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Building-Scale Flood Hazard Modelling for Risk Assessment of Cultural Heritage

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ABSTRACT

Flooding is among the most frequent natural hazards threatening cultural heritage sites, yet current flood hazard studies often operate at urban or regional scales. While building-scale damage models exist, they generally rely on flood depth inputs from large-scale inundation models, inputs that may fail to capture the internal complexity of heritage buildings. This paper presents a 2D building-scale flood hazard modelling approach designed to improve risk assessment, management, and adaptation for cultural heritage buildings. The method incorporates detailed architectural and structural features—such as basements; openings; uneven floor levels; and interior spatial layout—to simulate internal flood dynamics. The methodology is applied to the Marini Museum in Florence, Italy. An offline-coupled hydraulic model is used in conjunction with a 2D urban-scale flood model to simulate floodwater ingress, internal flow patterns, and the effects of mitigation measures. Our results indicate that relying solely on urban-scale flood maps leads to substantial overestimation of internal flood depths, whereas the building-scale model represents inundation processes within exhibition spaces. Such approach provides a more robust foundation for risk assessment and mitigation planning that supports heritage managers in the correct placement and display mode for vulnerable artworks, thanks to a risk classification of exhibition spaces. Future work will address model validation and extend this approach to heritage buildings with multiple levels under a variety of flood scenarios.

1 | Introduction

Built heritage and archaeological complexes are increasingly threatened by natural hazards, with fires, earthquakes, and flooding emerging as predominant causes of damage. Despite growing awareness, Disaster Risk Reduction (DRR) implementation remains limited, with few World Heritage sites adopting comprehensive strategies for multiple natural hazards (Li 2024). This deficiency underscores the urgent need for enhanced risk assessment protocols and mitigation measures tailored to the specific vulnerabilities of heritage assets (Romão and Bertolin 2022; Sesana et al. 2018). Moreover, climate change is expected to exacerbate these risks, particularly across hotspots in Northern Europe and Southern Asia (Arrighi 2021).

Risk analyses for cultural heritage (CH) operate at varying spatial scales and may address single or multiple hazards. This work focuses on hydro-meteorological hazards, summarising recent advances in flood risk assessment for CH.

At the supra-national level, Kapsomenakis et al. (2023) assessed 244 UNESCO cultural and natural heritage sites in the Mediterranean using exposure indices (e.g., number of heavy rainfall days). Their findings, based on EURO-CORDEX simulations, indicate increasing exposure toward the end of the 21st century. At the national scale, Figueiredo et al. (2020) evaluated flood risk to Portuguese CH using simplified depth–damage vulnerability functions. At the regional scale, studies such as that of Assen et al. (2024) on Ethiopia's Konso Cultural

Landscape revealed significant increases in extreme rainfall indices, while high flood exposure has been documented for heritage assets in Northern Italy (Arrighi et al. 2023), Spain (Garrote and Escudero 2020), and Taiwan (Su et al. 2024).

Flood hazard estimation methodologies vary widely. Some large-scale assessments use precipitation as a proxy for flood hazard, omitting hydrodynamic simulations (Assen et al. 2024; Kapsomenakis et al. 2023; Kim and Sung 2024). Others classify flood hazard through artificial intelligence and multi-criteria analyses (Nguyen et al. 2024). In contrast, hydrodynamic simulations are used at different scales, from global (Arrighi 2021) to regional or local (Bertolin and Sesana 2022), to derive more physically based hazard estimates.

The choice of flood model resolution critically influences flood risk estimation. Nobile et al. (2025) compared CH flood risk in Portugal and Italy's Po River basin and demonstrated that results differ substantially depending on whether global, regional, or local hazard maps are employed. Higher-resolution models yield more accurate identification of exposed heritage assets and better estimates of flood depths at the building level.

Micro-scale inundation models are typically applied at the urban or district scale, integrating high-resolution terrain data, hydraulic structures, and, in some cases, building geometry, either as impermeable blocks or macro-roughness elements (de Moel et al. 2015; Falter et al. 2013). Common modelling approaches include 1D/2D or fully 2D simulations (Alipour et al. 2022; Mignot et al. 2006; Rangari et al. 2019; Tom et al. 2022), and in dense urban settings, even micro-topographic street-level features are incorporated (Geng et al. 2024). With the growing availability of detailed topographic data, mesh resolutions of about 1 m or less are now common. Model outputs typically consist of inundation maps reporting the maximum flood depth in each computational cell, from which hazard indicators are extracted at the location of assets for damage estimation (Apel et al. 2009; Molinari et al. 2020).

Despite their value for urban-scale risk analysis, micro-scale models often lack the spatial and structural detail required to represent flooding dynamics inside individual buildings. A common simplification concerns basements: impact analyses frequently assume complete inundation whenever the simulated water depth at the building perimeter exceeds zero. However, basement flooding depends on the temporal evolution of floodwater, and the commonly used maximum depth metric may correspond to either brief or prolonged inundation. While this approximation may be acceptable for typical residential structures, it introduces substantial uncertainty when applied to CH assets with underground spaces, large footprints, or complex internal layouts containing valuable artworks or sensitive materials.

Recent technological advances have begun to address some of these limitations. Alexopoulos et al. (2025), used ultra-high-resolution digital terrain models (5 cm) derived from UAV photogrammetry to analyse pluvial flooding at the Temple of Apollo archaeological site in Greece, enabling detailed identification of ponding areas and flow paths. However, while such approaches are effective for open archaeological sites, they are less suitable for enclosed monumental buildings with complex interiors. Tamagnone et al. (2025) investigated pluvial flooding in CH buildings using a dual drainage hydraulic model to estimate flooded areas caused by sewer overflow.

At the same time, vulnerability assessment methods for CH have evolved toward asset-specific approaches that consider the unique structural, material, and artistic characteristics of heritage assets. Several studies have developed indicator-based frameworks and decision-support tools that integrate conservation-relevant parameters (De Lucia and Arrighi 2025; Figueiredo et al. 2021; Salazar et al. 2024; Snelling et al. 2024).

Despite these advances, an important gap persists in flood risk assessment for CH. Although vulnerability analyses increasingly recognise the uniqueness of heritage assets, flood depth, the key driver of damage, is still often derived from hazard models with insufficient spatial resolution to represent building interiors. Most current approaches extract maximum flood depths from catchment- or urban-scale models and directly apply them to impact analyses, neglecting flood duration and internal hydrodynamics. This limitation is particularly relevant for CH buildings with basements, elevated floors, or complex layouts, where external water levels do not necessarily correspond to indoor flooding conditions. Depending on flood duration and entry points, internal spaces may experience partial or full inundation, influencing both the severity and type of damage.

An additional research frontier concerns the visualisation and communication of flood risk. Traditional two-dimensional maps often fail to convey complex spatial relationships between water levels and heritage structures. Laefer et al. (2025) proposed a three-dimensional visualisation framework combining laser-scanned point clouds with shader-based rendering to create realistic, textured floodwater effects at sub-meter resolution. Similarly, digital twins are increasingly applied for risk communication and decision support in heritage management (Backhaus and Stamm 2025; Heyer et al. 2020). These tools emphasise the importance of understanding flood behaviour within buildings to enable effective visualisation, vulnerability assessment, and risk-informed decision-making.

The present study aims to improve the representation of flood hazard inside CH buildings, whose architectural complexity, such as intricate planimetric and altimetric layouts, often limits the reliability of micro-scale models for exposure and risk assessment. Specifically, we develop and test a novel building-scale inundation model applied to a museum in Florence, Italy. The model simulates flood depths across different museum spaces while accounting for flood return period and duration. Boundary conditions are derived from a conventional micro-scale urban model, whereas internal structural details are obtained from on-site inspections. To the authors' knowledge, this represents the first attempt to explicitly model inundation dynamics within a cultural heritage building, providing new insights for site-specific risk mitigation and management strategies.

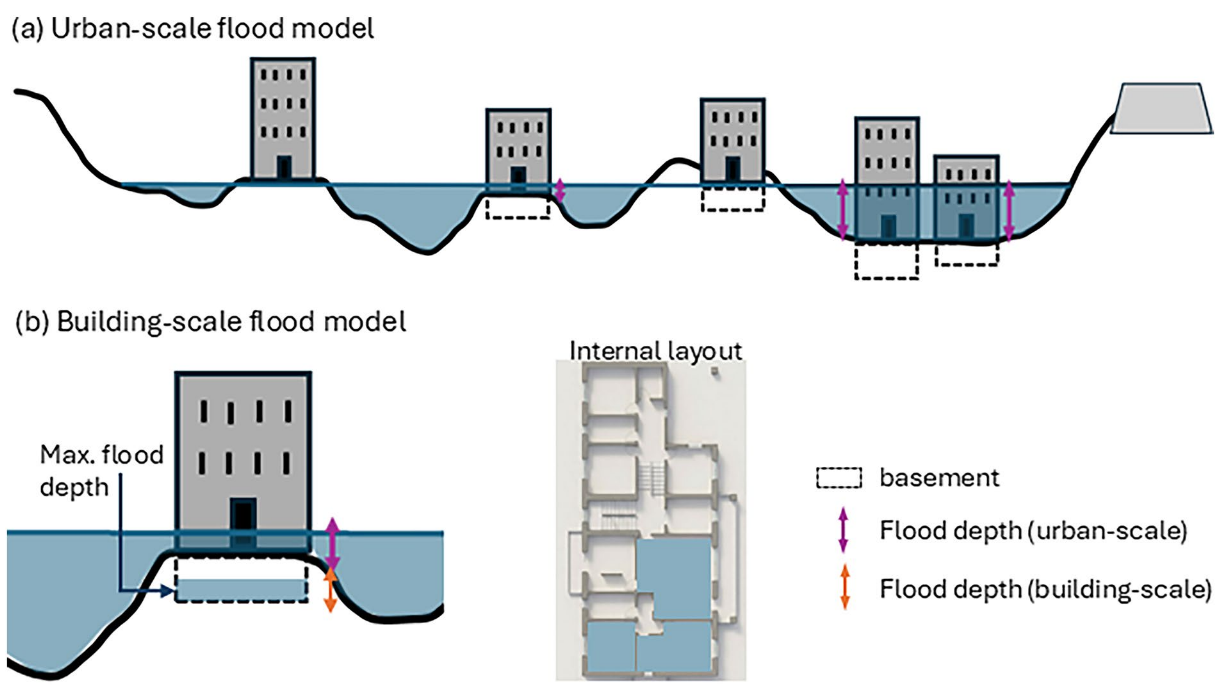


FIGURE 1 | Conceptual scheme of the urban and building scale flood models.

2 | Materials and Methods

The main methodological contribution of this study is the downscaling of an urban-scale flood model to a building-scale flood model (Figure 1). Changing the spatial scale of analysis, from the urban area to the building level, requires abandoning the use of maximum flood depth values obtained from the urban-scale model in favour of a dynamic representation of inundation within the building, which accounts for both flood duration and probability. The building-scale model, informed by boundary conditions derived from a re-analysis of the urban-scale model, provides a more accurate characterisation of flood risk and supports the identification of effective mitigation strategies for culturally significant buildings. This includes, for instance, determining which spaces are most suitable for displaying artworks. Section 2.1 describes the urban-scale inundation model, while Sections 2.2–2.3 detail the data requirements and setup of the building-scale model.

2.1 | Urban-Scale Flood Model

The flood simulation is conducted using a coupled 1D-2D hydraulic model within the HEC-RAS framework that allows the user to perform two-dimensional unsteady flow calculations through Reynolds averaged Navier–Stokes equations for incompressible flow, uniform density and hydrostatic pressure (Shallow Water equations). The water flow within the river is represented using a one-dimensional approach, where the cross-section geometry is derived from a detailed topographic survey that includes river bathymetry and key infrastructure such as bridges and weirs. The river is hydraulically linked to the floodplain through lateral weirs, which enable water to flow into the two-dimensional computational domain. This domain is modelled using a diffusive wave equation to simulate floodplain dynamics. The computational mesh, constructed from a LiDAR-derived digital terrain model, has a resolution of 1 m, and buildings are represented as impermeable blocks. The model incorporates a rating curve as the downstream boundary condition, while the upstream boundary condition is defined by river flow hydrographs of different durations and return periods (30, 100, 200, 500 years). The urban-scale model is validated against flood depths of the last historical event in the study area (Arrighi et al. 2022). The output export time is set according to the length of the overall simulation with an order of 15–30 min.

2.2 | On-Site Inspection of Cultural Building

Since cultural heritage buildings have structural peculiarities that prevent them from being generalised in the same way as other types of buildings, such as residential ones, an inspection is necessary to assess specific characteristics for flood hazard analysis. The first aspect to examine on-site is the elevation of the ground floor relative to the road pavement. This can be measured using laser meters or more advanced tools such as laser scanners. This element is crucial for determining whether the ground floor is located below potential floodwater levels.

The second aspect to investigate is the presence of a basement or underground floor. Since these levels are situated below the road pavement, their presence is a critical factor in understanding flood vulnerability.

The third analysis involves a perimeter inspection aimed at identifying the location of openings, their dimensions, their height above the road pavement, and their connection to either the ground or underground floor. Typical openings to assess include windows, doors, and ventilation grates. Finally, through an interview with the heritage managers, the presence of mitigation measures and effects of historical events are also clarified. Table 1 summarises the key elements to be inspected and the information to be collected for the building-scale flood model.

2.3 | Building-Scale Flood Model

The building-scale flood model is also created with the HEC-RAS software. The set-up of the building-scale flood model requires the standard definition of geometric properties of the study domain, boundary and initial conditions, and parameters. However, the computational mesh requires several steps to describe the architectural features of the building.

2.3.1 | Geometry

The first step for the mesh creation involves importing and georeferencing the floor plan image into a Geographic Information System (GIS) and drawing the floor plan as a polygon shapefile feature (Figure 2, panel a). Two separate shapefiles are created: one representing only the outer boundary without internal walls and another specifically for the internal walls. Next, a temporary DTM (Digital Terrain Model) is generated in GIS by clipping the portion of the urban-scale DTM that lies beneath the floor plan and modifying it according to the elevation values obtained from surveys and floor plans (Figure 2, panel c). This modification is performed using the Serval plugin available in QGIS or other similar raster editing tools. The lines corresponding to the boundary conditions are also drawn within QGIS as polylines.

Once these shapefiles are prepared, the next step is to import the floor plan shapefile (excluding internal walls) and the temporary DTM into RAS Mapper. To ensure the proper representation of steps or elevation changes across building spaces, breaklines are inserted at the locations of the stairs and other discontinuities.

TABLE 1 | Information collected on-site for the heritage buildings.

Element	Description
Storeys and floor plans	Number of building levels and their mean elevation with respect to the road pavement. Geometry of the floor plans
Basement	Presence of storeys with floor under the elevation of the road pavement
Openings	Presence, number, position and elevation of openings along the perimeter of the building, such as windows, doors, ventilation grates etc.
Previous flood events	Past events and their effect and consequences on the building
Mitigation measures	Presence of passive or active devices for flood prevention (e.g., flood gates, pumps)

The next stage involves creating a computational mesh. This is done by setting the point spacing in meters and then generating computation points with all breaklines (Figure 2, panel d). To capture the features of a heritage building, point spacing should be 0.5 m or lower. To incorporate internal walls, the modified temporary DTM that was previously imported into RAS Mapper is cloned as a virtual terrain. A new modification layer is added where walls are drawn as shapes, with an assigned elevation value equal to ceiling height. To ensure accuracy, the shapefile containing the walls is imported from QGIS and used as a reference for tracing. For each wall or column drawn, a corresponding refinement region is defined to improve the resolution of the computational mesh, setting the cell size to either 0.5 m or less depending on the size of the column or partition being considered (Figure 2, panel e).

2.3.2 | Boundary Conditions

The boundary conditions lines drawn in QGIS are imported into RAS Mapper. To extract the hydrograph from the urban simulation, the urban-scale model is opened, and RAS Mapper is used to define profile lines corresponding to the boundary condition lines. The hydrograph is extracted by choosing the option "Plot Time Series" followed by "Flow." The hydrographs are extracted for the simulated urban-scale flood scenarios if the flood reaches the position of the boundary line, that is, of the openings assessed during on-site inspection. The building-scale inflow hydrographs are temporally aligned with the urban-scale inundation model and inherit the temporal resolution of the urban-scale simulation output. Consequently, the building-scale inflow hydrographs may contain zero values until the inundation reaches the building, and hydrographs at different locations may have temporally shifted starting times. For buildings free on all the perimeter with openings on all sides it might happen that only one of the sides gets wet during the inundations, especially over uneven grounds or in case of large building footprints.

Moreover, different reduction coefficients are applied to the boundary conditions flows to understand the effect of a fully open aperture or a partly open aperture to account for possible mitigation scenarios for example, flood gates applied, sandbags applied etc. The model reproduces the inundation inside the building allowing for the understanding of the floors or environments potentially affected and the severity of the inundation, that is, water depth and velocity.

2.4 | Risk Assessment and Mitigation

The building-scale inundation model is capable of simulating water depths within the various CH spaces, which may differ significantly due to uneven floor elevations. By providing such detailed hazard information, the assessment of exposed spaces and artworks becomes more realistic, thereby supporting CH managers in determining which artworks can be displayed on flood-prone floors—those considered less vulnerable—and in deciding whether to relocate more susceptible elements.

In this study, we demonstrate the applicability of the building-scale flood hazard model for risk mitigation by considering the following precautionary actions:

FIGURE 2 | Building-scale flood model set-up. Building plan of the underground floor (a), picture taken during on-site inspection (b) elevation of the exhibition spaces (c), baseline mesh with resolution refinement (d), full mesh with architectural elements and elevations (e).

- Reducing the ingress of floodwater into the CH building by applying fixed scaling factors, to conceptually describe the adoption of some floodproofing strategies (prevention measure):
- Identifying exhibition spaces suitable for different types of artworks (with and without prevention measures) based on display type and material vulnerability (mitigation measures).

For simplicity, and without aiming to cover all possible display modes, we consider three main types of artwork display: (i) on the ground (e.g., statues), (ii) on walls (e.g., paintings), and (iii) on pedestals (e.g., small objects such as goldsmith's art or pottery). Regarding material vulnerability, we refer to the literature (De Lucia and Arrighi 2025; Figueiredo et al. 2021), which typically associates high vulnerability with artworks made of wood, canvas, and paper, etc. and lower vulnerability with those made of stone, metal, or ceramic.

To provide guidance for heritage building managers, the exhibition spaces are classified and colour-coded into three categories:

1. Spaces with low flood hazard and low simulated water depths, which are suitable for a variety of artworks, either with low material vulnerability and placed directly on the

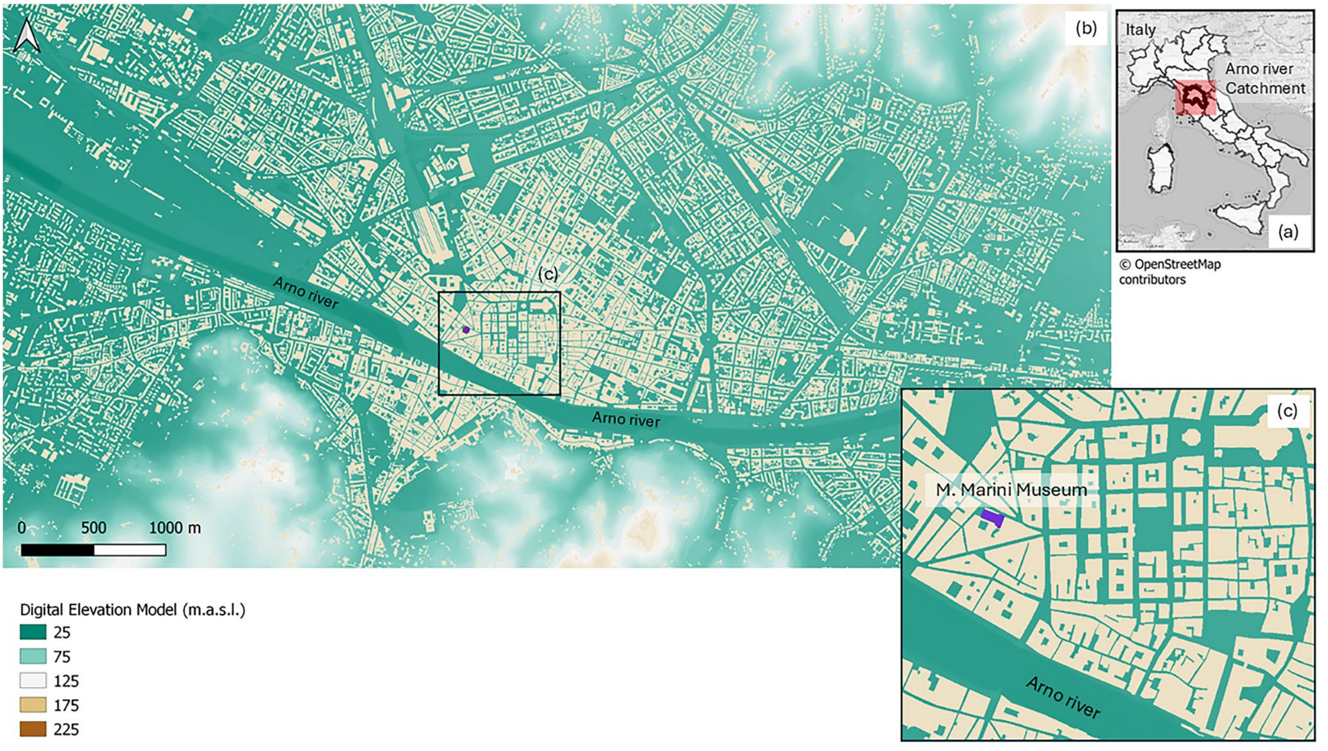


FIGURE 3 | Setting of the study area in the Arno river catchment in Italy (a), terrain elevation of the urban area (b), historical city centre and Marini Museum (c).

ground (e.g., metal or stone statues) or with higher vulnerability but displayed on walls or pedestals. Colour code: green.

2. Spaces with medium flood hazard and simulated water depths between 0.3 and 0.8 m, which are suitable for artworks with low material vulnerability placed directly on the ground, or for artworks with higher vulnerability if displayed on pedestals (typically available on the market with heights of 0.95–1.10 m). In this case, walls are considered prone to rising water infiltration; therefore, hanging paintings is not recommended. Colour code: yellow.
3. Spaces with high flood hazard and simulated water depths above 0.8 m, which remain suitable only for artworks made of waterproof materials. Colour code: magenta.

The classification proposed here is intentionally general and illustrative and does not account for the specific characteristics of individual artwork collections, which may include different material types and display modes.

3 | Case Study Florence and the Marini Museum

Florence (Italy) situated along the Arno River, faces a long-standing flood risk due to its geography, climate, and historic urban development (Figure 3). The most devastating flood occurred in November 1966, causing 38 deaths and severe damage to cultural heritage, including artworks and manuscripts. The city lies within a 4300 km^2 drainage area of the Arno basin (Figure 3, panel a), which spans diverse sub-basins in mountainous Tuscany. In Florence, the Arno flows through a confined channel with weirs and bridges that restrict its capacity, increasing flood hazard (Galloway et al. 2020).

Historical floods date back to the 12th century, with major events in 1333, 1557, 1844, and 1966—commemorated by plaques and maps across the city. The 1966 flood was triggered by over 200 mm of rainfall in 48 h, compounded by already saturated soil. The Arno exceeded its capacity for over 20 h, inundating the city with around 100 million m^3 of water. Peak discharges reached 4100 m^3/s, far above the channel's 2500 m^3/s capacity at the time. The floodwaters, laden with mud and toxic naphtha, caused lasting damage to buildings and cultural assets (Galloway et al. 2017).

The Marino Marini Museum (https://museomarinomarini.it/), located in Florence's historic centre, occupies the former church of San Pancrazio. Originally documented in the 9th century, the site saw various religious uses until a major restoration by Leon Battista Alberti (1457–1467), sponsored by the Rucellai family, who commissioned the creation of a side chapel on the west side—home to the Tomb of the Holy Sepulcher, a Renaissance masterpiece by Leon Battista Alberti. Deconsecrated in 1808 by Napoleonic edict, the building was altered, stripped of its furnishings, and repurposed over time—as a prefecture, tobacco factory (damaged by fire), and military depot. In 1988, after extensive restoration by architects Bruno Sacchi and Lorenzo Papi, it reopened as Florence's first museum of contemporary art, blending historic architecture with modern design. The Museum hosts Marini's artworks, mainly sculptures, drawings and engravings on four different levels, with the largest sculptures placed on the monumental ground floor. The building contains vast underground spaces, commissioned and built from the second half of the 14th century. These spaces are divided, and many are principally used for complementary and dynamic events enhancing the vitality of the museum, including: lectures, screenings, performances, and art exhibitions.

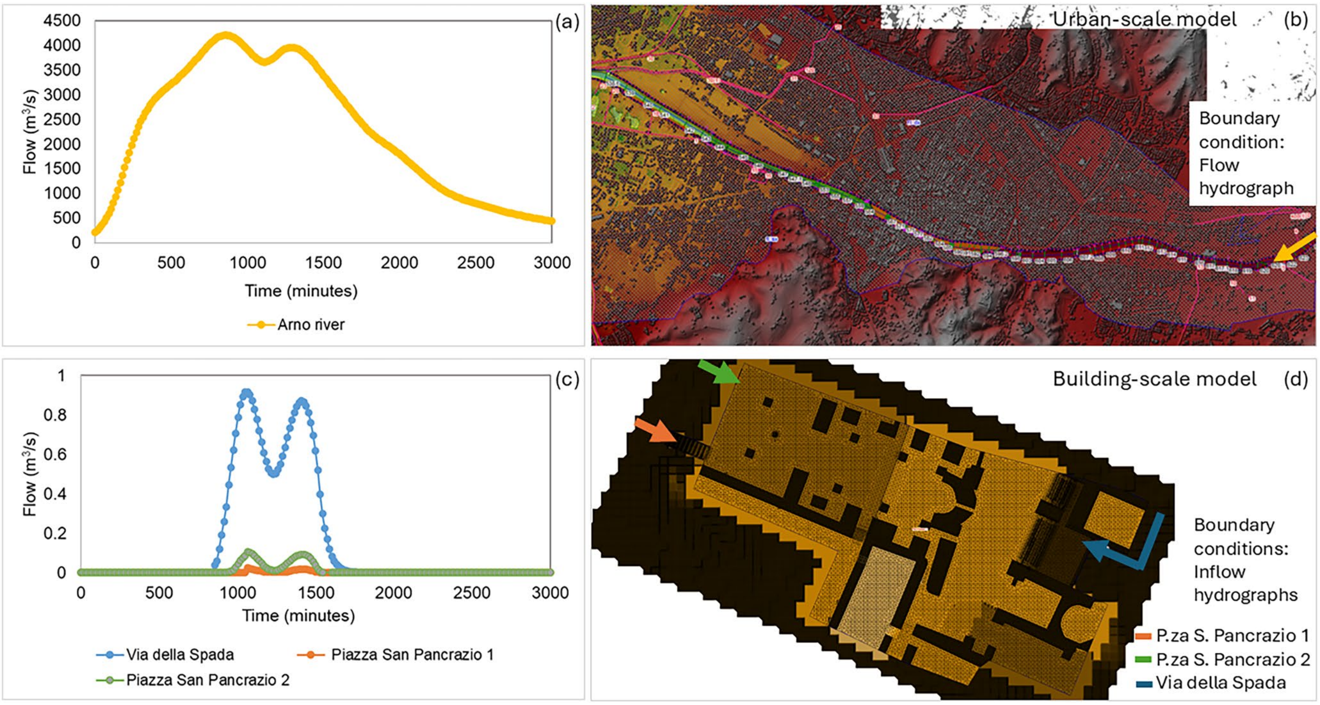


FIGURE 4 | Inflow hydrograph for the city scale (a) and the building scale (c) flood models for a 500-year return period. Location of the boundary condition upstream of the city (b) and at the building openings found during inspection (d). Note that for this flood scenario all three boundary conditions are active.

The museum is located in a medium flood hazard zone, according to official hazard mapping (Autorità di bacino del Fiume Arno 1999). Based on numerical simulations and historical flood events, even a severe event with a 500-year return period does not affect the ground floor, as it is situated more than 1 m above the adjacent road surface. In contrast, the basement (the former crypt of the Church of San Pancrazio) is exposed to flooding. It is connected to street level through three main openings that allow floodwaters to enter the building (Figure 2, panel e). The building openings—including a ventilation grille on the façade and two emergency exits (one on the façade and one at the rear)—are located at the elevation of the road pavement. Therefore, the inundation model setup focuses exclusively on the basement, using a base mesh resolution of 0.5 m, refined to 0.2 m in critical areas such as walls, steps, and pillars. The resolution of 0.2 m is considered appropriate as the smaller architectural detail is the step of a monumental staircase (approx. length 0.6 m). The roughness coefficient is assumed equal to 0.01 as the floor/wall materials are made of concrete, polished stone and ceramic. The final computational mesh includes 5300 cells. For the 200-year flood event, a single boundary condition is applied (corresponding to Via della Scala, Figure 2e), while three boundary conditions are active for the 500-year event.

4 | Results

The historical city centre of Florence (Figure 3, panel c) is exposed to flooding for return periods greater than 100 years, while downstream areas developed more recently are exposed even for a 30-years flood event. The two flood scenarios of interest for the building-scale model are the 200- and 500-years return periods, the latter characterised by a flood peak of approximately 4100 m^3/s like the 1966 historical flood. Different flood durations (18, 24, and 48 h) are also considered, consistently with the official hazard simulation made by the River District Authority. The 18-h hydrograph produces the highest peak discharge. In contrast, the 24- and 48-h hydrographs have lower peak discharges but longer flood durations leading to a larger flood volume entering the urban area. The validation of the urban-scale inundation model through comparison between the 1966 historical flood depths and the 500-years return period depths has been described in a previous work (Arrighi et al. 2022). Figure 4 presents the 500-year flood scenario, divided into four panels. It displays the inflow hydrograph with a 48 h duration (panel a) for the 1D-2D urban-scale model (panel b), and the corresponding building-scale inflow hydrographs with local durations between 9 and 15 h (panel c), which is applied at various openings shown in panel d. The arrows in panel d are colour-coded to match the hydrographs in panel c. The most significant floodwater ingress occurs via Via della Spada, with a peak flow slightly below 1 m^3/s. This corresponds to the largest opening, which is an emergency/service exit located at the end of a ramp. This entrance is used both for evacuations and for transporting artworks during exhibitions held in the basement. The two other openings, located on the main façade, contribute less to the flood ingress (with peak flows on the order of 0.02–0.1 m^3/s), as the elevation of the square is higher than that of Via della Spada.

In the 200-year scenario, the two openings on the square (main facade) are not reached by the flood; therefore, only the entrance from Via della Spada contributes to inundation inside the building, with a peak flow of approximately 0.02 m^3/s.

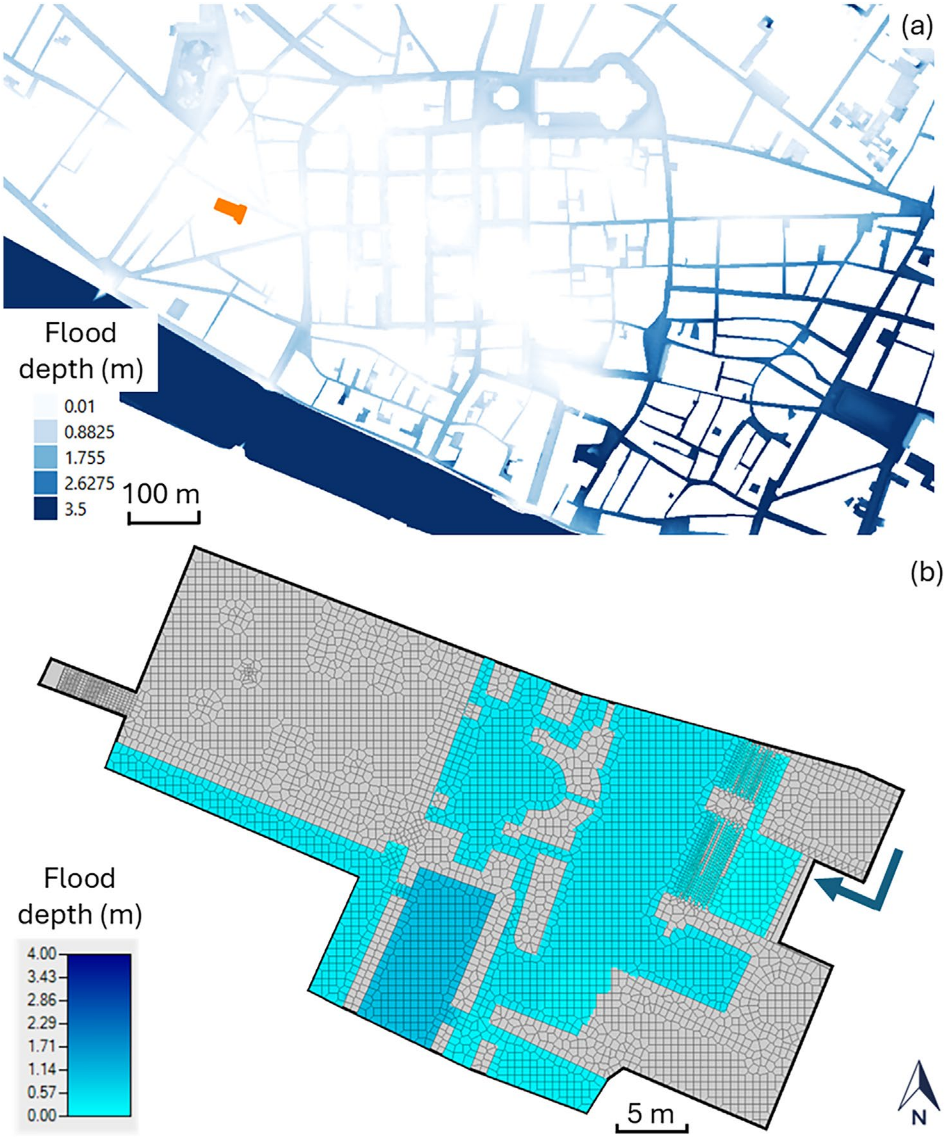


FIGURE 5 | Flood depth for a 200-years return period with a zoom on the city centre (a) and in the former crypt of the Marini Museum (b). The arrow indicates the active boundary condition. Please note that the colour scales of panels a and b are different due to different flood depth ranges at the two spatial scales.

The results for both the urban- and building-scale models are shown for the two flood scenarios in Figures 5 and 6. In Figure 5, panel a, we observe that under the 200-year flood scenario (with a duration of 18 h), the portion of the city centre where the Marini Museum is located is not among the most affected areas. Higher flood depths occur in the southeastern part of the map, whereas flood depths near the Marini Museum are about 0.5 m (Via della Spada is depicted in a light blue shade). Panel b of Figure 5 shows the inundation map inside the museum's basement, where only part of the exhibition space is flooded, with water depths on the order of 0.2–0.4 m.

In the 500-year flood scenario, the inundation more severely impacts both the city centre (Figure 6, panel a) and the museum. In this scenario, all exhibition spaces are affected, and the basement is flooded up to the ceiling. Since this scenario replicates the historical 1966 flood event, we can compare the simulation results with historical flood records. According to an interview with the museum's manager, the ground floor was not affected during the 1966 flood, while the basement was completely filled with mud up to the ceiling by the time renovation began in the 1980s. At the time of the 1966 flood, the building was no longer used as a depot and was not prioritised in post-flood recovery efforts, as other heritage buildings were considered to have higher social and cultural value.

To illustrate the effect of mitigation measures in preventing water ingress into the museum, we simulated scenarios where the inflow hydrographs were reduced to 50% and 10% of their original values. The results for the 500-year return period scenario are presented in Figure 7.

With a 50% reduction in inflow hydrograph (Figure 7, panel a), the basement remains significantly affected by flooding. While water depths are halved, they are still substantial—approximately

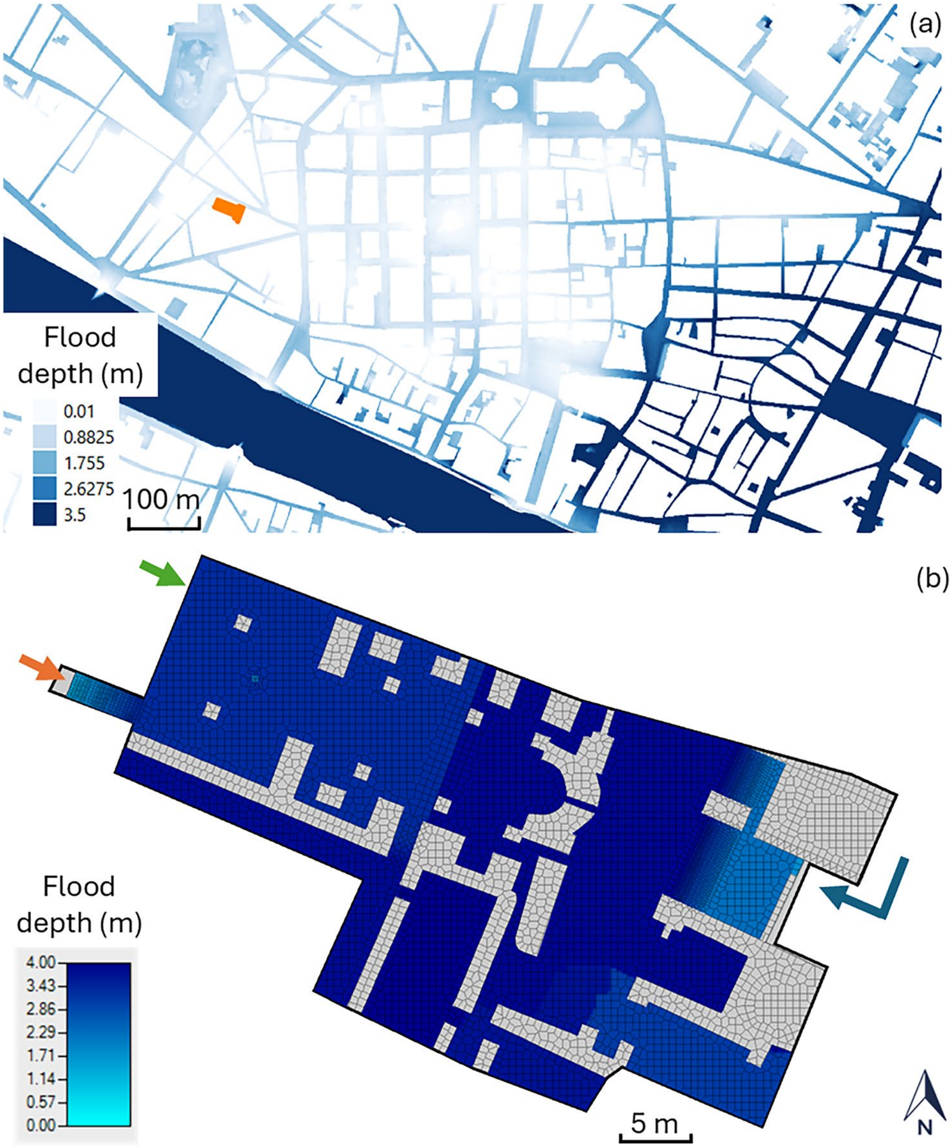


FIGURE 6 | Flood depth for a 500-years return period with a zoom on the city centre (a) and in the former crypt of the Marini Museum (b). The arrows indicate the active boundary conditions. Please note that the colour scales of panels a and b are different due to different flood depth ranges at the two spatial scales.

2 m in the lowest area (space 2; see Table 2 for reference). This floodwater elevation is not compatible with typical hanging heights of paintings during exhibition or presence of artworks on the ground, except for floodproof materials. When the inflow hydrograph is reduced to just 10% of the original hydrograph, the basement experiences a much more limited inundation. In this case, water depth in space 2 is approximately 0.6 m, while other spaces contain only a few centimetres of water (Figure 7, panel b; Table 2).

A depth of 0.6 m may be compatible with the display of small- to medium-sized paintings typically hung at adult eye level, or small and easily movable artworks placed on anchored pedestals, for example, goldsmith art or pottery typically at eye-level. However, it is not suitable for artworks placed on the floor, particularly if made from water-sensitive materials such as wood or paper. To support the Museum manager for temporary exhibition we can add a colour code (green to magenta) for each museum space and flood scenario (Table 2).

A combined mitigation strategy for the Museum could include both significantly reducing water ingress—for example, through the installation of flood gates at the ramp on Via della Spada—and limiting the exhibition in space 2 to artworks made from resilient materials, such as stone sculptures or artworks placed on anchored waterproof pedestals.

5 | Discussion

In this work, a new building-scale level of analysis for flood hazard modelling is introduced to address the specific challenges of risk analysis, management, and adaptation of cultural heritage buildings. The building scale adds an additional level of detail for flood hazard assessment, expanding upon the seminal work by de Moel et al. (2015). The peculiar nature of these structures, along with their intangible and inestimable values, justifies the effort required to analyse flood hazards at the building scale, as recently demonstrated by

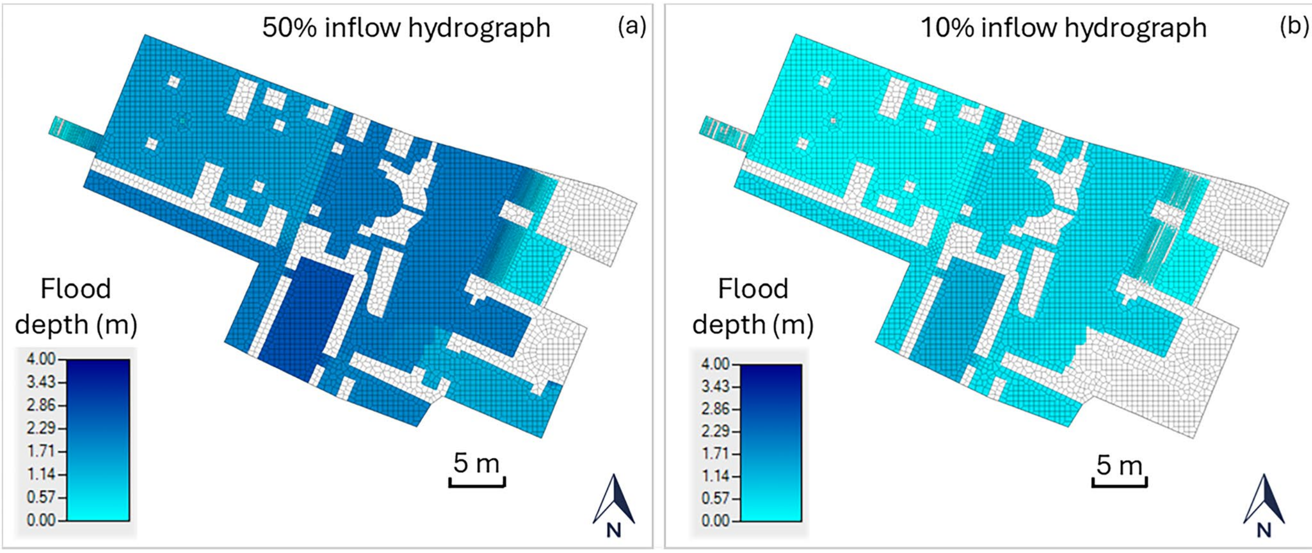
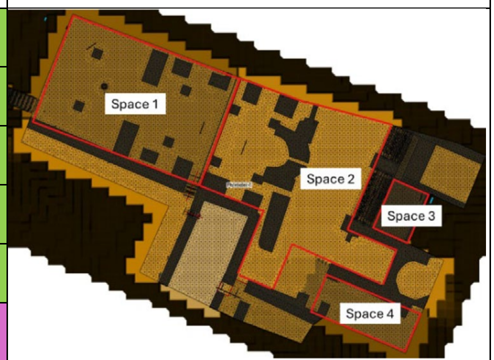


FIGURE 7 | Flood depths in the building for mitigation scenarios with 50% and 10% of the inflow hydrograph (a, b).

TABLE 2 | Flood depth in the different exhibition spaces of the Museum under normal and mitigated scenarios and support for artworks display according to expected water depths.

		Flood scenario		Flood depth (m) in the Museum Spaces			
		Return Period	Duration	Space 1	Space 2	Space 3	Space 4
Inflow Hydrograph	10%	Tr 200	18 h	0	0.004	0.01	0
		Tr 200	24 h	0	0.01	0.01	0
		Tr 500	48 h	0.03	0.58	0.03	0
	50%	Tr 200	18 h	0	0.02	0.01	0
		Tr 200	24 h	0	0.04	0.01	0
		Tr 500	48 h	1.55	2.11	0.5	1.3
	100%	Tr 200	18 h	0	0.23	0.03	0
		Tr 200	24 h	0	0.39	0.03	0
		Tr 500	48 h	3.34	3.95	2.29	3.09

Plan of the Exhibition Spaces



- Artworks hanged on the wall, on waterproof pedestals, or in waterproof materials.
- Artworks on pedestals or in waterproof materials.
- Artworks in waterproof materials.

Alexopoulos et al. 2025 and Tamagnone et al. (2025) for pluvial flood hazard in CH sites.

The methodology for building-scale flood hazard assessment here introduced goes in the direction of re-aligning the risk assessment scale with the scale of vulnerability models, overcoming the limitations of studies that adopt flood depths from larger-scale inundation models for risk assessment of CH (Arrighi 2021; Figueiredo et al. 2020; Kim and Sung 2024; Nobile et al. 2025; Simonelli et al. 2022).

Two important aspects, usually neglected, are addressed in this work: (i) the presence of basements, elevated ground floors, and uneven indoor layout, and (ii) the duration of flood depth at the building site, which governs the dynamics of inundation within the structure.

The complexity of heritage structures—particularly in identifying water ingress points and plan geometries—requires detailed on-site analyses, similar to those needed for the creation of highly detailed component-based vulnerability functions (Figueiredo et al. 2021). Interaction with local stakeholders and heritage managers is therefore essential to obtain insights into the building's structural details, service systems, and overall management practices. As is currently standard in seismic risk vulnerability analyses of heritage buildings (Chellini et al. 2014; Forcellini et al. 2019;

Sammartano et al. 2023), the increasing availability of 3D digital models obtained through laser scanning and Building Information Modelling (BIM) may facilitate in future the reconstruction of the computational mesh for building-scale inundation models.

In this study, the coupling between the urban-scale and building-scale flood models is implemented in an offline mode, meaning that the two models are run sequentially. An alternative approach would involve modifying the urban Digital Terrain Model (DTM) to directly include the building's basement in the urban-scale model as a local elevation change beneath the footprint. This method could allow the consideration of backwater effects, which are neglected in offline coupling. However, for basement configurations, these effects are generally of limited importance, as floodwaters cannot naturally flow out of building levels located below the road surface.

From a modelling perspective, downscaling from the urban to the building scale still presents several challenges, such as uncertainties related to high-resolution DTMs near the building boundaries—where the inflow hydrographs are extracted (e.g., artefacts, post-processing errors)—as well as the well-known sensitivity and uncertainty of flood models (Alipour et al. 2022). Nevertheless, adopting a static flood depth value from urban-scale maps, without considering the building-level inundation dynamics, would have resulted in a scenario of a fully flooded basement for both return periods considered, thereby overestimating the severity of inundation within the building under the 200-year flood scenario. Historical evidence from the 1966 flood, where the basement was completely filled with mud, qualitatively supports the simulated 500-year scenario. The information about the mud level has been provided during the interview with the Museum manager, but quantitative data are lacking and limit a full validation.

Regarding the mesh size adopted for the building-scale inundation model, a maximum cell size of 0.5 m and a minimum of 0.2 m near architectural details are considered acceptable, as the floor elevation remains constant within each space and the smallest features (e.g., the steps of a monumental staircase) are approximately three times larger. A sensitivity analysis of mesh size could be addressed in future research. Overall, for this specific application to the museum basement, the most sensitive aspect is the boundary inflow hydrograph, as the model simulates a filling process in which mass conservation is the key governing mechanism. Limited importance is attributed to mesh size, provided that the mesh can represent the main architectural features and to the roughness coefficient. The availability of quantitative data from past events, which are currently not available, would allow model validation and a better understanding of model sensitivities.

The identification of appropriate flood mitigation strategies—such as temporary flood gates, sandbags, or revised arrangements for temporary exhibitions—can be more effectively achieved using the proposed building-scale approach. Although the simulation simplifies the adoption of floodproofing measures by applying an arbitrary reduction factor, it conceptually demonstrates that a site-specific strategy depends on the availability and willingness of the museum manager to relocate items from the collection. Strong opposition to relocating vulnerable pieces may therefore require floodproofing measures with greater protective capacity. Furthermore, simulating inundation at this scale enhances communication and decision support for heritage managers, as flood visualisations greatly improve interpretability (Heyer et al. 2020; Laefer et al. 2025). The resulting digital flood information also offers opportunities for integration into digital twins or Building Information Models (Colucci et al. 2025), supporting more comprehensive heritage management frameworks (Li 2024). Possible integrations of building-scale inundation models and Building Information Models include the 3D visualisation of simulated water levels within different exhibition spaces (with potential applications in augmented reality), the visualisation of the colour-coded classification of spaces in terms of their suitability for artworks, and their potential combination within multi-risk analyses.

6 | Conclusions

This work has introduced building-scale flood hazard modelling with sub-metre resolution, as a tool for improving the understanding of flood risk and adaptation measures for cultural heritage buildings.

The main achievements of the study are as follows:

- Development, set-up, and testing of a novel building-scale inundation model capable of accounting for complex internal layouts, based on detailed information about the heritage structure (e.g., location of openings, floor elevations, internal spatial configuration, and architectural details), and its application to a case study of the Marini Museum (Florence, Italy).
- Enhanced understanding of flood hazard within exhibition spaces under various flood scenarios (return period and duration), in comparison with results derived solely from urban-scale flood hazard maps, by accounting for flood probability and flood duration.
- Simulation of mitigation scenarios, including reduced water ingress through openings to represent the adoption of floodproofing measures (e.g., flood gates or sandbags).
- Identification of suitable flood risk mitigation strategies, such as basement floodproofing and the reorganisation of exhibitions based on the vulnerability of artwork materials, at the resolution of exhibition spaces.

This approach demonstrates strong potential for integration into digital visualisation and management tools, thereby supporting heritage managers in the identification and planning of flood risk mitigation measures. Further research should focus on acquiring validation datasets and testing inundation models in multi-level buildings that are potentially exposed to flooding.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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