimating the exposure of even a single asset can result in substantial socio-economic losses. This underscores the need for implementing robust asset-by-asset risk assessments, despite the challenges posed by the resolution of global and continental hazard mapping. Moreover, the results strongly suggest the need for a more comprehensive sensitivity analysis of the factors influencing hazard estimation. In particular, the disparities in outcomes between the two countries indicate that spatial resolution is not the sole critical factor in hazard estimation. Several other factors may significantly impact the results, including:

- The flood defense assumptions: the exclusion of flood defenses during the flood modeling process of JRC maps can greatly influence the simulated flood extents.
- The DEM resolution: horizontal and vertical accuracy of the DEM can affect the adequacy of global and continental hazard maps, especially during the extraction of water depth values at point locations. This is one of the main reasons why the JRC global hazard maps result in very high values of water depth.
- The river morphology: the two countries have different river channel morphologies and therefore the water depth at the same relative distance from the river is very different, being most of the rivers in the Po Basin located in the alluvial plain.

This study presents two limitations related to the data coverage and data availability, The first limitation concerns the spatial coverage of the hazard maps used in the analysis. The comparison of the three different hazard maps was conducted in a limited number of areas because the global and continental hazard maps do not cover the entire countries but rather focus on rivers with an upstream drainage area larger than 5000 km^2 and 500 km^2, respectively. Similarly, the hazard maps developed under the EU Floods Directive are produced only for areas where a significant flood risk is considered to exist. This spatial limitation is particularly critical cultural heritage risk assessment, as the definition adopted at national levels of what an area of significant flood risk is does not necessarily consider the existence of cultural heritage, leaving many assets outside the extents of the modeled areas. Furthermore, different European countries may have varying standards for producing and publishing flood hazard maps, despite being regulated by the Directive 2007/60/EC of the European Commission. The second limitation relates to the availability and level of detail of cultural heritage data at the national scale. While this study benefits from the databases developed by Figueiredo et al. [29] and Arrighi et al. [44], not all European countries maintain databases with comparable levels of detail. A comprehensive flood risk assessment would ideally require information beyond asset location, including properties that influence damage estimation (such as material types and conservation state) and characteristics of contents (such as artworks and furniture). Although detailed information typically enables more sophisticated damage models, as demonstrated in residential building assessments [60], the limited information in cultural heritage databases necessitates a simplified approach. This data limitation particularly affected the development of the vulnerability model. The challenge of creating a standardized vulnerability classification system for cultural heritage at the country level stems from the distinct characteristics of heritage assets across different countries. The study adopted an expert-based approach to balance data availability and complexity across vulnerability classes. As noted by Schröter et al. [76], this trade-off between complexity and reliability is a central issue in flood damage models. While more detailed vulnerability classes could potentially provide more precise results, they would also introduce uncertainties due to data specificity. Therefore, the adopted classification focuses on describing the susceptibility of cultural heritage to flooding rather than distinguishing between different heritage types or their cultural characteristics.

Despite these limitations, this study contributes to the field of flood risk assessment of cultural heritage in multiple ways. The research describes the impact of using different hazard sources in risk assessment, underscoring the substantial uncertainty inherent in the flood risk analysis process through a novel comparative case study at the national scale. This analysis demonstrates how such uncertainty can significantly influence planning and decision-making processes. Additionally, the study provides a vulnerability framework valuable for large-scale assessments of cultural heritage where standard economic damage estimations are not feasible, helping to prioritize site protection.

Future developments of this work should address both hazard and vulnerability aspects. Conducting sensitivity analyses on different parameters involved in hazard modeling would provide a deeper understanding of how various factors influence hazard estimates at specific locations. This research will be crucial for improving how large-scale hazard mapping can better support risk assessments for cultural heritage. The vulnerability model could be further validated in other countries to broaden the applicability of the findings. Moreover, given the significant role of the vulnerability component in determining risk, integrating more detailed artistic and cultural profiles for each site could enable the development of a more sophisticated and nuanced vulnerability assessment approach.

7. Conclusions

This work presented a comparative study on flood risk assessment of cultural heritage in two European countries: Portugal and Italy. The objectives of the study are twofold: first, to evaluate how different spatial resolution hazard maps influence the flood risk assessment of cultural heritage assets, and second, to establish a common procedure for estimating flood risk on cultural heritage in the two different countries. Although the required level of detail for such asset-by-asset assessment does not match with the resolution of global and continental hazard mapping, this study could be taken as a starting point for decision-makers to rapidly identify assets or areas that need a more detailed investigation. The approach taken in this study strikes a balance between the need for detailed assessment and the practical limitations of data availability and cross-country applicability.

The significance of this study extends beyond the technical boundaries of flood risk assessment. By adopting the perspective of end-users of official data and established methodologies, rather than that of technical specialists, this research highlights uncertainties and limitations of available data and models. A key outcome is the demonstration of how different hazard data sources can lead to substantially different risk assessments for the same cultural heritage assets, raising important awareness about the proper use of flood risk data by non-technical users. While flood hazard maps, vulnerability assessments, and exposure data are increasingly accessible, each comes with specific uncertainties and limitations that must be considered for reliable application. Overall, the study underscores the importance of producing high-quality hazard maps on a large scale. Such maps are essential for effectively assessing the risk to cultural heritage and complying with the Directive 2007/60/EC of the European Union, which explicitly emphasizes the need to mitigate flood risk, including the protection of cultural heritage. Moreover, following the Directive, high-resolution hazard maps are typically generated only for areas with significant potential flood risk, often overlooking the spatial distribution of cultural heritage sites, an aspect that should be taken into consideration in the development of those maps.

CRediT authorship contribution statement

Elisa G.L. Nobile: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Rui Figueiredo:** Conceptualization, Methodology, Writing – review & editing. **Chiara Arrighi:** Conceptualization, Methodology, Writing – review & editing. **Xavier Romão:** Conceptualization, Writing – review & editing, Supervision. **Mario L.V. Martina:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105236.

Data availability

Data will be made available on request.

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