EDITOR – Prof. Mihai Niculita

General comment

You have now received three thoughtful reviews of your paper, and there is a need for major revisions. You already have proposed potential revisions, so I now invite you to make those changes to the manuscript. Please do this while tracking your changes. At the same time, please prepare a point-by-point response to the reviewers, as your revised paper will be sent back to the initial referees to ascertain their opinion of your changes. We very much look forward to receiving a revised manuscript.

Reply to Editor

We have carefully reviewed the manuscript according to the referees' suggestions. We provided below a point-by-point reply to each comment raised and where appropriate we made substantial changes to the text. Each comment is marked with **C followed by the number of the comment. Each reply is marked with R followed by the same number, e.g., C1 – R1.**

Reviewer 1 – Prof. Xavier Romão

General Comment

The study provides an interesting study that addresses the quantification of flood-related damage to cultural heritage assets in Florence. In this approach, the authors develop vulnerability functions for cultural heritage buildings and artworks, combining empirical data with synthetic modelling. While the topic is relevant and timely to current debates on heritage resilience and disaster risk reduction, the following comments highlight a few points that should be addressed in a revised version of the manuscript to increase methodological clarity and robustness.

C1- In Section 2.1, the authors refer that "the "content features" section of the survey focused primarily on the most common artwork types: panel or canvas paintings, frescoes, stone or wooden sculptures, and paper-based items", and that everything else is assigned to other "Other artworks". Assuming the authors are proposing a general methodology that could be applied in other scenarios outside the one they are using to illustrate their proposal, this seems to be an arbitrary decision that should be clarified or better discussed, at least. If the authors consider that in their case study, damage to metal- or textile-based artworks are negligible, this should be said, but it should also be highlighted that the methodology can be applied to any type of material as long as data to characterize the cost-related factors are available. Addressing this issue needs to also consider what is written in Section 2.4 on this matter. Moreover, if the authors decided not to include these other artworks because there are no data available to quantify these cost-related factors, this must be made clear, and the topic must be revisited in the discussion section to highlight the limitations of the presented results.

R1- The unit restoration cost of flooded artworks (Eq. 1) was obtained through two steps: 1) archival research in CRIA archive: in this step, for each type of artworks, we registered the most common operations necessary to restore the artworks; 2) the unit prices were derived by the current available price lists of restoration of artworks. The only exception was paper-based items (e.g., books and manuscripts), for which total restoration costs were provided by expert conservators (A. Sidoti, personal communication). From the archival research, mostly invoices of restoration of paintings on canvas, paintings on wooden panels, and wooden sculptures were found. Almost no data were available for metal or textile-based artworks. For this reason, even if we know that for example textile-

based artworks are severely damaged by flood, we decided not to include these artworks in our analysis. We introduce the parameter cost reliability index (CRI) (that considers the numbers of other works, not included in the total restoration cost) to keep track of this limitation. We clarified this aspect in section 2.1, 2.4 and in the discussion (sect. 4.4).

C2- In Section 2.2, the authors use the term "building's internal envelope", which is a rather unusual terminology. Do they mean "interior finishes"? This unusual terminology should be replaced across the manuscript.

R2 – The term "building's internal envelope" has been replaced with "interior finishes", as suggested. Moreover, as requested by other reviewers we worked also on other aspects related to the terminology to achieve a better consistency.

C3- In Section 2.2, when introducing Eq. (1), it should be referred that it is for each artwork k or the kth artwork, for clarity (otherwise k remains undefined).

R3 – The definition of k has been added into the text.

C4 - In Section 2.2, the authors should clarify the practical use implications of their restoration cost assessment framework. From my understanding of the proposed framework, it is not supposed to be used based on the availability of an estimate of the physical damage to a given artwork. This issue comes from the fact that 1) it is difficult to predict the actual level of physical damage that will occur if an asset is exposed to a certain water level (namely due to some of the uncertain factors listed by the authors such as floodwater contamination, the amount of water the artwork was submerged in, the duration, etc.) and 2) it is also difficult to estimate the level of physical damage of the damaged assets for which the authors have the repair cost values. In light of these issues, the practical application of the proposed framework seems to establish the repair cost of a given asset by assessing the expected water level that can be reached in a flood at the location of the asset, and it then assigns minimum and maximum values of the repair cost (which accounts for the referred uncertain factors) to the asset in case the water level reaches it. If this interpretation is correct, it should be clearly described in the manuscript. If not, the authors should clearly describe how the repair cost is established based on physical damage.

R4 - The minimum and maximum value of the restoration costs for each artwork type establishes a range of values to assess practically monetary damage assuming that an artwork is flooded (pending several uncertainties mentioned in sect. 2.2). Such monetary values also support (i) the estimation of maximum potential damage in a CH building (see Eq. 7) and (ii) the development of vulnerability functions assuming the occurrence of different flood depths in the building (section 2.4). This clarification has been added to section 2.2. The maximum potential damage for artworks for instance, is obtained by setting the maximum flood depth in a building in Eq. 7 (when w=Hmax) and therefore counting all the restoration costs for all types of artworks in that building. This is a practical use of the restoration cost to establish a maximum loss for a worst-case scenario. Otherwise, the restoration costs are used to determine the "shape" of the vulnerability functions.

C5- In Section 2.3, line 175, the parameter for opening heights ($h_{o,i}$) has an index i that is not defined. Note that, later, the letter i is used for the ith cultural heritage asset.

R5 - The index i at line 175 and in Table 1 has been substituted with letter q. It corresponds to the number of openings measured of a building. So, *ho,q* is the height of the *q-th* opening of the building. This definition has been added to the text.

C6- In the assumptions of Section 2.3, the authors should include that material uniformity is assumed along the height of a given floodable floor.

R6 - The material uniformity has been added as assumption in Section 2.3.

C7- In Section 2.4, more details should be provided (to ensure replicability of the procedure that was used) about the statistical analysis that was carried out to determine the average surface area potentially exposed to floodwater. What is a statistically significant sample in this context? What were the artwork typologies that were selected? Paintings on canvas and painting on panels, or others? Can the data that was used actually be accessed thought the link that was provided?

R7 - The website mentioned in the article (https://catalogo.beniculturali.it/) contains a catalogue of all recognised cultural heritage assets in Italy. For each cultural heritage asset, there is a record containing various details, including dimensions expressed in centimetres. Unfortunately, dimensions are not always provided. For this study, a selection was made of the records for paintings on canvas, on panels, frescoes, stone sculptures and wooden sculptures and furnishings displayed at the UNESCO World Heritage Site of the Historic Centre of Florence, provided they contained information on dimensions. In total, the following number of records were selected for the statistical analysis:

Type of artwork	Number of official datasheet considered for the statistical analysis available at (https://catalogo.beniculturali.it/)	Number of artworks surveyed in CH buildings in the study area
Paintings on canvas	115	174
Paintings on panel	174	200
Frescoes	33	126
Stone sculptures	48	929
Wooden sculptures	24	17

The average size of the selected works was then calculated. The number of works selected for each sample depended on the availability of geometric data, which was very often missing for sculptures.

However, although there is no exact correlation between the size of the samples and the number of artworks surveyed at the 48 sites in Florence's historic centre it is noted that:

- the smallest samples are those of wooden sculptures. Even during the field survey, this category was the least common at the sites where the model used in this research was applied.

- It is much less common to find the dimensions of sculptures (both wooden and stone), given the specific nature of the objects (which cannot be easily summarised in three dimensions); for this reason, although the number of stone sculptures is very high, the number of records containing all the information for this category is only 48. (NOTE: the number of works in this category is significantly increased by the tombstones in the Museo dell'Opera di Santa Croce, the works from the Opificio delle Pietre Dure and the numerous sculptures in the Museo Bardini.)

Below we provide an example of complete official datasheet on the left column (height and width of a painting are provided) against an incomplete one (only one dimension is provided) in the right column.

We clarified these aspects in a more synthetic way in section 2.4 and in the case study description (sect. 3.2).

CD - CODICI	
TSK - Tipo Scheda	OA
LIR - Livello ricerca	C
NCT - CODICE UNIVOCO	
NCTR - Codice regione	09
NCTN - Numero catalogo generale	00289735
ESC - Ente schedatore	L. 41/1986
ECP - Ente competente	S128
RV - RELAZIONI	
ROZ - Altre relazioni	0900289735
OG - OGGETTO	
OGT - OGGETTO	
OGTD - Definizione	dipinto

SCHEDA

CD - CODICI	
TSK - Tipo Scheda	OA
LIR - Livello ricerca	C
NCT - CODICE UNIVOCO	
NCTR - Codice regione	09
NCTN - Numero catalogo generale	00170240
ESC - Ente schedatore	S18
ECP - Ente competente	S18
OG - OGGETTO	
OGT - OGGETTO	
OGTD - Definizione	statua
SGT - SOGGETTO	
SGTI - Identificazione	Italia liberata
LC - LOCALIZZAZIONE GEOGRAFICO-AMMINISTRATIVA	
PVC - LOCALIZZAZIONE GEOGRAFICO-AMMINISTRATIVA ATTUALE	
PVCS - Stato	ITALIA
PVCR - Regione	Toscana
PVCP - Provincia	FI
PVCC - Comune	Firenze
LDC - COLLOCAZIONE SPECIFICA	
LDCT - Tipologia	palazzo
LDCQ - Qualificazione	statale
LDCN - Denominazione attuale	Opificio delle Pietre Dure
LDCU - Indirizzo	via degli Alfani, 78
LDCM - Denominazione raccolta	Museo dell'Opificio delle Pietre Dure
LDCS - Specifiche	sezione VIII
UB - UBICAZIONE E DATI PATRIMONIALI	
UBO - Ubicazione originaria	SC
INV - INVENTARIO DI MUSEO O SOPRINTENDENZA	
INVN - Numero	429
INVD - Data	1905

Missing pages ...

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Missing pages ...

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AUTH - Sigla per citazione	00000179
AAT - Altre attribuzioni	Botticelli Sandro
CMM - COMMITTENZA	

CMMN - Nome	Famiglia Doni
CMMD - Data	1477 ca.
CMMC - Circostanza	decorazione di un altare della famiglia nella Badia fiorentina
MT - DATI TECNICI	
MTC - Materia e tecnica	tavola/ pittura a olio
MIS - MISURE	
MISA - Altezza	157
MISL - Larghezza	89
MIST - Validità	ca.
CO - CONSERVAZIONE	
STC - STATO DI CONSERVAZIONE	
STCC - Stato di conservazione	mediocre
STCS - Indicazioni specifiche	Fessure, sporco, cadute di colore.
DA - DATI ANALITICI	
DES - DESCRIZIONE	
DESO - Indicazioni sull'oggetto	NR (recupero pregresso)
DESI - Codifica Iconclass	71 T 58
DESS - Indicazioni sul soggetto	Soggetti sacri. Personaggi: San Raffaele arcangelo; Tobia. Fig maschili: donatore. Attributi: (Tobia) pesce. Oggetti: lume; bo Paesaggi. Elementi architettonici: ponte; edifici; torri. Animali

DTSL - Validità	ca
DTM - Motivazione cronologia	bibliografia
AU - DEFINIZIONE CULTURALE	
ATB - AMBITO CULTURALE	
ATBD - Denominazione	manifattura fiorentina
ATBM - Motivazione dell'attribuzione	bibliografia
MT - DATI TECNICI	
MTC - Materia e tecnica	pietra dura/ intarsio
MTC - Materia e tecnica	pietra dura/ incisione
MIS - MISURE	
MISU - Unità	cm
MISA - Altezza	96,5
CO - CONSERVAZIONE	
STC - STATO DI CONSERVAZIONE	
STCC - Stato di conservazione	buono
RS - RESTAURI	
RST - RESTAURI	
RSTD - Data	1987
RSTE - Ente responsabile	GR 10230
RSTN - Nome operatore	Kumar F.
RST - RESTAURI	
RSTD - Data	2019
RSTE - Ente responsabile	GR 13991
DA - DATI ANALITICI	
DES - DESCRIZIONE	
DESO - Indicazioni sull'oggetto	La piccola statua, eseguita in diaspro di Sicilia, calcedonio di Volterra agata di Goa e finimenti in bronzo, rappresenta la figura allegorica dell'Italia, con elmo turrito, la spada nella mano sinistra, in atto di accarezzare con la destra il leone alato, simbolo di Venezia. La figura poggia su una base ottagonale di diaspro verde, con decorazioni di draghi alati in bronzo dorato. Sui lati formelle in fondo di lapislazzuli raffiguranti gli stemmi delle più importanti città italiane, è visibile anche lo scudo crociato della famiglia sabauda. Nella formella anteriore, sempre eseguita a commesso, si nota l'epigrafe.
DESI - Codifica Iconclass	44 A 51 (ITALIA)
DESS - Indicazioni sul soggetto	Allegoria: Italia

C8- In Section 2.4, explain the reasoning behind the seven levels of exposure heights that were considered for each asset. Why 7?

R8 - Seven levels of exposure for the artworks were identified within the sites analysed:

0<x≤0.5 (m)
0.5<x≤1 (m)
1<x≤1.5 (m)
1.5<x≤2 (m)
2.0<x≤3.0 (m)
3<x≤4 (m)
> 4 (m)

The choice of these thresholds was a compromise between a good level of detail and an acceptable processing speed. The greatest number of artefacts are distributed between 0 and 2 metres above ground level; consequently, this range has been divided into four 50-centimetre increments to achieve a more detailed distribution of the artworks' display. Between 2 m and 4 m, fewer works of art are usually displayed, as they are less visible to visitors at that height; for this reason, this range has been divided into two 1-metre intervals. Finally, a final interval has been included comprising works displayed at a height greater than 4 m. Among the sites analysed, artworks displayed above 4 m from ground level were found mainly in places of worship. It is important to note that, in the calculation assumptions, it was defined that small artworks are represented as a point and are considered completely damaged when the water level reaches the lower part of the artwork. This aspect has been clarified in section 2.4.

C9- In Section 2.4, additional clarification is necessary regarding Eq. (7). RCk,j is said to be the maximum unit restoration cost for artworks and, for the case of large of large artworks, it is also said the cost depends on the water level w. This means that, in Eq. (7), RCk,j should be a function of w. As it is, Eq. (7) only works if RCk,j a restoration cost per meter or if w is a water level normalized by a maximum water level value, but this is not said. Similarly, the component associated with small-sized artworks does not seem to depend on the water level. As it is, the expressions just adds a constant value, which does not seem right. In addition, parameter P is also not clear. This parameter is said to be the perimeter of the cultural heritage asset in Eq. (2) but its use in Eq. (7) implies that all large artworks cover the entire perimeter of a given building, but what is said at the beginning of this section is that "the affected area (or linear meters of damaged material) is quantified based on the building's perimeter", which is not the same. Detailed clarifications of these issues need to be included in the revised version of the manuscript to help the reader understand the proposed approach.

- **R9** – We acknowledge the presence of some inconsistencies in the equation 7 that have been corrected as well as the missing definition of some variables. Particularly, the dependence of M and N on the water depth (w) was not explicated in the previous version of the equation, in fact M and N depend on water depth as they represent the number of items exposed for a certain flood depth, based on the survey of the CH sites. Please note that $RC_{k,j}$ is the unit restoration cost for artworks (€/m^2) of type k on floor j that is multiplied by an area in both terms of the equation (large-sized and small-sized artworks.)

The amended Eq. 7 reads as follows (we made explicit the dependence on w):

$$RC_{A,i}(w) = \sum_{j=1}^{n} \sum_{k=1}^{m} [M_{i,k,j}(w) \cdot RC_{k,j} \cdot p_i \cdot w + N_{i,k,j}(w) \cdot RC_{k,j} \cdot A_{k,j}]$$

Where,

- *j* represents the floodable floor, and *n* is the total number of floodable floors.
- *k* denotes the type of artwork, and m is the number of artworks categories.
- $M_{i,k,j}$ is the total number of large-sized artworks and $N_{i,k,j}$ is the total number of small-sized artworks of the same type, exposed for a flood depth *w*.
- p_i denotes the length of the segment of the building perimeter (in the case of frescoes) or the linear extent (in the case of shelves) occupied by large-sized artworks.
- $A_{k,j}$ is the average area of small-sized artwork type *k* on floor *j*, and $RC_{k,j}$ is the maximum unit restoration cost for artworks (€/m^2) of type k on floor j.

Both components of Eq. 7 depend on water level w. For each water level, the restoration cost associated with large artworks is calculated multiplying the number of large artworks affected for that water depth, the unit restoration cost [euro/m2], the length of the perimeter of the cultural asset covered by the large artworks [m] (it could be all the perimeter of the cultural site or a part of the perimeter) and the water level [m].

Instead, the second term, associated with small artworks, increases with a stepwise form, again depending on the value of water depth. Indeed, for each step of water level the number of small artworks affected by flood water for each typology of artworks is counted. Consequently, the restoration cost is evaluated, multiplying the number of affected artworks Ni,k,j (w), the maximum unit restoration cost RCk,j [euro/m2] and the estimated surface area of the artwork [m2].

C10 - In Section 2.4, the role of the CRI (Eq. 9) is not clear. How is it expected to be used with the proposed methodology for developing vulnerability functions? It seems that its role is that of an uncertainty factor that provides extra information about the reliability of the predicted damage or vulnerability, but this is not clearly explained when the CRI is introduced. Moreover, the qualitative scale shown in Fig. 7 d) is not explained and justified.

R10 - The CRI is used as a measure of uncertainty in estimating restoration costs for artworks. It is classified into three categories (good, fair, and poor) to represent the reliability of damage estimates. When the CRI is poor (i.e., greater than 0.3), the corresponding vulnerability function is excluded from the calculation of percentile vulnerability functions for artworks, as it is considered unreliable. A CRI value of 0.5 corresponds either to spaces used for temporary exhibitions for at least six months per year (where no a priori assessment of the types of artworks is possible) or to cases in which 50% of the exposed artworks belong to the "other artworks" category. We clarified these aspects in section 2.4.

C11 - In Section 3.2, clarify what criteria were used to select the 48 sites (among the 175) to which the proposed methodology was applied to.

R11 - Firstly, flood maps of Florence's historic centre, derived from simulations of events with return periods of 30, 100, 200 and 500 years, were overlaid. All sites that were not exposed in any of these simulations were excluded from the dataset (30 buildings out of 175). Then, all the managers of cultural heritage sites potentially affected by flooding were contacted for the data collection with the help of the UNESCO site management office but only 1/3 of them replied to our request. The managers of the 48 sites shown in purple in Figure 2 agreed to provide the data required for the research and access to the

building for the data collection. Overall, the distribution of potentially exposed CH buildings (not surveyed) is as follows: 30% museums, 28% places of worship, 26% libraries/archives, 16% other (e.g., theatres or train station).

The distribution of the surveyed 48 CH buildings is as follows: 43% museums, 42% places of worship, 15% libraries/archives. Therefore, especially for museums and places of worship the surveyed sample reflects quite well the distribution of CH not included in the work. This aspect has been clarified in section 3.2.

C12- Regarding the costs reported in Section 4.1, it is assumed that they are corrected for inflation, but this should be said, nonetheless.

R12 - The costs reported in Section 4.1 are obtained by current available price lists of restoration of artworks (year 2025), so it is not necessary to correct them for inflation. In Italy the price list of materials and works of restoration of artworks is updated periodically and it can be bought online or in some bookshops. For this research we used the price lists freely available online and in the library of the University (year 2025). This aspect has been clarified when commenting the prices of Table 2.

C13- Section 4.4 should discuss/refer a few aspects that underline the proposed application: the applicability of the proposed methodology relies on the availability of enough detailed post-disaster data to establish the repair cost components that are considered in the method. While this is something that should be clearly emphasized to highlight the importance of collecting and sharing such data. In cases where such data are not available, the authors should discuss how to proceed. What proxies or what approach could be used to determine these cost components? This is particularly important in order to clarify the scalability of the proposed methodology.

R13 – The discussion has been enriched to clarified these aspects and the paragraph now reads as follows:

[...] In particular, billing notes from conservators following the 1966 flood were analyzed to reconstruct typical restoration procedures and to align them with current price lists. However, validation data for artworks remains limited, as is generally the case for flood damage across many asset types, including residential buildings. In the absence of comprehensive damage records, estimating restoration costs based on restoration steps, required operations, and unit prices provides the most reliable approach. However, also archival research of the billing notes is challenging and makes the reconstruction of necessary restoration steps difficult. In absence of billing notes from past events, expert-based judgement (e.g., by conservators) could support the estimation of restoration costs. Damage records and restoration costs after flood events should be more systematically collected and shared to allow for model validation and further research advancements. [...]

C14- In the Conclusions the authors refer that one of their contributions is the “monetary assessment of direct total flood-related losses to CH”. This is a bold statement that implies a level of comprehensive loss/damage analysis that is not achieved. Even if the “other artworks” are indeed negligible, what the authors achieve is an estimate of the quantifiable direct losses represented by the repair costs. These are not the total direct losses. For example, losses due to destroyed assets (i.e. irreparable) are not accounted for, as well as the loss in market value of assets that may have a market value. In light of this, this final statement should be rewritten accordingly.

R14 – The bullet point of the conclusions has been reformulated as follows:

- Monetary assessment of direct flood-related losses to CH in the city of Florence, expressed in terms of restoration costs, for a 500-year recurrence interval flood scenario. This excludes irreparable losses, artworks with unknown restoration costs, as well as transportation, storage, and conservation costs.

Reviewer 2 - Anonymous Referee

General Comment

Thank you for the opportunity to review this manuscript. I consider the work to present a valuable scientific contribution, particularly in its development of vulnerability functions that account for non-structural damage of cultural heritage buildings and artworks. The study appropriately addresses libraries/archives, museums, and places of worship, using synthetic modelling informed by data from past flood events, applied to 48 cultural heritage sites located in the historic centre of Florence. Additionally, the inclusion of repair cost estimations for flood-related losses to cultural heritage under a defined flood scenario enhances the practical relevance of the findings. I recommend the manuscript for publication. However, I also concur with the comments raised by Reviewer RC1, which align with several issues I detected during my evaluation. These points highlight aspects of the paper that are not entirely clear in their current form and could benefit from further explanation or reformulation to improve readability and methodological transparency. While I will outline specific comments from my review below, I emphasize that many of RC1's observations reflect broader structural issues that, in my view, warrant careful attention and revision.

Specific comments:

C1- Lines 309 and 315: I suggest that the authors reconsider the terminology used in Section 4.1, as in this section refers to 'cultural heritage sites', which is technically correct, as a cultural heritage building can be considered a site. However, throughout the paper, the application of the methodology is predominantly described in relation to 'cultural heritage buildings', and this terminology appears more building-oriented in other sections. For clarity and uniformity, I recommend homogenizing the terminology across Section 4.1. using consistently the term 'buildings' or clearly distinguishing the terms along the manuscript, when necessary.

R1 - In this work the term "cultural heritage sites" refers to the overall site. For each cultural heritage site we distinguished it into cultural heritage building and artworks. The manuscript has been reviewed substituting "Cultural heritage site" when we consider the site as a whole, while we use "cultural heritage building", when we are focusing on the structure. Moreover, we made this distinction more explicit at the beginning of the methodology section as follows "In this work, we use the term *CH site* as a general designation for all types of cultural heritage, including both buildings and artworks. When referring to these specific components individually, we use the terms *CH building* and *artworks*, respectively."

C2- Lines 71–72: The statement "To the best of our knowledge, this is the first study to undertake a comprehensive analysis of restoration activities and their associated costs, enabling the quantification of direct economic losses." could benefit from rephrasing. As written, it presents a broad claim that may imply novelty across all hazard types. I suggest specifying that this assertion applies within the

context of flood-related impacts, since comparable analyses may exist for other hazards, such as seismic vulnerability studies, even if the authors are unaware of them. Clarifying the hazard scope would prevent potential misunderstanding and strengthen the credibility of the claim.

R2 - Thank to the referee for the suggestion, the statement has been rephrased to refer to the flood-context.

C3- In Table 1, I suggest reconsidering the terminology used for 'location of openings' and 'location of artwork'. As written, their meaning becomes clearer only after reading the subsequent explanation. To avoid ambiguity, I recommend adopting more explicit terminology in Table 1 that directly reflects the intended context. At first reading, 'location' could be interpreted as referring to the room/spatial placement inside the building, or to vertical positioning (e.g., basement, ground floor, upper floors). Clarifying this distinction would guide the reader more intuitively and reduce potential misinterpretation when consulting the table.

R3 – We made some adjustments to Table 1 to make it self-explanatory with respect to location and height of the openings, location and height of the artworks.

Extract from Table1 with track changes

Building envelope features	N° of floors
	Presence of basement
	Current use of basement
	Location of openings in the building perimeter
	Height of openings ($h_{o,i}$) above the road pavement
Contents features	N° of paintings on panels N° of paintings on canvas N° of frescoes N° of stone sculptures N° of wooden sculptures N° or linear meters of artworks in paper materials N° of other artworks
	Location of each artwork (e.g., basement, ground floor, upper floors)
	Height of exposure of each artwork (from the floor level)

C4- In Section 2.2, several parameters are assigned a value of 0. While this may appear self-explanatory, it could be helpful to include a brief note or general remark before presenting the equation to clarify that the value 0 is used in cases where certain factors are not applicable to specific cultural items. Providing this explanation upfront would prevent the reader from having to infer the reasoning and would improve transparency in the interpretation of the parameters.

R4 - Thank to the referee for the suggestion. The following statement has been added:

"Eq. 1 consists of nine terms, representing the unit prices of different restoration operations. Since not all operations are relevant for every type of artwork, terms corresponding to non-applicable operations are set equal to zero when evaluating the total unit restoration cost of a specific artwork.".

C5- In Lines 119–120, the phrase "only the internal non-structural components of the building (Custer et al., 2015)" could benefit from further clarification. As currently written, the sentence may lead the reader to infer that structural damage may have occurred but was excluded from the analysis for the sake of simplicity. It is not clear whether structural damage was present but disregarded, or whether it

simply lies outside the scope of the study. I suggest briefly specifying the rationale, either indicating that structural damage was not observed in the selected cases or clarifying that it was intentionally excluded because the objectives of the study focus solely on non-structural, interior components. This clarification could also be reflected in the introduction (Lines 69–70) to reinforce the defined scope from the outset. This observation also corresponds with RC1's comment regarding terminology: the expression 'building envelope' may be less precise in this context, and 'interior finishes' might more accurately convey the type of elements assessed.

R5 - The authors know that structural damages can be registered in case of flood characterized by very violent flow velocity or debris flows. However, this type of damage was intentionally excluded as quite rare in case of flooding and not reported for any CH site in the study area after the 1966 flood event. We explained this assumption at the beginning of section 2.2 as follows "For the sake of simplicity, and since structural damage is rarely observed in case of flooding (De Lucia et al., 2024), this study considers the damage to interior finishes of the building (Custer et al., 2015)". The term 'interior finishes' has been adopted as suggested, replacing all occurrences in the manuscript.

C6 - Lines 461–463: Here, it may be beneficial to mention the specific contents of the museums when discussing the three most affected institutions. While it is logical that libraries generally incur higher repair costs, in this case the costs appear closely linked to the type of contents they hold. For example, the results for the National Library and the University Library seem consistent with their holdings of paper-based materials and books, which are highly susceptible to water damage. However, for the Archaeological Museum, it would strengthen the discussion to briefly indicate the types of collections that contribute to their high ranking in artwork-related damages. Specifying the materials or artifacts affected would help the reader better understand the rationale behind.

R6 - The Archaeological Museum, in addition to a huge collection of archaeological finds, hosts at the exposed levels a huge archive of books and manuscripts on papyrus and parchment (almost 100'000 items) and photographs documenting archaeological campaigns since the XIX centuries (more than 2 million, as declared by the museum manager). Therefore, all the three most affected institutions contain paper-based materials, which are highly susceptible to water damage. To be thorough, the National Library also hosts 10 paintings on canvas, 6 paintings on panel and 4 stone sculptures. To clarify this point we added the following paragraph in the comment of the results "Artwork-related damages are predominantly concentrated in libraries and certain museums, with the three most affected institutions—the National Library, the Archaeological Museum, and the university library—each incurring losses exceeding €10 million. The Archaeological Museum, in addition to its vast collection of artefacts, houses, within its flood exposed levels, an extensive archive of books, as well as papyrus and parchment manuscripts (nearly 100,000 items), and photographs documenting archaeological campaigns since the 19th century (over 2 million, according to the museum manager). Therefore, all three of the most affected institutions contain paper-based materials, which are highly susceptible to water damage."

C7- Lines 486–493: In line 490, the manuscript notes that the repair costs from the 1966 floods, as reported by conservators, were aligned with current price lists. I wonder whether this adjustment accounts for inflation, as also noted by RC1, or if other factors were considered when aligning historical costs with present-day values. Additionally, when referring to 'current price lists', it would be helpful to clarify whether this refers to a standardized current list of material costs and labour rates for specialized conservators/restorers in Italy, and whether such a reference exists in a document or table that could be cited. If my interpretation is correct, the authors analysed the receipts from 1966 and updated the

material and labour costs to present-day values. However, it is not clear whether there might be elements from the original receipts that are currently considered necessary for restoration (e.g., administrative and permit-related expenses required for the intervention), and whether those aspects were accounted for in the alignment process. If appropriate, I suggest refining the methodology description to improve transparency and reproducibility.

R7 – The Archival research of historical billing notes was carried out to find the necessary restoration operations. The costs reported in Section 4.1 are obtained by current available price lists of restoration of artworks (year 2025), that includes material costs and labour rates for specialized conservators/restorers in Italy so it is not necessary to correct them for inflation. In Italy the price list of materials and works of restoration of artworks is updated periodically and it can be bought online or in some bookshops (e.g.,https://www.lafeltrinelli.it/prezzario-restauro-dei-beni-culturali-libro-vari/e/9791255050810?utm_source=google&utm_medium=cpc&utm_campaign=pmax_kelkoo_libri&gad_source=1&gad_campaignid=17182894279&gbraid=0AAAAAC8kHMQUYijyaBnGg08vcWWT9IeP-&gclid=Cj0KCQiAgvPKBhCxARIsAOlK_EoQ_SWmnqVQGn1aD2mqLqDOVX8yN-gow6ulDv0ecIsgDsdxgbljj5QaAvZJEALw_wcB).

For this research we used the price lists freely available online and in the library of the University (year 2025). This aspect has been clarified when commenting the prices of Table 2. Other costs such as administrative, transportation, storage and conservation costs (e.g., flooded books in refrigerated cells) are not included. This aspect is also discussed in section 4.4 as follows “Moreover, the restoration cost estimates do not account for two critical components: (i) the conservation of artworks during the waiting period before restoration (e.g., storage in refrigerated environments with significant energy costs), and (ii) the safe transportation of large pieces—such as panel paintings—to restoration laboratories, which can be particularly costly and finally (iii) any administrative costs.”

Reviewer 3 - Anonymous Referee

General Comment

This manuscript addresses a genuinely underexplored problem, the quantitative assessment of flood-induced damages to cultural heritage assets at city scale, and the development of detailed vulnerability models. Furthermore, the data collection effort is substantial. However, the manuscript requires significant revision before it can be considered for publication. The main concerns relate to: (i) inconsistent and not clear terminologies, (ii) insufficient justification of site selection, (iii) an overreaching objective statement relative to the actual analytical scope, (iv) extension to city-scale assessment.

C1- **Inconsistent terminologies.** The manuscript employs multiple terms (e.g. cultural heritage assets, cultural assets, cultural heritage sites, and cultural buildings) without definition or consistent application. The authors are encouraged to adopt a single term throughout; cultural heritage buildings and contents would align naturally with the two-component structure of the damage assessment (building fabric and artworks) and would be immediately interpretable.

Beyond this, several category-level terms require clarification. Libraries and archives are used interchangeably, yet they are institutionally distinct: libraries typically hold publicly accessible collections, while archives manage records under different access and conservation regimes. It is unclear whether this distinction is material to the vulnerability functions derived, and the authors should address it explicitly.

Places of worship is used throughout as a typological category without specification of the building types it encompasses. The category plausibly includes Catholic churches, oratories, monasteries, and baptisteries, which differ considerably in spatial configuration, artwork distribution, and flood exposure profile. A brief characterisation of the building types included is necessary, particularly given that vulnerability curves are aggregated at this category level.

Finally, building envelope defined by the authors as internal non-structural components (plaster finishes, flooring, and utility systems) is non-standard and likely to mislead readers familiar with the conventional use of the term to denote the external building shell. A clearer alternative, such as interior building fabric or non-structural interior components, should be adopted and defined at first use.

R1 – We worked extensively to improve the manuscript terminology in the following ways:

- We clarified the terms site/building/artworks in the beginning of the methodology section (2) as follows "In this work, we use the term *CH site* as a general designation for all types of cultural heritage, including both buildings and artworks. When referring to these specific components individually, we use the terms *building* and *artwork*, respectively."
- We made explicit that for the vulnerability of the building we only consider damages to interior finishes (section 2.1 and 2.3), as structural losses are rare in case of flooding, and not applicable to our study area based on historical records.
- Libraries/archives. We acknowledge that libraries and archives are institutionally distinct, however, from the point of view of the vulnerability of the contents (paper material) and display arrangements (i.e., in shelves) they behave very similarly. This aspect has been clarified in section 3.2.
- Places of worship. In the surveyed CH sites, 42% is a place of worship (19 buildings). This includes 15 churches, 2 oratories, 1 baptistry church and 1 jewish temple. Each building was analysed to develop the vulnerability function for the building and the artworks. Overall, we notice that the main peculiarity of each site is about the artworks and not the building. In fact the vulnerability functions for the buildings are grouped only based on two patterns regardless of the CH type, while the building type is considered for the artworks, as the display mode and constructive materials are better classified in this way. This aspect has been clarified in sections 1 (introduction), 2.3 (method for vulnerability function for buildings), 3.2 (case study) and 4.1 (results of vulnerability function for buildings)
- We checked all the manuscript to ensure a consistent use of the above terms.

C2 - **Site selection.** The reduction from 175 classified CH sites to 48 inspected sites is stated but never justified (284–285). For example (309) states that the analysed sites include places of worship, museums, and libraries. While (287-288) refers also to museums, places of worship, palaces, libraries, and archives. Based on these inconsistencies, the following questions must be addressed:

Were the 48 sites selected based on flood exposure (i.e., falling within the modelled inundation zone)?

Was selection driven by managerial availability, implying potential self-selection bias toward better-resourced, more prominent institutions?

Is the sample proportionally representative of the 175 sites population by typology and footprint size?

Were any sites excluded due to access restrictions or data insufficiency?

Without answers to these questions, the representativeness of the derived vulnerability curves is unknown, and the upscaling to the full city (Section 4.3) cannot be made (470-473). A dedicated

paragraph addressing selection criteria and representativeness is essential, ideally with a statistical comparison of the sample versus the full population by typology distribution and/or building footprint area.

R2 – With respect to the description of the surveyed sites, we removed the ambiguities which arise from the fact that a former noble palace can nowadays exhibit collections as a museum. As previously mentioned and clarified in the text, the vulnerability functions for the buildings are independent of the CH type and the vulnerability functions for artworks are grouped in classes that share similar features (places of worship, museums, and libraries/archives).

With respect to the selection of the 48 surveyed CH sites we adopted the following method. Firstly, flood maps of Florence's historic centre, derived from simulations of events with return periods of 30, 100, 200 and 500 years, were overlaid. All sites that were not exposed in any of these simulations were excluded from the dataset (30 buildings out of 175). Then, all the managers of cultural heritage sites potentially affected by flooding were contacted for the data collection with the help of the UNESCO site management office but only 1/3 of them replied to our request. The managers of the 48 sites shown in purple in Figure 2 agreed to provide the data required for the research and access to the building for the data collection. This aspect has been clarified in section 3.2. Among the managers who were available to support the research, we observed a highly heterogeneous sample in terms of institutional affiliation and risk awareness, including directors of sites of Outstanding Universal Value, directors of local/national museums, and church custodians. Within this group, some respondents were fully aware of the flood risk affecting their sites—regardless of the institution's prominence—while others were entirely unaware of it. Based on our observations, willingness to participate did not appear to depend on the importance of the institution, but rather on individual sensitivity to the issue. Although we cannot determine whether this introduces a bias, the sample of 48 sites encompasses a wide range of buildings and artworks, which we consider sufficient to represent the diversity of cultural heritage (CH) in the study area. We clarified this aspect in the discussion and in section 3.2 (inspections and parameters assumptions).

With respect to the representativeness of the sample, the footprint area of the surveyed sample has the following characteristics:

Mean	2250.61
Median	1292.39
St dev (pop)	2643.78
St dev (sample)	2671.76
Minimum	102.151
Maximum	13326.2

While the remaining CH sites exposed to flooding (not surveyed) have the following statistics with respect to footprint area:

Mean	2652.68
Median	1433.2
St dev (pop)	4522.24
St dev (sample)	4548.15
Minimum	46.9
Maximum	37743.5

Therefore, since the mean and median of the footprint area are fully comparable, we believe the upscaling to the city is feasible. Moreover, the use of the unitary damage per cubic meter in the upscaling, resolves the issue of having a wide range of footprint sizes.

Finally with respect to the type of CH the surveyed and not surveyed samples are similar as each CH site class has a similar weight in the two samples.

Surveyed: museums (43%), places of worship (42%), libraries/archives (15%)

Not Surveyed: 30% museums, 28% places of worship, 26% libraries/archives, 16% other, e.g., theatres.

The above aspects (size and CH type) have been clarified in section 3.2.

C3 - **Objective and analytical scope.** There is a significant mismatch between the stated objective and the actual analytical scope that must be addressed. The study frames its aim as developing vulnerability functions "at the city scale" (66) and evaluating "overall city-scale damage" (72), yet the methodology is applied to 48 selected buildings within the perimeter of Florence, not the city as a whole. The authors themselves acknowledge this implicitly by describing the sample as "selected buildings" (74). These two characterisations are irreconcilable without explicit clarification of what "city scale" is intended to mean in this context. The authors should either reframe the objective to reflect what the study actually delivers - a site-level synthetic vulnerability assessment applied to a sample of CH buildings within a historic urban core, with city-level aggregation presented as a secondary, exploratory estimate rather than a primary result - or provide a more detailed explanation, as the current formulation (66–72) would benefit from substantial clarity improvements. Additionally, the claim that this is "the first study to undertake a comprehensive analysis of restoration activities and their associated costs" (71–72) requires careful qualification: the analysis explicitly excludes several artwork categories for which archival data were insufficient, and validation is demonstrated only for places of worship, making the descriptor "comprehensive" difficult to sustain.

R3 – We thank the referee for highlighting this ambiguity in the research objectives. The primary aim of this study is to develop vulnerability functions for cultural heritage (CH) buildings and artworks, while the city-scale aggregation represents a secondary outcome intended to provide an order-of-magnitude estimate of losses associated with restoration costs. Indeed, given the numerous challenges involved in estimating the monetary losses of CH assets due to flooding, even order-of-magnitude estimates can support decision-makers, particularly in the absence of widely accepted standards for damage assessment. The paragraph has been restructured as follows:

“This study aims to develop new vulnerability functions specifically tailored to cultural heritage buildings and artworks, considering direct economic flood losses associated with restoration activities. By integrating extensive fieldwork with statistical analysis of existing datasets, common damage

patterns were identified across several types of cultural heritage buildings. These were used to derive mean and percentile vulnerability functions accounting for damage to interior finishes. Similar functions were also defined for artworks across three CH typologies: places of worship, museums, and libraries/archives.

To the best of our knowledge, this is the first study to undertake a comprehensive analysis of restoration activities and their associated costs, enabling the quantification of direct economic losses in the context of flooding. Additionally, a distribution of unit damage per flooded volume of CH (€/m^3) is derived through statistical analysis of estimated losses, allowing the assessment of overall city-scale damage, including for CH buildings not inspected in detail."

C4 -City-scale assessment

The extension of median volumetric damage (EUR 875/m3) to 127 non-inspected buildings, yielding an additional EUR 257 million and a city total of EUR 527 million (470–474), is the most problematic step in the manuscript. The authors acknowledge that CH buildings are highly heterogeneous in spatial configuration, artwork distribution, and flood exposure, and that this heterogeneity is precisely what motivates individual site inspection rather than generalised damage functions. The extrapolation step effectively reverses this position by assuming that 127 non-inspected buildings are sufficiently comparable to the 48 inspected ones to warrant application of a single median damage metric. Moreover, there is an unresolved numerical discrepancy between "EUR 550 million" in the abstract and "EUR 527 million" in Section 4.3. These figures must be reconciled. The authors should either present the city-scale total as a rough-order-of-magnitude estimate with explicit uncertainty bounds, clearly separated from the validated site-level results, or relocate it entirely to a limitations and future work section.

R4 – The numerical discrepancy arises from the use of a rounded value in the abstract (€550 million) instead of the more precise estimate (€527 million) reported in the results. To avoid any ambiguity, we have now harmonized the figures and report the same value in both the abstract and the results.

The use of the median unit volumetric damage to extrapolate total losses for non-inspected buildings is intended solely to provide an order-of-magnitude estimate. This approach is based on a statistical analysis of the surveyed buildings, which were shown to be broadly comparable to the non-inspected ones in terms of typology and footprint area.

We emphasize that this estimation, which occupies only a few lines in the manuscript, is not a primary outcome of the study but rather a demonstrative application. It illustrates how data collected for CH vulnerability assessment can support approximate evaluations in cases where detailed analyses are not feasible or available. Given the current state of the art in this field, even order-of-magnitude estimates can provide valuable support to decision-makers.

We decided to reformulate the paragraph to better clarify the purpose of the extrapolation as follows "The total estimated damage for the 48 inspected CH buildings amounts to approximately €270 million. Extending the median unit volumetric damage values to other, non-inspected but comparable CH buildings yields an additional **rough** estimate of €257 million **(€447 million when considering the 75th percentile**). This results in a total estimated monetary damage to cultural heritage within the municipality of approximately €527 million. We note that these estimates do not account for: (i) artworks with unknown restoration costs, (ii) artworks in temporary exhibitions, and (iii) conservation and transportation costs."

Moreover, we made the concept explicit also in the bullet points of the conclusions.

C5 -In the introduction section (42-45):

The paragraph introduces the Vecvagars (2006) value taxonomy to contextualise the scope of the damage assessment, but the conceptual link between the cited framework and the methodological approach actually adopted is not established. Specifically the taxonomy adopted in the Vecvagars (2006) refers to "extractive use value" in terms of market-observed revenues generated by the asset, not restoration expenses following a damaging event. Restoration costs represent a measure of physical loss, not a direct proxy for market value. The authors should either clarify explicitly how their approach maps onto the cited framework, or replace this conceptual framing with a more appropriate theoretical grounding for cost-based damage assessment.

R5 – We reformulated the paragraph to clearly distinguish the taxonomy of CH values by Vecvagars and the direct impacts due to restoration costs. The section now reads as follows: "Quantifying flood-induced damages to CH is a complex task. Vecvagars (2006) categorized CH value into "use value" (i.e., market-related) and "non-use value" (i.e., non-market-related). Use value can be further subdivided into extractive and non-extractive types. Moreover, physical losses to CH resulting from contact with floodwater (direct impacts) can be quantified in terms of restoration costs for both artworks and CH buildings. However, such economic assessments are inherently limited: cultural assets may suffer irreversible loss, and restoration efforts may span decades (Benassi et al., 2016; De Lucia et al., 2024). Furthermore, floods can lead to indirect losses, such as reduced tourism due to prolonged closures (Arrighi et al., 2022). CH also includes intangible or non-use values—such as historical, social, spiritual, and evidential significance—which are notably difficult to monetize (Romao and Pauperio, 2019)."

In the methodology section:

C6 - Fig.1: Missing "Restoration cost for "envelope" - so the Figure should also include the integration of the Dottori et al. (2016) model.

R6 – We modified Fig. 1 to add a new box for the restoration costs for the interior finishes of the building.

C7 - The survey forms from Molinari et al. (2014) and De Lucia et al. (2024) are cited as inspiration, but the degree of adaptation is unspecified (92-94). Clarify what was retained, modified (and why), or added for the CH-specific pre-event vulnerability survey context.

R7 – We specified in the text the changes made to the existing survey forms. The text now reads as follows: "Compared to the survey forms by De Lucia et al. (2024), which were designed to assess damage to CH after flood events, we included more specific information to: (1) develop synthetic vulnerability functions for buildings—by collecting data on the location and elevation of openings through which water may enter; and (2) develop synthetic vulnerability functions for artworks—by gathering information on their position and elevation."

C8 - Overall, I believe that the manuscript is of great interest and it addresses relevant methodological gaps and so for this reason I hope my comments are contributing in improving the clarity of the presented work.

R8 – We thank the referee for their comments and believe that addressing them has improved the rigor of the manuscript.