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A GIS-based flood damage index for cultural heritage

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ABSTRACT

Evaluating potential consequences of floods on cultural heritage is one of the objectives of the 60/2007/EC Floods Directive. Nevertheless, the peculiarities of cultural heritage in terms of data availability, exposure values and vulnerability, make flood damage and risk analyses rarely applied. This work aims at developing a GIS-based Flood Damage Index for Cultural Heritage (FDICH) that (i) weights exposure based on the level of listing, (ii) weights vulnerability based on ad-hoc taxonomy, (iii) provides a damage density per unit surface instead than a point classification. FDICH is intended for large scale applications, e.g., regional or District ones, to identify damage hotspots and support risk mapping and management. The method is applied to the Po River District Authority, the largest in Italy, within a project framework for flood damage analysis of all exposed assets. In the territory of the district, a new spatial database of cultural heritage counting ca. 125,000 items is created and enriched with exposure and vulnerability attributes. The results allow for identifying 5 main cultural heritage damage hotspots and the calculation of FDICH shows the potential for cross-compare damages at District but also al local scales, for prioritization of mitigation measures.

1. Introduction

Floods are among the costliest natural hazards [1]. They affect numerous human structures, infrastructures, and natural environments. The urgent need of understanding and managing current and future flood risk has fostered research in the assessment of flood damages in the last decades which yielded many vulnerability models [2,3]. Vulnerability models have been developed for most of exposed assets, and are dominated by damage functions for buildings [4–8], just to cite a few examples.

However, flood impacts on cultural heritage (CH) have been rarely explored by research with respect to other types of hazards, e.g., earthquakes, and in contrast with the growing concerns related to climate change [9–11]. Moreover, cultural heritage can be severely affected by flooding with the peculiarity that (i) the direct tangible losses, such as the detachment of painted surfaces, can be irreversible, (ii) the intangible losses, i.e. historical, spiritual, aesthetic, and social values affected, often lead to indirect economic losses, including loss of livelihoods [12–14]; [24] and (iii) replacement costs are hardly estimated for assets which are unique and outside of the market. These challenging aspects make flood risk assessment of cultural heritage rarely applied. Nevertheless, the European Floods Directive [15] asks the countries to evaluate the potential consequences of floods also on cultural heritage.

The examples of flood damage and risk analysis to cultural heritage can be subdivided by the scale of analysis from global to single-asset. Flood risk of cultural heritage has been recently analysed at global scale for UNESCO World Heritage Sites (UNWH) [12] showing

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that 21% of UNWH cultural sites are exposed to floods and 2% is at extreme flood risk. Analyses have been carried out at regional scale in Spain and at national scale in Portugal with a semi-quantitative approach based on hazard maps and vulnerability classification of heritage typology [16,17]. At site scale, a flood risk framework has been applied to the historical city of Alzira (Spain) with a catalogue of morphological and constructive characteristics of monuments [25], to the historical city of Florence, (Italy) with a distinction of cultural buildings and contained artworks [18]. and to the Sucevita catchment (Romania), which hosts UNWH monasteries [19]. Asset-specific, component-based flood vulnerability functions have been developed for two churches in Portugal [20].

Large scale analysis, e.g., national, or regional usually adopt simplifying hypotheses on the degree of vulnerability of cultural heritage and on its relative importance, to identify high risk hotspots. At the Italian level the institute for environmental protection and research (ISPRA) identifies cultural heritage exposed to flood and landslides as one of the risk indicators by cautiously equalling to 1 the degree of loss for all CH assets [27]. Site scale or single-asset analyses deeply investigate materials, presence of artworks etc. and require detailed inspections. For the common purposes of the EU Flood Risk Management Plans issued by the river district Authorities, site scale or single-asset analyses are not possible due to the large extent of territory to be covered. However, also the existing national or regional approaches which map points with different degrees of impacts or risk, lack of the potential of being integrated with other damage metrics, such as residential or agricultural losses, which are expressed as monetary damages per unit surface. The need of spatial integration of multiple damages requires a spatial flood damage metric for cultural heritage.

The overarching objective of this work is developing a damage metric for cultural heritage that (i) overcomes the point layer representation, (ii) helps in identifying geographic hotspots rather than single high-risk objects, (iii) ranks damage levels, i.e., a combination of exposure and vulnerability, rather than counting the number of assets affected as they were all the same. The damage metric with such a conception is specifically designed for application at large scales, e.g., the scale of the flood risk management plans, but with a sub-municipal output resolution compatible with local assessment of flood mitigation measures. A specific objective necessary for the demonstration of the method is also the creation of a cultural heritage spatial database with a taxonomy that supports flood damage analysis. The method is applied to the Po River Hydrographic District in Northern Italy within the MOVIDA project framework [21]; [28].

2. Materials and methods

The methodology is summarized in Fig. 1. First, a screening of all possible data sources for cultural heritage data in the study area is carried out to create a new spatial database with a clear taxonomy. Second, exposure and vulnerability are classified, and new attributes are associated to the cultural heritage spatial database. Finally, the intersection with flood hazard data yields the spatial damage index for cultural heritage. Sections 2.1-2.5 describe the study area and the data collection, the data taxonomy, the exposure and vulnerability classification, and the damage index respectively.

2.1. Study area and data collection

The Po River District (Fig. 2, a) is located in Northern Italy and bounded by western and central Alps and the Adriatic Sea. It is the largest catchment in Italy with a surface area of ca. 86,900 km^2. It includes 8 administrative Regions, one autonomous province and 3348 municipalities where 19,85 million inhabitants live. 40% of the national GDP is produced in this area. The Po River District is subdivided into 154 flood-prone areas called APFSR (Areas at Potentially Significant Flood Risk) of which 21 are of District direct competence, 130 are of regional interest, and 2 are of interregional interest (Fig. 2, b).

As in all the national territory, cultural heritage is widespread in the district, with different typologies, styles and periods of constructions. At first, research of all possible sources of cultural heritage data in open repositories and cartographic data portals was carried out. The database of the Italian Ministry of Culture (MIC), the UNESCO website and the cartographic data portals of four Regions contained useful information related to cultural heritage that are summarized in Table 1. The cartographic data portals of

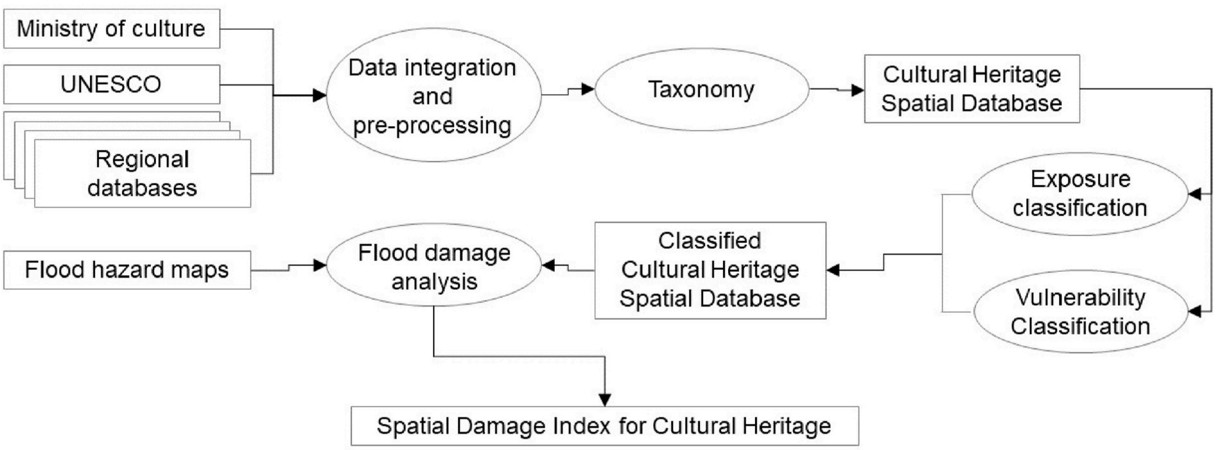

Fig. 1. Methodological workflow.

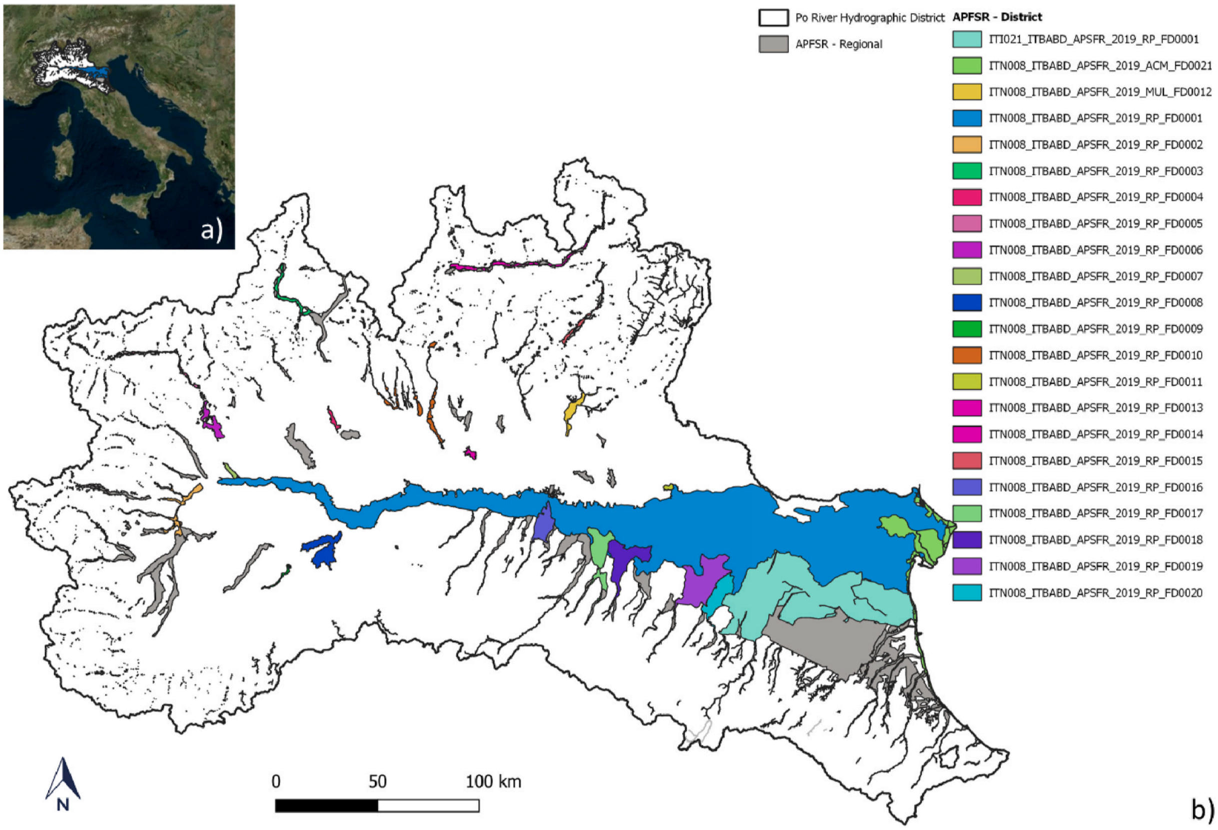

Fig. 2. Setting of the study area in Northern Italy (a) and extension of the areas at potentially significant flood risk (APFSR) (b).

Veneto, Liguria and Tuscany did not provide additional information but were included in the national MIC database.

The Regional data in Table 1 were pre-processed and checked to identify possible superimposition or duplication of items within the same dataset and among datasets. Both name and georeferencing where cross-checked to account for cultural heritage (CH) assets which share the same location but do not coincide, e.g., two different museums in the same building. Items with coincident coordinates and asset name were removed within the same dataset (less than 2% of points was removed). Finally, all the pre-processed sources were merged, and again coincident point coordinates and asset name were checked in order to avoid duplication. No duplication of assets was found between the national and regional databases. The dataset obtained counted 124974 features.

2.2. Cultural heritage data taxonomy

The original 14 layers (national MIC dataset, UNESCO and 12 regional datasets) had different attributes and description and in most of the cases only the name of the item was available, however a classification of heritage typology was considered necessary for damage analysis, thus a new GIS layer taxonomy was created. Cultural heritage assets were classified with a semi-automated GIS selection procedure into 10 categories, namely (i) religious architecture, (ii) residential and tertiary architecture, (iii) fortified architecture, (iv) rural architecture, (v) museum, (vi) open space, (vii) monument, (viii) infrastructure and plant, (ix) industrial and productive architecture, (x) archaeological site. The typology of items included in each category is shown in Fig. 3.

The typological classification was obtained with the following step-procedure:

1) First, based on pre-existing classification of the original source dataset (where available); e.g., 'description' = 'palace' was classified as "Residential and tertiary architecture"
2) Second, based on the analysis of the name of the item by string selection of the most frequent toponyms, e.g., 'name' = 'Church of St. Catherine' was classified as "Religious architecture"
3) Third, manually for the remaining items (without typology and/or infrequent toponyms); e.g., 'name' = 'hemp mill' (*canapificio* in Italian) was classified as "Industrial and productive architecture"

The classification procedure has some degree of uncertainty itself for the following reasons:

- In case of classification of step 3, the name alone may not allow univocally assigning a category;

Table 1
List of cultural heritage geographic information data collected in the study area.

Region	Dataset	Source	Access	Number of items
Italy	Ministry of Culture	http://vincoliinrete.beniculturali.it/vir/vir/vir.html?listaBeniImmobili=392733	Available on request	59115
Global	UNESCO World Heritage sites	https://whc.unesco.org/en/syndication	Open access	71
Emilia Romagna	Cultural heritage (Regional Secretariat of the Ministry of Culture)	https://www.patrimonioculturale-er.it/webgis/	Open access	9584
	Art and Culture places (Regional Tourist Office)	https://dati.emilia-romagna.it/dataset/arte-e-cultura–f97ad51b	Open access	4331
	Archaeological complexes (Regional Landscape Plan P.T.P.R)	https://datacatalog.regione.emilia-romagna.it/catalogCTA/dataset/ptcp-art21a-complessi-archeologici-1496228620123-6719	Open access	14
	Museums (Regional institute for natural and cultural heritage)	https://dati.emilia-romagna.it/dataset/musei-emiliano-romagnoli–1942770d	Open access	542
Lombardy	Historical and monumental heritage database (Regional Cartographic office SIRBeC)	https://www.geoportale.regione.lombardia.it/metadati?p_p_id=detailSheetMetadata_WAR_gptmetadataportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_detailSheetMetadata_WAR_gptmetadataportlet_uuid=%7B29DA690D-D717-4D66-ABEF-6F8FAFAFD06F%7D	Open access	16693
	Protected Architectures of particular interest (Institute for Restoration and Regional Secretariat of the Ministry of Culture)	https://www.geoportale.regione.lombardia.it/metadati?p_p_id=detailSheetMetadata_WAR_gptmetadataportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_detailSheetMetadata_WAR_gptmetadataportlet_uuid=%7BF1B34AA7-33C4-4F08-8781-755C48FC1B17%7D	Open access	11646
	Archaeological complexes (Regional Landscape Plan P.T.P.R)	https://www.dati.lombardia.it/Territorio/Presenze-Archeologiche/tiig-muk3	Open access	1043
	Museums	https://www.geoportale.regione.lombardia.it/metadati?p_p_id=detailSheetMetadata_WAR_gptmetadataportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&_detailSheetMetadata_WAR_gptmetadataportlet_uuid=%7B0AEC2750-E51E-4DF5-937C-934FBB99A95D%7D	Open access	260
Piedmont	Architectural and urban heritage (Regional Cartographic office)	http://www.geoportale.piemonte.it	Open access	20636
	Archaeological complexes (Regional Landscape Plan P.T.P.R)	http://www.geoportale.piemonte.it/geonetworkrp/srv/ita/metadata.show?id=3836&currTab=rndt	Open access	127
	Museums in the city of Turin (Municipal Office)	http://geoportale.comune.torino.it/geonetworkcoto/srv/ita/metadata.show?id=942&currTab=rndt	Open access	51
Valle d'Aosta	Cultural buildings (Regional Secretariat of the Ministry of Culture)	https://www.regione.vda.it/cultura/patrimonio/richieste_autorizzazioni_fotografiche/riproduzione_documentazione_i.aspx	Available on request	1077

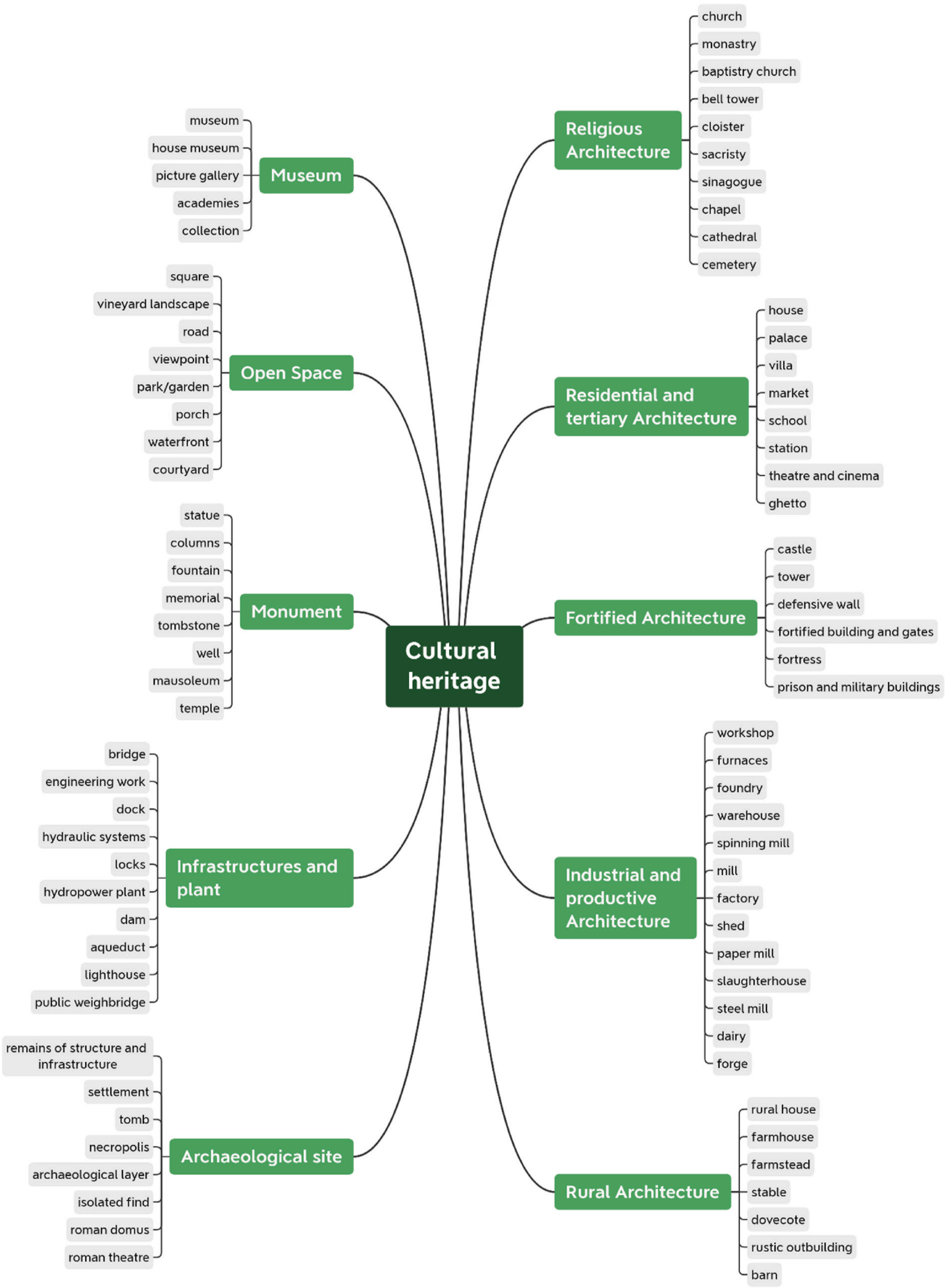

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Fig. 3. Taxonomy of tangible cultural heritage categories created for the classification of the dataset in the Po River Hydrographic District.

- Some cultural heritage assets might have had multiple functions during their life, e.g., a religious building transformed into a school. In this case the most recent use has been used for classification, because it is assumed that the main original traits have been lost;
- Some cultural heritage assets might be composed by multiple parts, e.g., a villa with a park. In this case the category potentially suffering more flood damage has been assigned to the item; in the example, "residential architecture" was indicated, rather than "open space".

2.3. Exposure

Exposure is usually defined as the position of an asset with respect to the inundated area and its value. For residential buildings footprint area is considered as key variable for estimating exposed value through market prices or replacement costs. For cultural heritage the determination of value is not an easy task, especially at River District scales, while example of prioritization of heritage items is possible at the single-asset level [26]; in fact, cultural heritage significance can range from the UNESCO World Heritage Site designation to CH items that are of interest to local communities only [22]. Finally, CH value is not strictly related to areal extension.

In this work a qualitative distinction of exposure values is based on their original classifications, i.e., the level of listing, which allow identifying three exposure categories: (i) world significance (UNESCO), (ii) national significance (MIC dataset), (iii) local significance (datasets identified at regional and sub-regional levels). Corresponding exposure scores E_i equal to 40 (UNESCO items), 2 (national items) and 1 (regional and sub-regional items) were subjectively assigned on the basis of expert judgment of the Regional Secretariats of the Ministry of Culture, involved as advisory board in the MOVIDA project, during group meetings and then revised. The exposure scores here adopted do not only considers the physical damage usually accounted in damage analysis, but includes considerations about potential indirect impacts in the territory, i.e., loss of revenues related to tourism activities, with a holistic perspective.

2.4. Vulnerability

Vulnerability is the degree of harm occurring on a flooded item. Standard vulnerability functions used for residential buildings are not applicable to cultural heritage. At the River District scale, without the possibility of inspecting and understanding the main features of 124974 CH assets, the vulnerability is expressed in qualitative terms through classes and corresponding scores based on the average susceptibility of constructive typologies, average finishing levels, materials, and presence of contents (e.g., artworks, pieces of furniture, etc.). The approach recalls the methods used for national scale risk assessments [16,17] but with a different vulnerability classification based on the peculiarities of Italian cultural heritage.

Four vulnerability classes and respective vulnerability scores V_i have been introduced:

1) Very high vulnerability. Assigned to CH assets characterised either by architectonical details, above-average finishing levels, precious and water-sensitive construction material (e.g., wood) and/or significant presence of fragile contents, artwork, pieces of furniture in susceptible materials (e.g., canvas, paper, wood etc.) which are expected to undergo very serious damages due to the contact with water. Score = 1.
2) High vulnerability. Assigned to assets characterised either by limited architectonical details, average finishing levels, more resistant construction material and with limited presence of susceptible contents, which are expected to undergo serious damages due to the contact with water. Score = 0.5.
3) Medium vulnerability. Assigned to assets characterised either by poor finishing levels, resistant construction material and without contents, which are expected to undergo modest damages due to the contact with water. Score = 0.25.
4) low vulnerability. Assigned to assets characterised by limited built structures and normally exposed to weather conditions which are expected to undergo very limited damages due to the contact with water. Score = 0.125.

Religious, residential fortified architectures, and museums were assigned to the very high vulnerability class. Industrial, rural architectures and monuments were assigned to the high vulnerability class. Archaeological sites and infrastructures/plants were assigned to the medium vulnerability and finally open spaces to low vulnerability.

By combining exposure and vulnerability scores a qualitative damage score w_i was obtained for each combination of cultural heritage category (vulnerability) and level of listing (exposure) as shown by the damage matrix of Table 2.

The combination of exposure value and vulnerability in the damage matrix of Table 2 also allows a classification of cultural heritage assets in terms of damage class, i.e., very high damage ($w_i \geq 10$), high damage ($5 \leq w_i < 10$) moderate damage ($0.25 \leq w_i < 5$), and low damage ($w_i \leq 0.25$). Damage is thus expressed in terms of reference unit damage, that can be visualized as a church or museum of local interest affected, or as a monument of national interest affected, which all have a damage score w_i equal to one. The damage scores here obtained reflect the characteristics of the study area and transferring the method to another region would probably require an adjustment to obtain scores that fit the peculiarities of the area under study. Moreover, vulnerability scores also reflect the extent of the study area and the level of available information on CH assets. For national/regional application only the building type is usually available, while local analysis which considers a limited number of assets can properly refine vulnerability information and scores through rapid visual survey [23].

2.5. Spatial flood damage index for cultural heritage

To overcome the point analysis usually adopted to rank cultural heritage risk at different scales, in this work we propose a spatial

Table 2
Damage matrix for cultural heritage, the final damage score w_i is shown in shades of blue.

Damage score w_i			Exposure Score E_i World 40	National 2	Local 1
Vulnerability Score V_i	Religious architecture Residential and tertiary architecture Museum Fortified architecture	1	**40**	**2**	**1**
	Industrial and productive architecture Rural Architecture Monument	0.5	**20**	**1**	**0.5**
	Archaeological area Infrastructures and plants	0.25	**10**	**0.5**	**0.25**
	Open spaces	0.125	**5**	**0.25**	**0.125**

Flood Damage Index for Cultural Heritage (FDICH) which is considered more suitable for spatial planning and flood risk mitigation at River District scale. The reference unit of territory is here the census polygon, it covers the whole national territory and has a size depending on the population density, smaller in urban settlements where it might coincide with a building block and larger in rural/wild areas. The FDICH combines the importance and the vulnerability of cultural heritage asset and the flooded surface of territory in the census polygons with a weighted sum that can be calculated in a GIS environment.

$$FDICH_k = \frac{\sum_{i=1}^{n} w_i \bullet CH_i}{A_k} \tag{1}$$

where CH_i is the i-th element of the flood-exposed cultural heritage all-ones vector the census polygon, n is the number of exposed cultural heritage assets contained in the k -th census polygon, w_i is the damage score of the asset (Table 2) and A_k is the surface flooded area in the census polygon expressed in km^2. The numerator in Eq. (1) represents the absolute qualitative damage in reference unit damage of the k-th census polygon. Thus, FDICH is expressed as reference unit damage per km^2 of flooded area. Flood hazard maps for high-, medium- and low-probability are provided by the District and represent the most updated and high-resolution hazard information in the study area.

The type of result provided by FDICH is a spatial damage density which can be equally high when many cultural heritage assets with low damage score w_i lie in a flooded area or when few cultural heritage assets with high w_i are present.

Flood depth, which is usually the main driving factor for damage models, is not accounted for in FDICH. This is due to the difficulties in generalizing damage functions for assets which are different from standard buildings and have peculiarities that can be identified only at single asset level. Moreover, the point representation, without a clear identification of the surface extension of the asset creates high uncertainties in assigning water depths to each asset, which might have significant variations from cell to cell (i.e., in raster maps with 1–5 m resolution). Thus, a cultural heritage asset is considered as affected and damaged if its representative point location lies in the inundated area.

2.6. Sensitivity analysis

The scores assigned to exposure and vulnerability classes, although agreed by experts, are subjective, thus a sensitivity analysis is required to understand how FDICH might change when w_i changes. In order to better understand how FDICH is affected by the selected scores the following aspects are investigated:

- is the UNESCO exposure value of 40 disproportionate with respect to other types of CH? The sensitivity analysis is carried out by removing a UNESCO site for a test area to understand the changes to FDICH quantiles;

- are specific high-vulnerability classes (e.g., religious/residential architectures) driving the FDICH quantiles of the location of the damage hotspots? The sensitivity analysis is carried out by removing the categories other than religious/residential architectures for a test area to understand the changes;
- what happens to FDICH if local and national assets are assigned the same exposure score of 1?
- What if all the CH items are considered of equal damage regardless of any classification?

The analyses above look for the changes in FDICH both in relative and absolute terms and since one of the main purposes of the work is prioritizing mitigation measures, the sensitivity is critical to understand issues in identifying damage ranking. This aspect is investigated by means of rank correlation.

3. Results and discussion

Based on the perimeter of the low-probability hazard maps in the District, 37381 out of 124974 cultural heritage assets are exposed to floods, i.e., almost the 30% of the items. 24 Items are listed as UNESCO World Heritage Sites, 21503 are of national interest and the remaining are of local interest. The most exposed categories are the residential architectures (17484 assets) and the religious architectures (10382 assets). Table 3 shows the exposed cultural heritage assets per category and level of listing.

Fig. 4 shows the spatial distribution of cultural heritage per category and the exposure (i.e., level of listing). It can be noticed that a significant number of items is located in the area comprised between the mid catchment and the coast, while in the upper catchment flood prone areas are narrower stretches. Different asset categories are evenly distributed with some clusters of residential architectures in the main cities and rural architectures in the lower floodplain. With respect to other study areas, e.g., the mainland Portugal [16] the number of cultural heritage items is surprisingly high in the study area. On one hand, the historical and socio-economic contexts play and important role, but on the other hand, the criteria used to list heritage in national or local databases can be crucial as well. Moreover, the use of local (regional) sources does not ensure that the same criteria have been adopted across regions. In this sense, some differences have been observed, e.g., more attention to rural and residential architectures in the Emilia-Romagna floodplains, or more attention to minor shrines in Piedmont. However, these inhomogeneities cannot be resolved without the creation of a unique database based on agreed criteria. This aspect highlights a significant gap in the knowledge base for risk assessment of cultural heritage.

Another significant aspect emerged during the analysis is the limitation of the point geometric representation of cultural heritage items. Again, some inhomogeneities have been observed. The Lombardy region is the only one providing for some assets type also a polygon shapefile instead of a point shapefile. For flood risk analysis this is a crucial aspect in the exposure assessment. In fact, large cultural properties, such as palaces with gardens/outbuilding, castles or even monasteries might have significant areal extent and consequently a higher probability of being flooded in some parts of the overall asset which are not captured by a centroid point. Adding to a point feature the surface area attribute, that can be turn into a geometric buffer could improve the exposure analysis. However, the surface area is not commonly available, except in the UNESCO database [12].

The cultural heritage density map weighted by the damage score w_i identifies some significant hotspots at district scale for a low probability flood, as shown in Fig. 5. The density map is processed with a standard Kernel Density Estimation algorithm available in QGIS. Four out of the five hotspots identified are located in the Emilia Romagna Region (a, b, c, e) and the other is in Lombardy (d). The area (a) is the city of Ferrara built in the Renaissance period and listed as UNESCO World Heritage since 1995. Some listed Renaissance palaces are also located outside of the city very close to the Po River. The area (b) comprises the small art cities of Guastalla, Novellara and Gualtieri with a significant amount of heritage of national interest again dating back to the Renaissance period. Guastalla and Gualtieri in particular are located at 1 km distance from the Po River. The city of Piacenza (c) also hosts numerous heritage asset of national interest. Between hotspots (c) and (b) several small cities (Parma, Reggio Emilia and Modena) feature cultural heritage assets of interest as shown by the lighter color. The cities of Mantua and the surrounding Sabbioneta (d) and Ravenna (e) are both UNESCO World Heritage sites, Mantua and Sabbioneta for urban, architectural and artistic realizations of the Renaissance and Ravenna for the early Christian monuments decorated with mosaics dating back to the 5th and the 6th century aD. It is worth mentioning that Ravenna and Ferrara are located in APFSR of regional interest.

The FDICH and its percentiles have been calculated in the 21 APFSRs of District interest (Fig. 6 panel a). Fig. 6 shows in detail two

Table 3
Exposed cultural heritage per category and level of listing (low-probability flood) in the Po District.

Cultural Heritage category	Number of assets exposed	UNESCO	UNESCO %	National	National %	Local	Local %
Fortified Architecture	1766	–	–	1019	57.7	747	42.3
Industrial Architecture	963	2	0.2	365	37.9	605	62.8
Residential and Tertiary Architecture	17484	8	0.0	11558	66.1	5918	33.8
Religious Architecture	10382	9	0.1	5653	54.5	4720	45.5
Rural Architecture	3075	–	–	1436	46.7	1639	53.3
Archaeological site	746	5	0.7	293	39.3	448	60.1
Infrastructure and Plants	820	–	–	400	48.8	420	51.2
Monument	678	–	–	267	39.4	411	60.6
Museum	654	–	–	52	8.0	602	92.0
Open Space	813	–	–	469	57.7	344	42.3

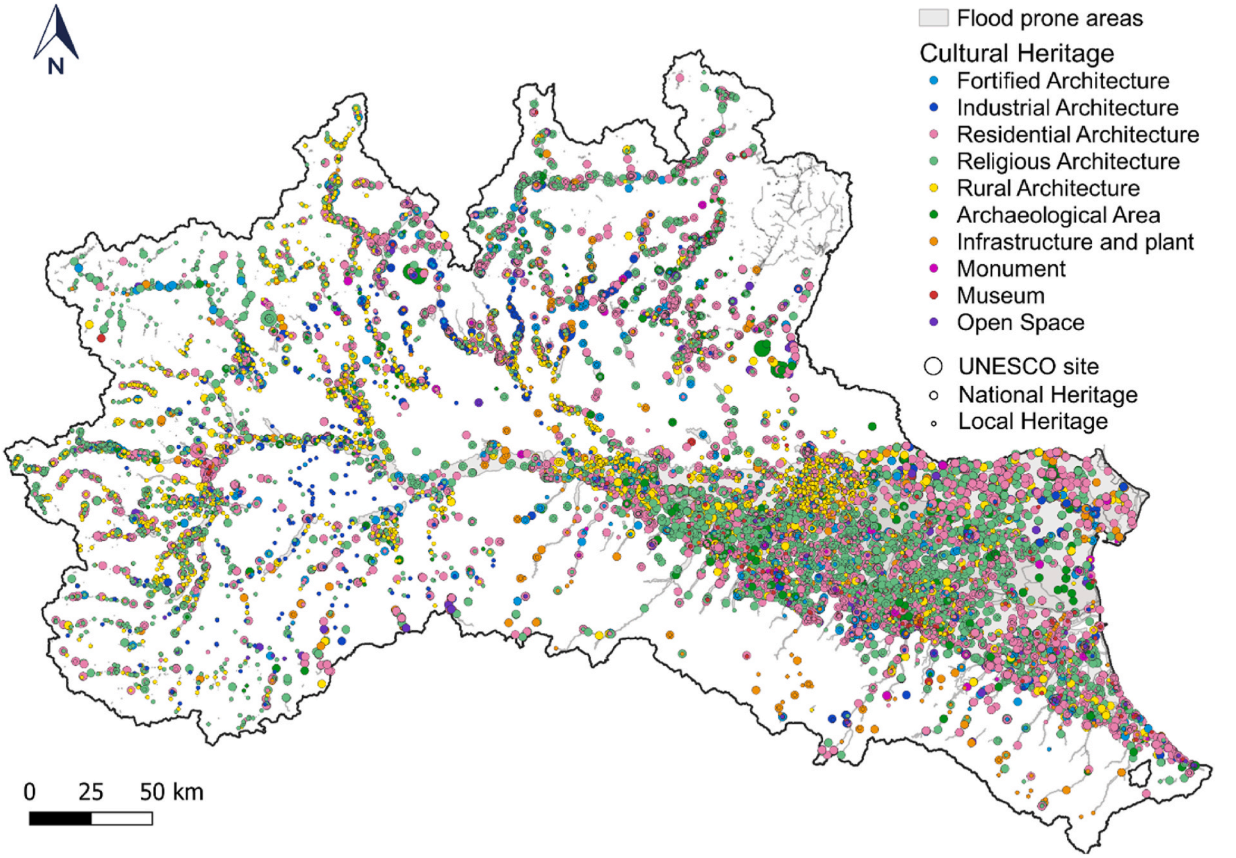

Fig. 4. The 37381 cultural heritage assets exposed for a low recurrence interval flood according to the proposed taxonomy (point color) and level of listing (point size). Details of specific areas available as supplementary figure.

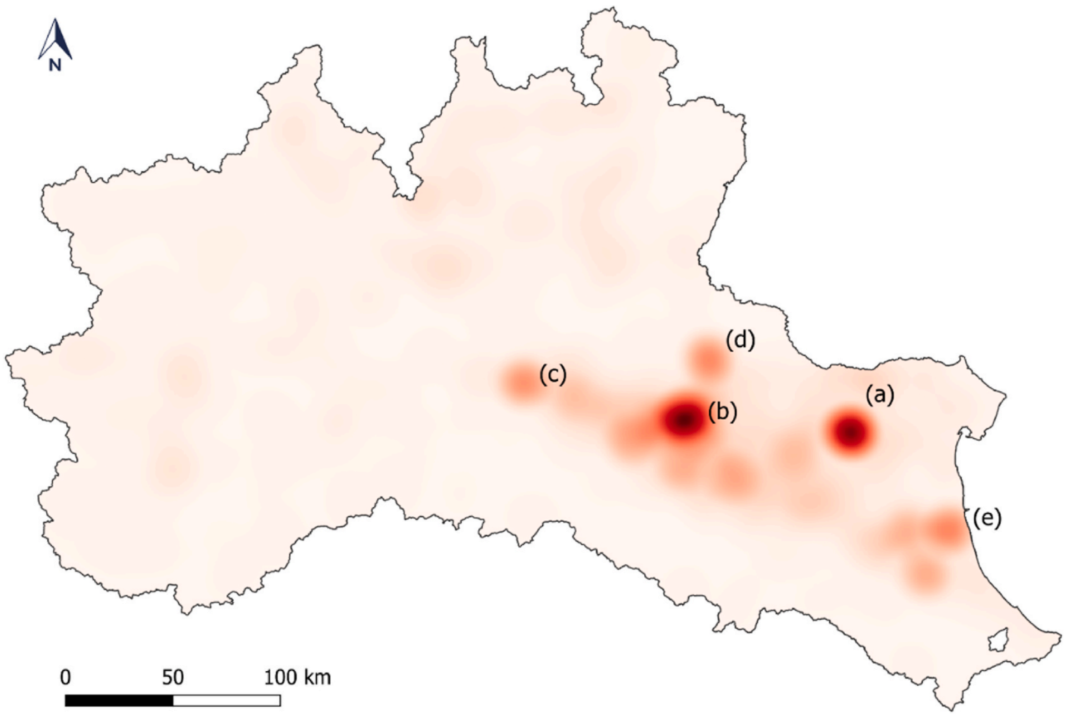

Fig. 5. Cultural heritage point density map at District scale exposed for a low recurrence interval flood scenario. Hotspots are Ferrara (a), the area of Guastalla, Novellara and Gualtieri (Province of Reggio Emilia) (b), Piacenza (c), Mantua (d), Ravenna (e).

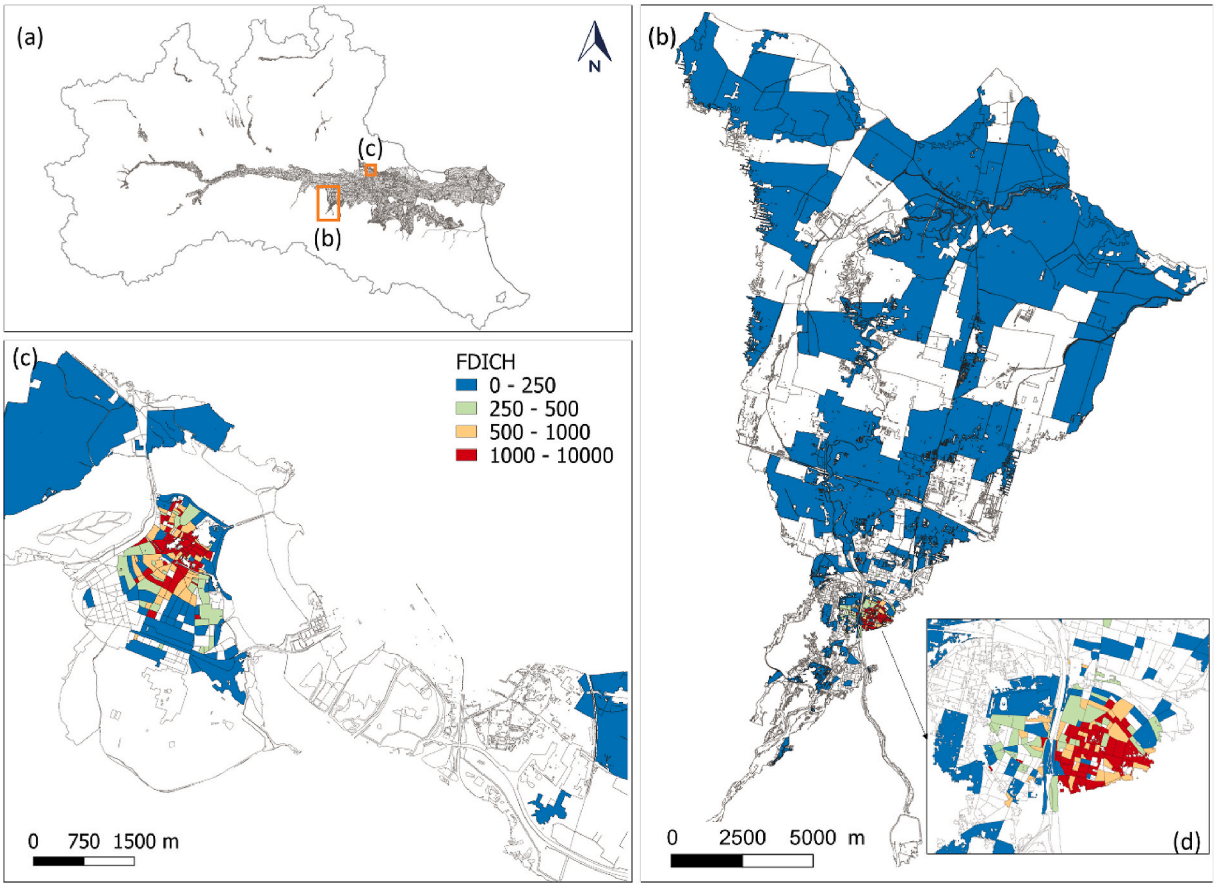

Fig. 6. Flood Damage Index for Cultural Heritage (FDICH) for two example areas in the District (a), the APFSR of Parma (b) with a zoom on the city centre of Parma (d) and the APFSR of Mantua (c).

examples of results in APFSRs with different characteristics for a low recurrence interval flood scenario. The first one (Fig. 6, panel b) is the Parma APFSR on the Baganza River, a large area characterised by the main city of Parma (inset of panel d), some minor settlements and large agricultural areas. The second one is the Mantua APFSR (Fig. 6, panel c) on the Mincio River and lakes which has a much smaller size and mostly includes the urban and suburban area of the city of Mantua. It has been identified as a damage hotspot for cultural heritage (Fig. 5, hotspot area d). In the maps of Fig. 5 the use of the same color scale highlights significant hotspots for damage to cultural heritage as shown by the red shades of FDICH. Nevertheless, the distributions of FDICH in the two APFSRs are quite different (see also Table 4). The 10th percentiles of FDICH are 4 and 66 for Parma and Mantua respectively. The 90th percentiles of FDICH are 1542 and 2599 for Parma and Mantua respectively. Thus, although the historical city centres are damage hotspots in both cases, the relative comparison of FDICH percentiles clearly identifies Mantua as more significant in terms of cultural heritage damage. Mantua historical city centre is in fact a UNESCO heritage site, as demonstrated by the high concentration of protected historical architectures of which 333 of national interest and 639 of local interest within a surface area of ca. 5 km^2. Moreover, the most frequent cultural heritage categories are the residential architectures (749 assets) of national interest which fall into the very high vulnerability class (Table 2). The blue census polygons in panels b and c (Fig. 6) represent the presence of sparse cultural heritage items.

Table 4 shows the number, typology, and damage class of cultural heritage assets in the two areas of Parma and Mantua for a low probability flood scenario. It can be noticed that the APFSR of Mantua hosts a significant number of exposed assets, for some categories comparable to Parma, but within a much smaller inundated area (8.9 km^2 vs 116.1 km^2). Mantua has a particularly high number of residential and tertiary architectures (749) and fortified architectures (32) with respect to Parma. Moreover, the number of high-damage assets is almost the same in the two areas (970 and 929 in Parma and Mantua respectively). This implies that in absolute terms the two APFSR suffer the same damage to cultural heritage for a low probability flood scenario. In fact, the APFSR of Parma and Mantua experience an overall absolute damage of 798 and 796 reference unit damage per km^2 respectively. If we assume to prevent flooding for a low probability scenario in the two APFSR, the benefit in terms of damage reduction is equivalent in Parma and Mantua. Nevertheless, the costs for protecting flood prone areas of ca. 110 km^2 (Parma) or ca. 9 km^2 can be significantly different. In this sense, if we assume to protect from flooding one km^2 of APFSR at a fixed cost, the benefit is much larger in Mantua than in Parma, due to a significantly higher damage density expressed by FDICH (average FDICH equal to 571 and 1130 in Parma and Mantua respectively).

The sensitivity analysis is performed for the two APFSR of Mantua and Parma as representative of different territories, CH density, damage classes and listing types. Tables 5 and 6 show the results of the sensitivity analysis of FDICH to perturbations of w_i, E_i and types

Table 4
Number and type of cultural heritage assets exposed for a low probability flood in the two APFSR, FDICH significant values and indication of the total flooded surface A.

Cultural Heritage category	Number of assets Parma A = 116.1 km^2	Number of assets Mantua A = 8.9 km^2
Fortified Architecture	20	32
Industrial Architecture	10	9
Residential and Tertiary Architecture	581	749
Religious Architecture	292	134
Rural Architecture	45	2
Archaeological site	15	3
Infrastructure and Plants	19	3
Monument	17	14
Museum	21	5
Open Space	37	22
Level of Listing		
UNESCO	0	1
National	768	333
Local	289	639
Damage class		
Low damage	10	12
Moderate damage	77	31
High damage	970	929
Very high damage	0	1
FDICH (reference unit damage/km^2)		
Average	571	1130
Median	236	714
Maximum	4487	9585

Table 5
Sensitivity of selected FDICH percentiles for four cases in the APFSR of Mantua: when the UNESCO site is removed (a), when only religious and residential architectures are considered (b), when Exposure score E_i is put equal to one for both local and national assets (c), when $w_i = 1$ for all assets (d).

	baseline	(a)		(b)		(c)		(d)	
		UNESCO site removed	relative Difference %	Only religious and residential architectures	relative Difference %	Exposure score Local = National = 1	relative Difference %	$w_i = 1$ for all CH	relative Difference %
10th	64	66	−1	44	−32	47	−27	51	−21
20th	168	166	−2	139	−17	117	−30	130	−22
50th	714	714	0	644	−10	537	−25	546	−24
80th	1405	1400	0	1349	−4	1112	−21	1130	−20
90th	2644	2523	−3	2541	−4	1980	−25	1973	−25

Table 6
Sensitivity of selected FDICH percentiles for three cases in the APFSR of Parma: when only religious and residential architectures are considered (b), when Exposure score E_i is put equal to one for both local and national assets (c) when $w_i = 1$ for all assets (d).

	baseline	(b)		(c)		(d)	
		Only religious and residential architectures	relative Difference %	Exposure score Local = National = 1	relative Difference %	$w_i = 1$ for all CH	relative Difference %
10th	4	0	−100	2	−43	3	−34
20th	24	6	−74	15	−37	16	−33
50th	236	197	−16	146	−38	173	−27
80th	1111	1067	−4	665	−40	671	−40
90th	1553	1521	−2	900	−42	978	−37

of assets considered in terms of changes in some percentiles of the distribution of FDICH values in the census polygons.

The sensitivity analysis for Mantua (Table 5) shows a negligible effect in FDICH percentiles when the UNESCO site is removed. In fact, although the specific FDICH value in the census polygon reduces from 4473 to 1925, the distribution of FDICH is not affected. The effect can be different when the UNESCO site is in an isolated context without surrounding CH. In the District area most UNESCO sites are a historic portions of a city (e.g., Vicenza, Ferrara, Mantua etc.) or are inside an urban area (e.g., Early Christian Monuments of Ravenna). Only the sanctuary of Oropa and the Prehistoric pile dwellings around the Alps are not surrounded by the urban texture.

Reducing the damage analysis only to residential and religious architecture has instead a significant effect on lower percentiles of FDICH with up to −32% change and a limited effect on higher percentiles with ca. −4% change. This highlights the loss of information in some areas, mostly out of the denser urban area, due to the exclusion of several CH asset with low vulnerability. For the third case, when local and national CH are equalled in terms of exposure value, FDICH percentiles show a similar behaviour with a reduction of ca. −25% for all classes. When all CH are assigned the same damage score $w_i = 1$ the 80th percentile reduces of 20% while all other percentiles reduce between 21% and 25%.

The sensitivity analysis for Parma (Table 6) shows that reducing the damage analysis only to residential and religious architecture has a stronger effect on lower percentiles of FDICH (10th-20th) with values in 20% of the census polygons that are almost zeroed. This highlights the loss of information in rural areas where most CH assets are rural architectures, industrial architectures, infrastructure and plants, witnessing a different use of the territory. For the third case, when local and national CH are equalled in terms of exposure value, FDICH percentiles show again a strong reduction of FDICH values with all census polygons percentiles reducing of about −40%. For the case (d) when all CH is assigned a damage score of 1, i.e., regardless of listing and vulnerability classes, the changes in percentiles are pretty similar to case (c) showing that the damage index distribution has similar sensitivities to exposure classes and overall damage classes.

It is interesting to notice that the sensitivity of case b is significantly different in the two APFSR of Mantua and Parma because of their different areal extension and land use, mostly urban vs mostly rural respectively. Moreover, when local and national exposure scores are equalled, the FDICH values in Parma are much strongly affected than in Mantua because although the sum of CH assets is similar (1057 and 972 in Parma and Mantua respectively) Parma has a dominance of Nationally listed CH (768) with respect to Mantua (333). This means that the FDICH method here developed is more stable to changes in parameters and data in urban APFSR with high density of CH, typically religious and residential in historically developed textures, while mixed agricultural and urban APFSR with a more diverse type of sparse CH are more difficult to model. The sensitivity analysis in absolute damage terms for the whole APFSR is less marked in case (b) for both Parma and Mantua with a damage reduction of ca. −6% of reference unit damage. Instead, for case (c) Parma and Mantua have a damage reduction of −40% and −25% of reference unit damage per km^2 respectively. Similarly for case (d) the overall absolute damage value is more sensitive in Parma (−37%) than in Mantua (−23%).

If we look at the sensitivity maps of Fig. 7, we clearly notice that urban city centres are not significantly affected when we reduce

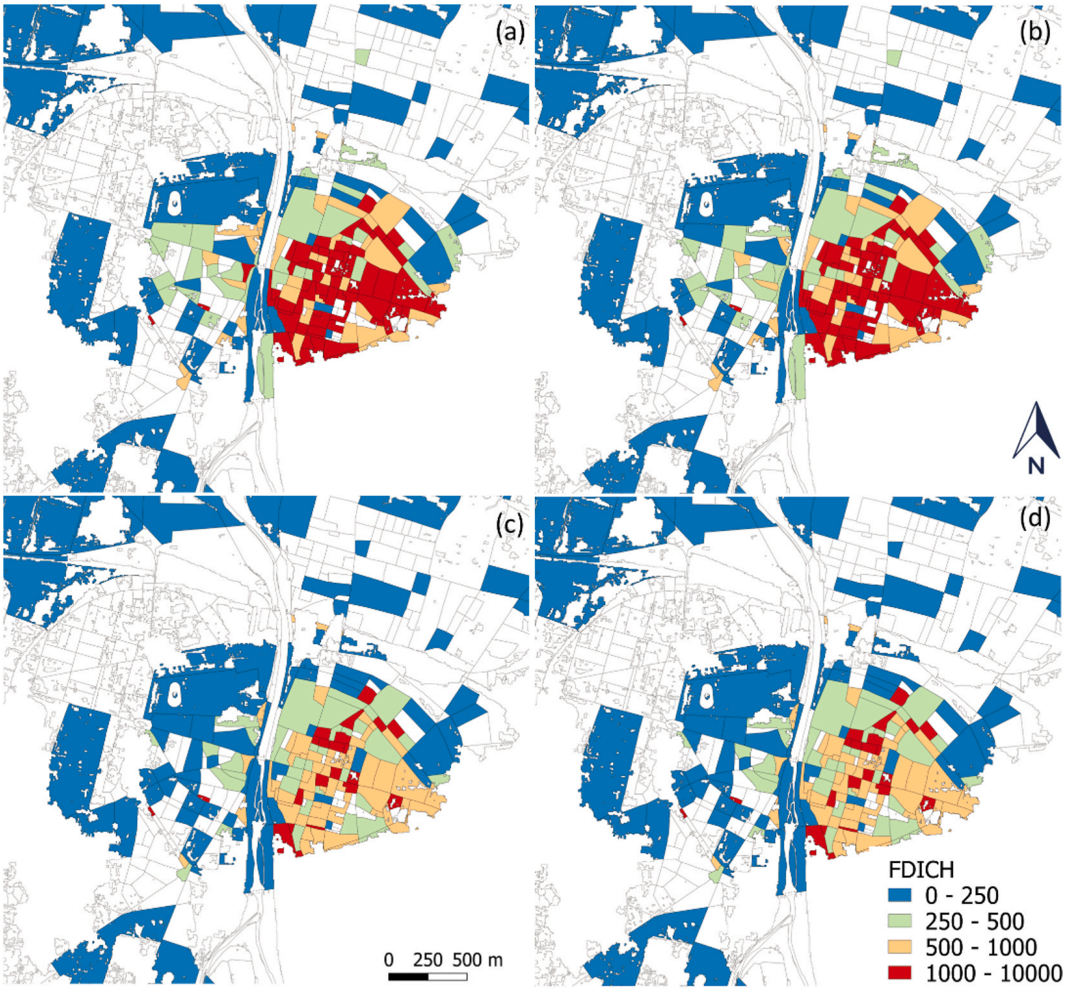

Fig. 7. Sensitivity of FDICH for the urban part of the Parma APFSR: baseline (a), only religious and residential architectures considered (b), national and local CH exposure values equalled (c), $w_i = 1$ for all assets (d).

from the baseline analysis (panel a, all CH types considered) the type of CH considered to religious and residential types only (panel b). Instead, when we equal national and local CH, reducing the exposure score of national ones, we see that the values of FDICH decrease with a reduction of the hotspot area in city centres (panel c). A similar change occurs when $w_i = 1$ for all assets (panel d).

Finally, the question is if the sensitivity of FDICH can compromise the identification of priorities for flood risk mitigation. In other words, if the sensitivity of FDICH, besides affecting absolute values and percentiles, as seen above, might confuse the relative values. To understand this aspect a Spearman's rank correlation between (i) baseline FIDCH values and cases (b, c, d) FDICH values in census polygons are calculated.

In Mantua APFSR the Spearman's rank correlation are 0.96, 0.99, 0.98 between baseline and case (b), (c) and (d) respectively. In Parma APFSR the Spearman's rank correlation are 0.96, 0.99, 0.97 between baseline and case (b), (c) and (d) respectively. Thus, the sensitivity of FDICH has a negligible effect on CH damage ranking, although the sensitivity analysis reveals relevant changes in FDICH percentiles and overall absolute damage especially in Parma APFSR. This shows the importance of a vulnerability and exposure classification agreed with main stakeholders to correctly identify CH flood damage priorities.

In light of the sensitivity analysis, the method appears adequate to identify the census polygons producing the higher CH damages and consequently provides a support for prioritization of measures. Moreover, while urban APFSR are less sensitive to a reduction of CH types considered or to a simpler damage classification ($w_i = 1$), rural or mixed ones lose significant information. This justifies the effort in (i) creating a complete CH database where not only the main urban assets are included, but also the local and low-vulnerability ones, such as those typically found in rural areas, and (ii) agreeing exposure and vulnerability scores with main stakeholders.

The analysis clearly identifies spatial hotspots of damage to cultural heritage with the following advantages:

(i) at APFSR scale it identifies the census polygons with the highest qualitative damage density to cultural heritage to be used for risk ranking and prioritization of local mitigation measures;
(ii) at District scale it identifies the most significant areas (hotspots) for prioritizing large-scale interventions;
(iii) FDICH expressed in reference unit damage per km^2 can be combined in a multi-criteria analysis with other damage categories, such as damage to residential buildings or agriculture, which are expressed in €/km^2, to build an overall damage index. This goes into the direction of spatially combining different damage metrics, to compare diverse territories rather than ranking CH points.

FDICH is not obviously intended as a quantitative or monetary damage metric, although the reference unit damage per km^2 can be considered as a qualitative metric, but is a useful tool for District Authorities to achieve the Floods Directive objectives in terms of damage mapping and risk management because it allows a direct comparison of different portions of territories in relative terms.

4. Conclusions

In this work a spatial Flood Damage Index for Cultural Heritage (FDICH), expressing the reference unit damage per km^2, e.g., a local church or museum, or national monument affected per unit surface, has been developed with the objective of providing a damage density metric that can be combined to other types of losses with the ultimate purpose of mapping and managing flood risk at large District scales. FDICH supports the comparison among different territories through spatial aggregation of damage, e.g. in census polygons or municipal areas, and the identification of damage hotspots which is not possible with the commonly adopted analyses whose outcome is a ranked point layer [16,17]; [12]. The procedure allows for the identification of damage hotspots at District and local scales.

To demonstrate the methodology on the Po River District, a new cultural heritage spatial database has been created by merging 14 different data sources, and enriched with a taxonomy of heritage types, listing level (here assumed as a proxy of exposure value) and vulnerability level. The combination of exposure and vulnerability classes identified damage scores for cultural heritage. The application demonstrates the capability of highlighting flood damage hotspots for cultural heritage at large scales but also at the scale of the single APFSR.

However, the analysis highlighted several limitations in flood damage analysis of cultural heritage related to data availability and quality and to vulnerability assessment. On the side of data, the main issues are:

- the lack of an official spatial database including different levels of listing (i.e., UNESCO, national and local ones), asset classification and description of the item which can support the understanding of vulnerabilities and values, not only for flood risk but also for multi-risk analyses (e.g., landslides).
- the use of point features, rather than polygons which does not allow for a realistic analysis of flood hazard because water depths might vary significantly from cell to cell especially when the areal extension is significant. This might imply that an asset of significant importance and areal extent is not considered exposed when, for instance, its main entrance door or the centroid are dry.
- Subjectivity and geographic inhomogeneity in listing cultural heritage of local interest, in absence of a unique official database.

On the side of exposure and vulnerability analyses the main limitations are:

- the subjectivity in assigning relative exposure values among local, national and international cultural heritage given the complexity of intangible values (e.g., historical, social, aesthetic, religious etc.)
- the subjectivity in assigning vulnerability values per categories rather than per feature, for assets that are sometimes unique and with peculiarities that can be understood only at single asset level.

- The lack of object-specific vulnerability models that link flood depths with expected damages with respect to other asset categories, with few exceptions for single asset analysis [20].
- The relevance of indirect impacts in areas with significant concentration of cultural heritage where socio-economic activities are tourism-oriented, e.g., in art cities [24].

In conclusion, further works should address the above limitations to give the necessary attention to cultural heritage exposed to natural hazards to bridge the gaps with respect to other types of assets. A general agreement on a method for assessing flood damages to cultural heritage and a homogeneous exposure dataset at national/European scale are strongly advocated to respond to the requirements of Floods Directive.

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.

Data availability

Data will be made available on request.

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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.2023.103654.

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