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Modelling Resilience to Floods in Art Cities: A Historical Perspective

Chiara Arrighi[1,2] | Fabio Castelli[1,2]

[1]Department of Civil and Environmental Engineering, University of Florence, Florence, Italy | [2]RETURN Foundation, Corso Umberto I, 40, Napoli, Italy

Correspondence: Chiara Arrighi (chiara.arrighi@dicea.unifi.it)

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ABSTRACT

Art cities are characterized by peculiar exposure and vulnerability aspects which are rarely addressed in flood risk studies. This works investigates art cities in terms of exposure and resilience by considering the effects of cultural heritage. Flood hazard considers a "what-if" scenario comparison based on an historical event as it occurred in the past and as it would occur today and in future with countermeasures in place. The analysis is carried out in the city of Florence (Italy), a UNESCO World heritage site, affected by the last flood in 1966. The results show that countermeasures have slightly reduced inundation extent (−7%) and depths. Exposure of buildings has increased (+17%), but the exposed residential population has decreased (−38%) due to gentrification. On the other side, the fluctuating population exposure has dramatically increased (+1511%). Finally, despite the limited flood hazard reduction, resilience has increased, with a reduction of post-event recovery time (−21%). In future, completed mitigations works will reduce substantially flood hazard and exposure of residents and tourists. It appears that cultural heritage plays a twofold and contrasting role. On the one hand, it attracts a fluctuating population, which increases exposure, and, on the other, it fosters the recovery.

1 | Introduction

Art cities are recognized as having art as a central feature of their cultural identity and usually base their economy, their existence, and their tourism on Cultural Heritage (CH). CH can be severely damaged by floods and might be increasingly threatened by climate change effects (Cassar and Pender 2005; Fatorić and Seekamp 2017; Gizzi 2021; Marzeion and Levermann 2014). Different aspects of culture, risk reduction, and resilience are considered crucial by international disaster risk reduction frameworks (UNISDR 2015; United Nations 2005) for promoting risk management and preserving cultural assets. Postdisaster recovery of communities and art cities is facilitated by the presence of CH (Galloway et al. 2020; Genova et al. 2020; GFDRR 2020; Jigyasu 2016; Kumar 2020). One of the definitions of resilience is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard" (Heinzlef et al. 2020; McClymont et al. 2020; UNISDR 2015). Resilience is facilitated by the revenues generated from tourism activities, pending the magnitude of impact as well as the efficiency of community participation and governance (Min et al. 2020; Nair and Dileep 2020; Rosselló et al. 2020).

The understanding of flood risk and resilience is crucial to finding appropriate adaptation countermeasures and the adoption of a historical perspective, that is, analyzing the settings that shaped flood risk and its components in the past can unveil significant aspects to investigate. Analyses of historical data are common in flood risk studies, especially when dealing with frequency analysis of floods (Lam et al. 2017; Viglione et al. 2013) or when assessing the effectiveness of countermeasures (Tong et al. 2021). The understanding of past evolution of floodplains is also one of the most relevant topics in socio-hydrology (Di Baldassarre et al. 2013). However, few studies have analyzed from a historical perspective the evolution of both hazard and exposure to flooding (Akhter et al. 2021; Di Baldassarre et al. 2017).

Particularly in art cities, some evolutionary mechanisms can be different from other study areas, and vulnerable assets and types of impacts, either tangible or intangible, direct or indirect, are peculiar. Typical intangible losses to CH refer to historical, spiritual, aesthetic, and social values that constitute the cultural significance of a property (Appiotti et al. 2020; Spennemann and Graham 2007). Thus, although significantly related to many profitable economic activities that generate revenues and employment, the exposure of cultural heritage is hardly monetizable (Bowitz and Ibenholt 2009; CHCfE 2015). Direct damages to CH due to physical contact with floodwaters can be irreversible or might take decades to be repaired, such as in the case of long restoration of artworks. Besides direct impacts to CH, indirect impacts that occur later are relevant for the economy based on tourism (Biardeau and Sahli 2024). For the above reasons, the assessment of disaster losses on cultural heritage is less advanced than other exposed assets and is considered quite challenging due to the multidimensionality of the problem (Romão et al. 2020; Romão and Paupério 2021; UNDP 2013). A recent work developed a model to estimate indirect impacts on art cities that interconnect vulnerability, resilience, and recovery (Arrighi et al. 2022). The work adopts the number of visitors to CH as a proxy of their socioeconomic value and utilizes the number of visitors as a reference state variable of the art-city system.

The presence of visitors is another peculiarity of art cities. A massive presence of tourists not only represents an additional source of exposure, that is, a fluctuating population to add to the residential one but also shapes the urban neighborhoods. In fact, tourists are recognized as a source of additional pressure on cultural heritage (García-Hernández et al. 2017) and as the driver of important displacement of residents, that is, gentrification (Cocola-Gant 2023; López-Gay et al. 2021). In fact, studies in tourist cities, for example, Venice (Italy), Barcelona (Spain), and Kyoto (Japan), indicate that tourism gentrification has caused a population decline in historical areas (Genc et al. 2022; Tanaka et al. 2023), which might induce one to believe that population exposure has decreased. Although tourism gentrification is recognized as crucial for decision-makers as a process that triggers many negativities, the relationship between exposure to natural hazards and gentrification has not been studied so far. Most of the works in the literature deal with exposure to floods of the resident population by leveraging census data or remote sensing data (Mohanty and Simonovic 2021; Scaini et al. 2024; Tellman et al. 2021). However, as recently highlighted by a work focusing on mobility-based exposure, that is, commuting to work or school (Li et al. 2024), fluctuating population emerges as a topic little explored, which might reveal social inequalities. Nevertheless, works that address the exposure of fluctuating populations related to tourism and CH are rarely found.

The general aim of this work was to explore some of the peculiarities of flood risk in art cities, that is, in a context with a high concentration of CH and visitors that feed the local economy. We adopt a historical perspective (Paprotny et al. 2018; Tanoue et al. 2016) to understand how flood hazard, exposure, and resilience have changed in the past decades after an important flood event (with high impact-low probability) and how planned mitigation measures will change the risk of flooding in future. The aspects taken into consideration are (i) the change in flood hazard due to countermeasures, (ii) the evolution of exposure of three main assets, that is, buildings, CH, and population (both residents and fluctuating), and (iii) the change in recovery time and resilience through cultural heritage.

The study area is the art city of Florence (Italy), which hosts about 370,000 inhabitants and approximately 10 million tourists each year. The reference *what-if* flood scenario is the historical 1966 flood as occurred in the past compared to the same hydrologic event as if it occurred today. The two research questions to be answered are: “How did the hazard and exposure evolve in the city?” and “Did the prevention measures undertaken after the 1966 flood increase the resilience of the city?”

2 | Materials and Methods

Understanding how a city has evolved after a major disaster is not an easy task, especially if the event has occurred in the past with limited documentation and data availability. This work, given the peculiarity of art cities, considers a historical perspective focused on three main aspects: (i) the comparison between the historical flood and the same flood hydrograph as if it occurred today, that is, the level of flood hazard prevention achieved, (ii) the evolution of exposed buildings, cultural heritage and population (resident and fluctuating), and (iii) the comparison between recovery times and resilience achieved through cultural heritage today (with the past hazard and today hazard).

The workflow is structured around three main steps: first, the flood hazard modeling and mapping, second, the exposure analysis, and third, the resilience model for cultural heritage. Exposure analysis is carried out for three main assets, that is, population, residential buildings, and cultural heritage buildings. A short description of the study area is included in the following section.

2.1 | Case Study

The study area is the art city of Florence located in central Italy (Figure 1a). The historical city center is inscribed in the list of UNESCO World Heritage sites since 1982 (Figure 2b, blue polygon) where most CH buildings are located (orange polygons in Figure 1b). The city was affected by a flood in 1966 which had a significant impact on CH and a world resonance (Galloway et al. 2017; Kumar et al. 2021). Numerous marble plates describe the level reached by floodwaters in 1966 (Figure 1, panels d, e). Florence is one of the most visited art cities in Italy (and the in world) with more than 10 million presences in 2019 (IRPET 2019).

Since the last flood in 1966, the only significant interventions were the lowering of the aprons of two bridges in the center of

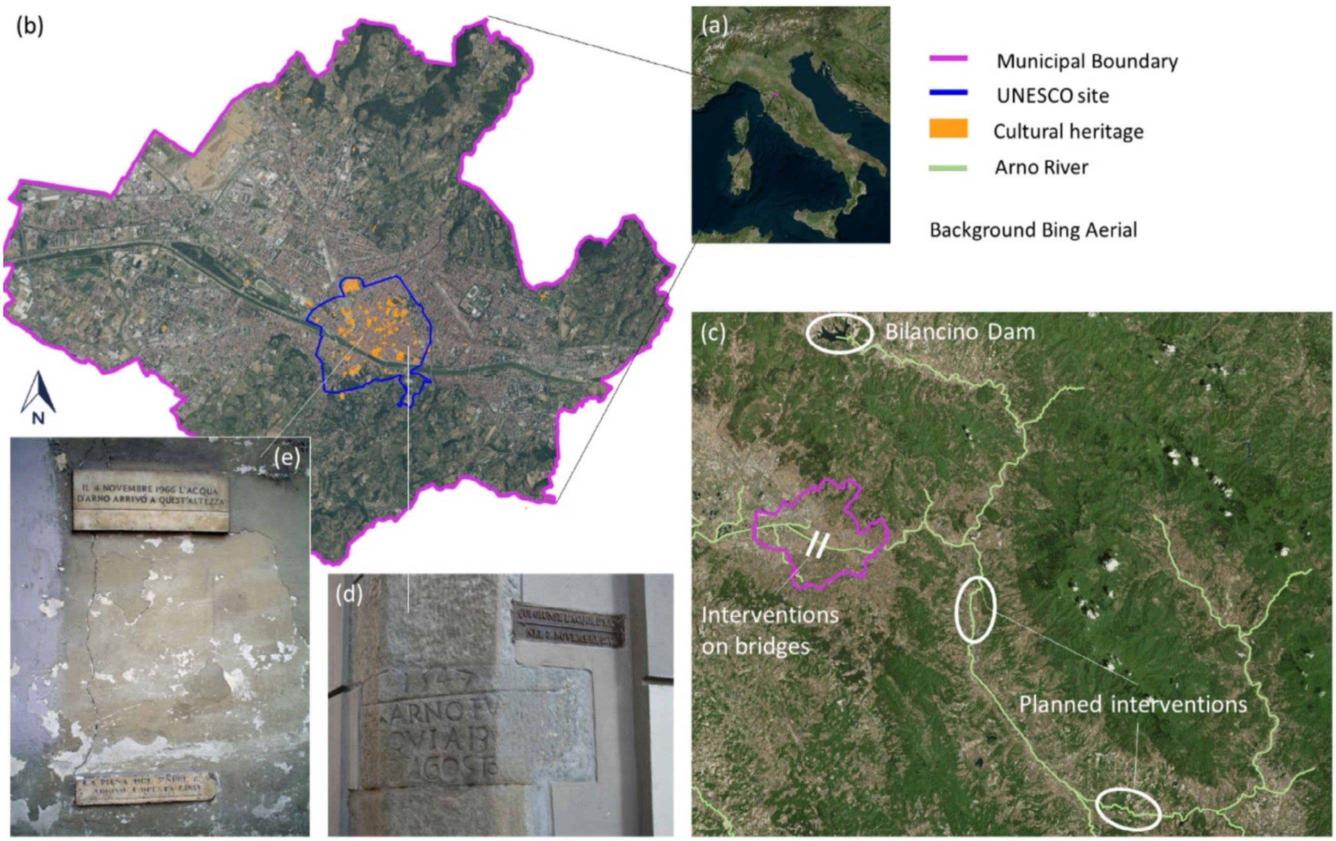

FIGURE 1 | Setting of the municipality of Florence (central Italy, a) and the UNESCO site perimeter (b). Locations of the existing and planned interventions for flood hazard reduction (c), pictures of the historical marble plates indicating water level in the city (d, e) (credits: curiositadifirenze.blogspot.com).

the city, which increased the conveyance capacity of the Arno River in the urban reach from 2500 to 3100 m^3s^{-1} (3400 m^3s^{-1} with no safety allowance) and an upstream dam which reduced the flood flow in Florence by 100–200 m^3s^{-1} (Galloway et al. 2020) (Figure 1, panel c). In this area, the so-called "levee paradox" (Di Baldassarre et al. 2013) is not observed, and the general perception is that a low-probability, high-damage event should have limited importance in flood risk decisions (Merz et al. 2009).

The mitigation measures currently under design and construction (Figure 1, panel c) have the ambition of reducing almost completely flood risk in the historical city center. The planned interventions that will become operational in future are (1) four retention basins, (2) the increase in the height of the dam crest in the Levane reservoir, and (3) the increase of volume for retention in the Bilancino reservoir.

2.2 | Flood Hazard Mapping

The flood is simulated by a coupled 1D-2D hydraulic model within the HEC-RAS 5.0.7 environment. The water profile in the river is simulated with a 1D approximation with the cross-section's geometry provided by the District of the Northern Apennines and based on a detailed topographic survey of river bathymetry and infrastructures, for example, bridges and weirs. The river is connected to the flood plain through lateral weirs, which allow the water to enter the 2D computational domain, modeled through a diffusive wave equation. The computational mesh has a resolution of 1 m based on a LiDAR-derived digital terrain model, and buildings are considered waterproof blocks. The downstream and upstream boundary conditions are a rating curve and a reconstructed historical river flow hydrograph, respectively. The reconstructed historical flood hydrograph is obtained from a fully distributed hydrological model (Yang et al. 2014) of the Arno River catchment with the precipitations recorded at rain gauges during the event. The historical flood map of 1966 is freely available and drawn after the event through the collection of water level data in the area.

To consider the effect of the planned flood mitigation measures, the 1D-2D hydraulic model is run with a different river flow hydrograph obtained by a 1D model of the river and tributaries with fully operational works.

2.3 | Exposure Analysis

The analysis of exposure identifies three different asset typologies that lie in the inundated area, namely population, buildings, and cultural heritage. To reconstruct the historical population, an ad-hoc method has been constructed and validated (see Section 2.3.2).

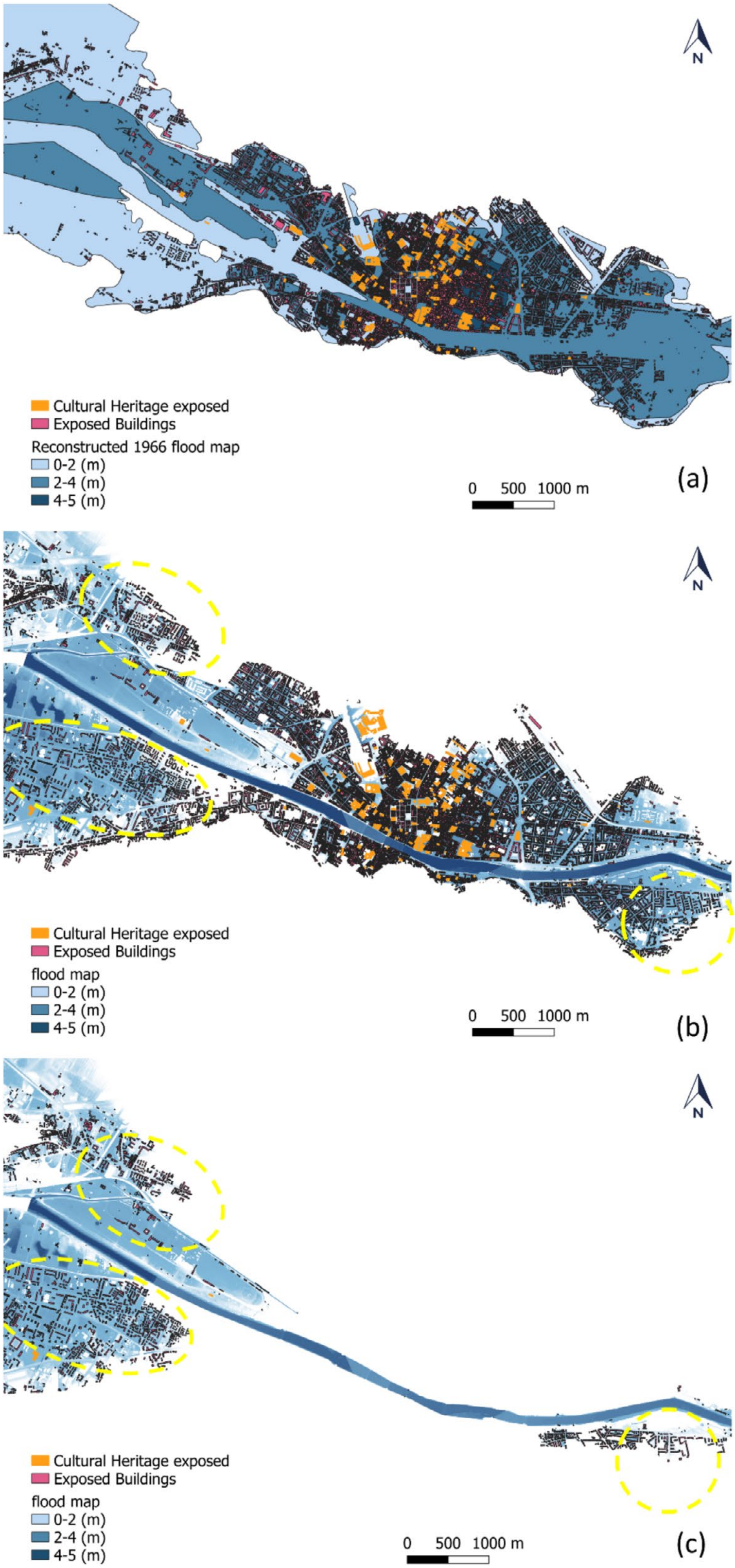

FIGURE 2 | Reconstructed 1966 historical flood map (a), simulated hydrologic event today (b), simulated hydrologic event with mitigation measures. Yellow dashed circles (panels b–c) highlight changes in building exposure since 1966.

2.3.1 | Residential Buildings and Cultural Heritage

For the exposure of buildings in present times, the current digital cartography (scale 1:2000) of the area has been used. For the buildings in the 60's, the results of the work by (Lucchesi et al. 2009) have been adopted. The work has reconstructed the period of the buildings based on historical cadastral maps of the beginnings of the XIX century and the aerial imagery collection of 1954–1956.

For cultural heritage buildings, a shapefile has been provided by the local Hydrographic District of the Northern Apennines. The historical flood levels at the CH buildings and river cross sections are retrieved from a dataset of the Hydrographic District of the Northern Apennines.

2.3.2 | Population

For the exposed population, we consider both the residents and the tourists (fluctuating population). To determine the population in 1966, the census data of 1966 have been used (Istituto Centrale di Statistica 1966). The data refers to the overall municipal population; however, the exposure analysis requires a more detailed spatial distribution of the people. A model to redistribute residents has been constructed as follows. The average volumetric density of residents D_P has been calculated by dividing the overall municipal population in 1966 P_{66} by the volume V_{66} of the buildings obtained by multiplying the footprint surface A_{66} by the number of storeys f.

$$D_P = \frac{P_{66}}{\sum_{i=1}^{n} A_{66i} * f_i} \tag{1}$$

where n is the number of buildings. The population in the ith building $P_{66\_B\_i}$ is then obtained by multiplying D_P by the volume of the ith building.

$$P_{66\_B\_i} = \frac{D_P}{A_{66\_i} * f_i} \tag{2}$$

To validate the methodology, the same Equations (1) and (2) have been applied for the current population and current buildings and compared with the anagraphic data available per each building, using as an aggregation unit of the census polygons.

For the fluctuating population, the estimation of the annual number of visitors at the level of each cultural building is possible only for the present time, due to available reports. In the past, we have the overall number of tourists in the municipality. It is assumed that visitors are distributed in the UNESCO perimeter during the daytime to visit cultural heritage and around hotels and accommodations at nighttime. Moreover, we assume a constant presence of tourists during the year, which is indeed verified by a very limited seasonality of fluxes in the study area.

2.4 | Resilience Model

The resilience model (Arrighi et al. 2022) combines a depth-idleness vulnerability function with a dynamic recovery model which accounts for (i) the reopening time of the flooded cultural heritage building, (ii) the number of visitors in the building, and (iii) the attractivity of the site. The model has been conceived both to estimate indirect losses to CH in terms of lost visitors and recovery time after an event. In this work, the model is applied to investigate some of the benefits of flood hazard reduction in a quantitative way, that is, reduction of indirect losses to CH and increase of resilience. The depth-idleness vulnerability function yields about 3 months of closure T_O for each meter of floodwater in the CH building (for more details refer to Arrighi et al. 2022).

For the resilience model, the number of visitors in the city is assumed as the state variable to be assessed in time. The number of visitors lost is also the metric for flood indirect impacts. The resilience model initializes with the average daily number of visitors $V_{i,0}$ in normal conditions, that is, all CH open to the public. The application of the vulnerability function for each flood scenario provides T_O for each building. In time, each ith attraction $M_i(t)$ can be either open or closed. The willingness to visit the site reduces if only part of the CH is accessible. In other words, there is a sort of delay in coming back after a flood event because the site loses its attractivity (Dube and Nhamo 2020). Thus, the dynamic of visitors $V(t)$ is also a function of attractivity according to a power law with exponent k,

$$V(t) = V_{\text{pot}} \left(\frac{\sum_{i=1}^{m} V_{i,0} M_i(t)}{V_{\text{pot}}} \right)^k \tag{3}$$

where V_{pot} is the potential number of visitors if all the attractions are open in business-as-usual conditions, and $\sum_{i=1}^{m} V_{i,0} M_i(t)$ is the number of visitors for the open attractions at time t, $V(t)$.

At each time step, the loss of visitors $V_{\text{loss}}(t)$ is the difference between V_{pot} and $V(t)$. By integrating $V_{\text{loss}}(t)$ in the time between the flood (T_{shock}) and the end of the recovery (T_{end}), the total loss for the selected exceedance probability scenario $1/T_R$ is obtained.

By integrating all the losses occurring for each scenario the risk expressed as the annual average number of visitors lost can be estimated as

$$\text{Risk} = \int_0^1 \int_{T_{\text{shock}}}^{T_{\text{end}}} V_{\text{loss}}(T_R, t)\, \text{d}t\, d\left(\frac{1}{T_R}\right) \tag{4}$$

2.5 | Data

Table 1 summarizes the different datasets used in the work, their resolution, and their source.

3 | Results and Discussion

The first comparison is based on the flood hazard in the study area. With respect to the historical flood of 1966, the same hydrologic event today would have an average reduction of about 0.55 m of flood depth and a reduction of inundated area of 2.2 km^2. With the hazard mitigation measures fully operational the inundated area will reduce to 9.9 km^2 (reduction of −67% with respect to the 1966 inundated area). Figure 2 shows the reconstructed historical flood map (panel a) and the present simulated flood map (panel b) that appear similar. The city center within the UNESCO perimeter remains

TABLE 1 | Datasets for flood hazard, exposure, and resilience modeling.

	Data	Description	Source
Flood hazard	Area inundated in 1966	Official map describing inundation extent and water depth intervals	Municipality of Florence, https://opendata.comune.fi.it/
	River cross-section	Topographic survey of river and hydraulic works (bridges, weirs, levees, etc.)	Hydrographic District of the Northern Apennines http://www.adbarno.it/opendata
	Digital Terrain Model	1 m resolution LiDAR-derived	Tuscany Region https://www502.regione.toscana.it/geoscopio
Potential impacts and resilience	Buildings (present)	Digital Technical cartography 1:2000 (shapefile)	Tuscany Region https://www502.regione.toscana.it/geoscopio
	Buildings in 1966	Periodization of the built environment 1:2000–1:10000	Tuscany Region https://www502.regione.toscana.it/geoscopio
	Cultural heritage buildings	Polygon shapefile 1:10000	Hydrographic District Of the Northern Apennines http://www.adbarno.it/opendata
	Population (present)	Anagraphic data, single building resolution (2021)	Municipality of Florence, personal communication
	Population in 1966	Census data at municipal resolution	Istituto Centrale di Statistica (1966)
	Visitors (present)	Number of annual visitors to each cultural building (2019)	Tuscany Region (2021)
	Visitors in 1966	Number of annual visitors in the municipality	Tourism archives, municipality of Florence (web page)
	Tourist accomodation	Number of activities and capacity	Municipality of Florence, Osservatorio Turistico di Destinazione (2015)

affected. Simulated flood depths (panel b) in the city center exceed 4 m in the most depressed areas. In fact, the hydraulic works and interventions made after 1966 are recognized as not effective for low-probability flood scenarios such as the historical 1966 flood, which has an estimated return period of ca. 500 years. In future, with the system of four retention basins upstream of the city and larger available volumes in two existing reservoirs, the inundated area will be limited to the area outside the historical city center both upstream and downstream (Figure 2, panel c).

If the historical and present inundation have limited differences in terms of depth and extent, the situation changes when looking at exposed buildings. Panel (b) of Figure 2 highlights with yellow dashed circles and three areas inside the inundated area that were flooded in 1966 with limited urbanization and are still flooded today with increased urbanization. According to the geospatial analysis, approximately 6500 new buildings have been constructed after the 1966 flood in historically inundated areas. The same areas, urbanized after the 1966 floods, appear to be exposed also when mitigation measures are fully operational (Figure 2, panel c).

Cultural heritage buildings (depicted in orange in Figure 2) are concentrated in the city center and show a similar level of exposure to historical and present floods, while they are almost unaffected by the future scenario with mitigation measures (see also Table 2). With respect to the population, the spatial redistribution model of Equation (1) and (2) is considered adequate to simulate the residents in 1966, as the coefficient of determination of the population model is 0.85. the result can be seen in the density scatter plot of Figure 3, panel (d). The scatter plot shows on the x-axis the current population data provided by the anagraphic office of the municipality, and on the y-axis the current simulated population according to Equations (1) and (2) applied in the present time. The color scale also shows the areas with the higher density of points (yellow shades) and points close to the bisect line appear denser than the others.

In Figure 3, panel (a) shows the current population from anagraphic data, and panel (c) shows the population distribution in 1966 as estimated by the model. The dashed orange circle identifies the historical city center. It can be clearly noticed that the population distribution has changed since 1966. In fact, at present, the residents have moved out of the city center, also occupying the buildings constructed after 1966 in flood-prone areas, as highlighted in Figure 2, panel (b). But more importantly, the city center today hosts a very limited number of residents with respect to 1966. This phenomenon is dominated by tourism activities which made it more convenient to transform residences into tourist accommodations, as clearly visible by panel (b) of

TABLE 2 | Summary of the comparison between historical, present, and future flood scenarios.

	Historical 1966 flood	Historical flood occurring today	Change % 1966-today	Historical flood with operational interventions	Change % 1966-mitigation
Flooded Area (km^2)	30.5	28.3	−7.2	9.9	−67.5
Resident population	456,121	366,548	−19.6	366,548	−19.6
Exposed population	235,997	146,325	−38.0	32,732	−86.1
Annual number of tourists (Mln)	1.9	10	+426.3	10	—
Exposed tourists (daily)	1700	27,400	+1511.8	650	−61.8
Exposed accomodation	—	1433	—	35	—
Buildings	59,746	77,475	+29.7	77,475	29.7
Exposed buildings	28,584	33,415	+16.9	4603	−83.9
Cultural heritage	176	176	—	176	—
Exposed cultural heritage	156	150	−3.8	4	−97.4

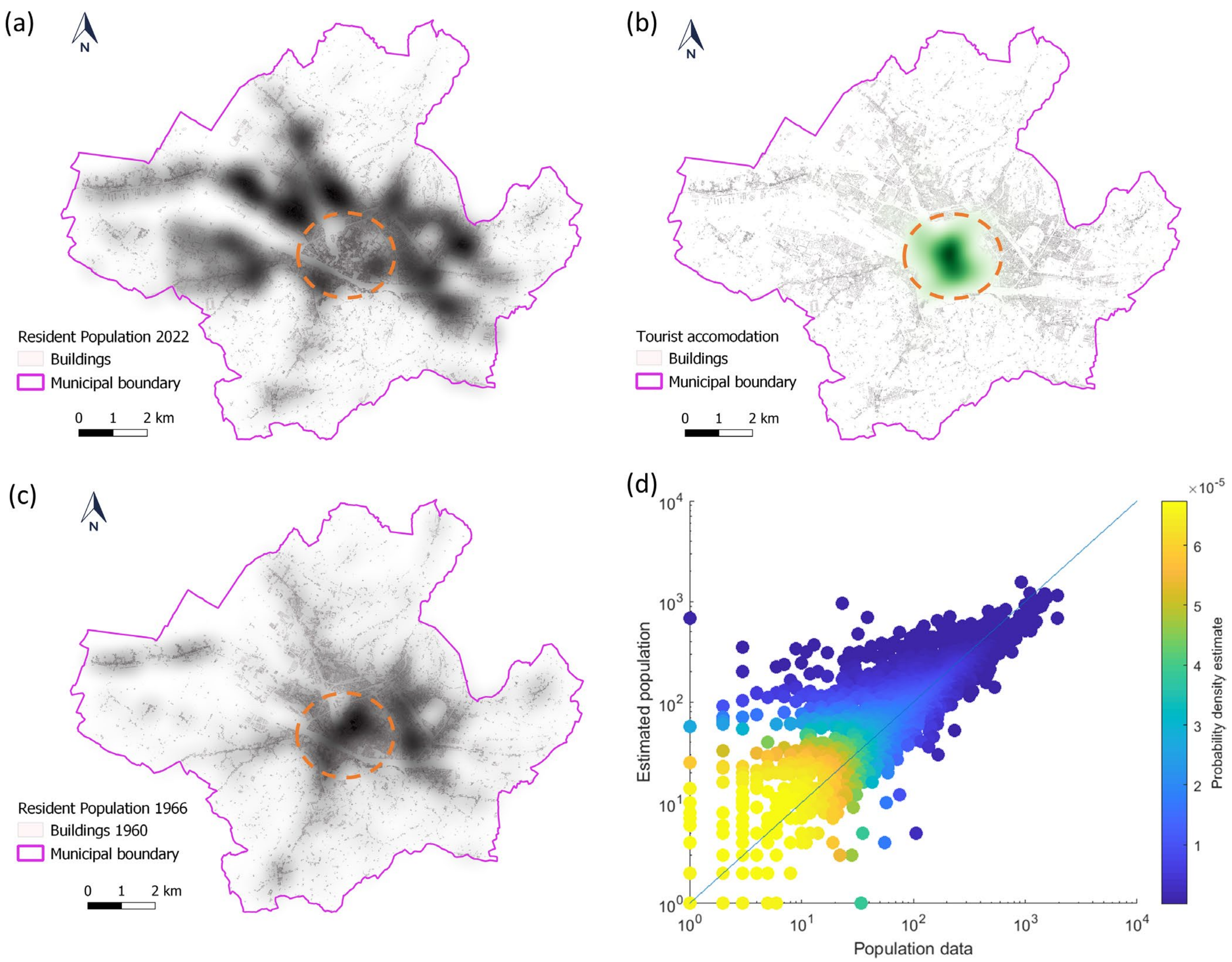

FIGURE 3 | Current population (a), density of tourist accommodation (b), simulated population in 1966 (c), performance of the population distribution model (d).

Figure 3 which shows the density of tourist accommodation (traditional accommodation, hotels, and B&B).

Moreover, the general population trend in the municipality presents a strong decrease from 1966, when approximately 456,000 people resided in the municipality up to approximately 366,000 residents in present times, that is, −19% (Table 2). In terms of exposure to floods this means that in 1966 approximately 236,000 people were exposed, while today 146,000 residents are exposed, that is, −38%. Thus, in part the reduction in population exposed can be attributed to the general decrease in population, in part to the abandonment of the city center. However, the city center is characterized by significant tourism fluxes, with 10 Mln visitors in 2019 (daily average of 27,397 people) before the pandemic and approximately 1.9 Mln visitors per year in the 60's (daily average of 1700 people) (Comune di Firenze 2021). According to the municipality offices (Osservatorio Turistico di Destinazione 2015), the maximum number of guests in the traditional accommodation is 32,000, mostly concentrated in the flood-prone city center (Figure 3, panel b). Based on the data, the fluctuating population is similarly distributed at day- and nighttime inside the city center (UNESCO perimeter), and it is therefore exposed to flooding. Table 2 shows a summary of the results of the comparison of the three hazard scenarios considered, that is, the historical 1966 flood, the same event as if it occurred today and the event with mitigation measures fully operational.

Therefore, although flood hazard has slightly decreased for the first two scenarios, in terms of exposure, the situation shows a twofold behavior. Exposed buildings have increased by 16.9% since 1966 due to the city expansion. On the other hand, the exposed resident population has decreased by −38%, but exposure has been partly replaced by a fluctuating population, that is, the tourists that show a dramatic increase in relative terms (+1550%). In absolute terms, the total population, that is, residents plus visitors, is lower today (173,725 vs. 237,697 in 1966). This decrease is not due to the awareness of the population but to gentrification which makes it more profitable to rent a house to tourists in the city center and reside elsewhere (in the periphery or even in neighboring municipalities). The lack of community awareness is also shown by the fact that many new buildings have been constructed in flood-prone areas after the 1966 flood, and this locally increased the population exposed in these specific areas (see also Figure 2 panel a with respect to panel c) where water depths are higher than in the city center. At the city level, this has unintentionally led to a transfer of flood risk from citizens to tourists inside the city center. The fluctuating tourist population today represents ca. 20% of the total population exposure, which is nonnegligible, with respect to the past when tourists represented less than 1% of the total population exposure. In other words, the city has transferred to a fluctuating population part of its flood risk, and consequently, this aspect should be seriously taken into consideration since nonresidents might be more vulnerable, for example, unaware of warnings in a different language, unprepared and less aware of the risks to be faced.

The last two columns of Table 2 show the results for the 1966 flood scenario with fully operational mitigation measures, by keeping constant the total number of buildings, residents, and tourists at present values. The effect of the mitigation measures with respect to the historical 1966 flood is significant, in fact, the exposed resident population decreased by more than 86%, and exposed CH and tourists decreased by −97% and 61%, respectively. The exposed buildings decreased by 84% although most of them are located in the areas urbanized after 1966.

Flooded cultural heritage implies intangible impacts and losses to manifold values, for example, historical, aesthetic, and spiritual, which are very difficult to estimate and out of the scope of this work. The high number of visitors also represents a source of indirect impacts due to the lack of accessibility of cultural heritage and consequent loss of revenues for

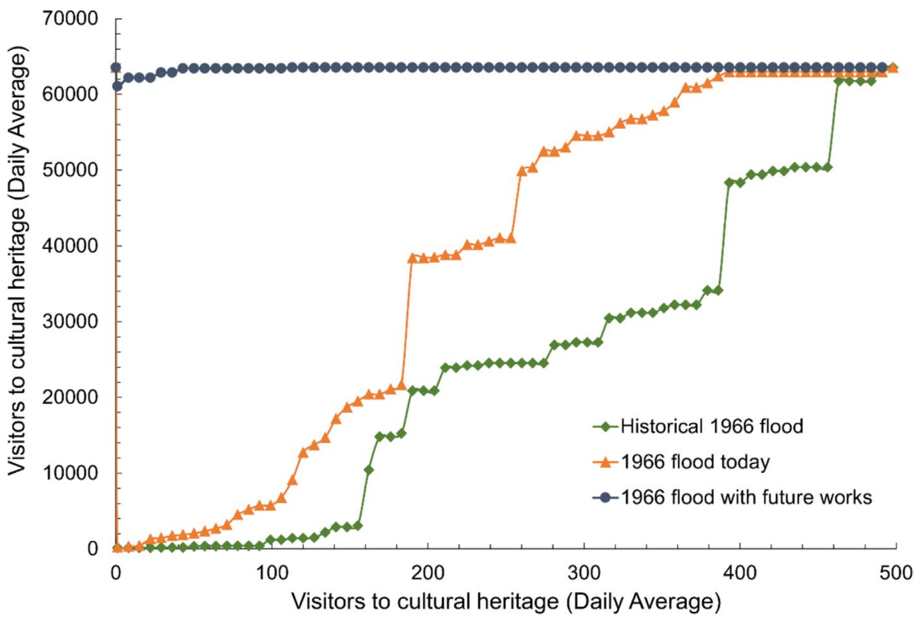

FIGURE 4 | Resilience of the art city for the historical, present, and future inundation (the number of visitors refers in all cases to present times, i.e., 2019).

many economic activities but at the same time a booster for recovery. As described in Table 1, the number of visitors to each cultural building is not available for 1966. Thus, the evolution of resilience and recovery time considers the current number of visitors and compares the historical 1966 flooding, the same event if it occurred today, and the same event with mitigation works. To compare the historical flooding with the present and mitigated situation, the resilience model of Equation (3) is applied, with the water depth as measured at the CH buildings in 1966 and second, with the mean simulated water depths in a buffer area of 2 m around the CH building. The number of visitors to CH is kept constant in the three scenarios and is equal to the visitors in 2019. It should be noted that the daily number of visitors to cultural heritage sites exceeds the actual number of people present in the city, as tourists typically visit multiple attractions per day (usually 2–3) and many do not stay overnight. The results of the resilience model are shown in Figure 4. The green and orange lines depict the recovery of the city for the historical 1966 flood and the same event today, respectively. It is possible to observe that, thanks to the prevention measures undertaken, the 1966 flood occurring today would have a faster recovery, $T_{end} = 386$ days instead of 491 days (−21%) and a significantly lower loss of visitors as clearly visible by the difference of the areas under the two curves. The estimated loss of visitors obtained by the inner integral of Equation (4) yields a loss of 8.4 Mln visitors for the 1966 event today with respect to a loss of 12.8 Mln visitors for the historical inundation, with a benefit of indirect loss reduction of 4.4 Mln visitors. Moreover, besides the reduction of T_{end}, we can observe that the system today (orange curve) reaches the 50% of recovery, that is, the 50% of normal visitors, in 185 days with respect to the 351 days of the historical event (green curve). Quickly reaching a defined reference state value, for example, 50% of recovery can be crucial in situations where delays in the first phases of recovery can compromise the overall post-event dynamics. In Figure 4, there are few sudden jumps due to the reopening of particularly attractive CH. The large jump for the historical scenario (around $T = 150$ days) refers to the "simultaneous" reopening of about 22 CH buildings which does not find a counterpart in the 1966 flood today, this demonstrates the importance of flood depths in changing both the spatial distribution of damage and the temporal recovery dynamics, that is, the two curves are not just merely shifted on the time axis. If we consider the mitigation works currently under construction upstream of the city (Figure 1, panel c) only four CH buildings are affected; therefore, the recovery time T_{end} is ca. 100 days and the lost visitors are about 64,400 (Figure 4. gray curve). Mitigation works are thus almost completely safeguarding CH and related economic activities.

4 | Conclusions

This work has adopted a historical perspective to better understand how a world-renowned art city has reacted after a major flood occurred in 1966. The methodology can be easily transferred to other case studies where similar datasets are available. The evolution of the study area has been investigated in terms of (ii) flood hazard reduction, (ii) exposure of three main assets, that is, buildings, cultural heritage, and population (residents and tourists), and (iii) resilience through cultural heritage.

The city has exhibited in the last 60 years a risk-prone behavior since limited hazard reduction measures have been undertaken. Moreover, the city expansion has occupied flood-prone areas, which increased the number of exposed buildings. On the contrary, a general reduction of residents has also led to a reduction of exposure. The most surprising result is the increase in the share of the exposed fluctuating population with respect to the total. Finally, despite the limited hazard reduction at present, the ability to recover is faster and allows a significant reduction of indirect losses due to cultural heritage inaccessibility. The adoption of the planned mitigation strategies will significantly reduce both exposure and recovery time.

In summary, the following are the main conclusions of the work:

- In art cities, the tourists fluctuating population can represent a significant fraction of the exposed population; thus, it should be considered in flood risk management and civil protection plans. Tourists can be particularly vulnerable due to scarce preparedness for floods in an unfamiliar environment. The study area of Florence tourists represents almost 19% of the flood-exposed population, a nonnegligible fraction that is usually disregarded.
- Cultural heritage represents a key driver for flood risk and resilience in art cities. CH not only is a peculiar element potentially exposed to floods but also a driver for other types of exposures, which deserve further attention in future research. This work in the Florence study area demonstrates and quantifies how the presence of CH acts as an attractor of the fluctuating exposed population, that is, tourists, and as a driver of gentrification which favors tourist accommodation with respect to residences, with consequent apparent reduction of the exposed residential population.
- The adoption of a historical perspective allows us to highlight different evolutionary paths in flood hazard and risk with different behaviors driven by socioeconomic development, which still affects the present and future flood risk and response. Particularly, the urban development after the 1966 flood in the flood-affected areas remains one of the main causes of flood impacts to buildings and residents also when flood hazard will be substantially reduced by mitigation measures.

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Data Availability Statement

The data that support the findings of this study are openly available in web repositories of the source. The river cross-section data and CH building shapefile that support the findings of this study are available upon request from Autorità di Bacino Distrettuale dell'Appennino Settentrionale.

References

Akhter, F., M. Mazzoleni, and L. Brandimarte. 2021. "Analysis of 220 Years of Floodplain Population Dynamics in the US at Different Spatial Scales." *Water (Switzerland)* 13, no. 2: 141. https://doi.org/10.3390/w13020141.

Appiotti, F., V. Assumma, M. Bottero, et al. 2020. "Definition of a Risk Assessment Model Within a European Interoperable Database Platform (EID) for Cultural Heritage." *Journal of Cultural Heritage* 46: 268–277. https://doi.org/10.1016/j.culher.2020.08.001.

Arrighi, C., A. Carraresi, and F. Castelli. 2022. "Resilience of Art Cities to Flood Risk: A Quantitative Model Based on Depth-Idleness Correlation." *Journal of Flood Risk Management* 15, no. 2: 1–15. https://doi.org/10.1111/jfr3.12794.

Biardeau, L. T., and M. Sahli. 2024. "Investigating the Non-Linear Impacts of Seven Types of Natural Disasters on Inbound Tourism: Insights From the EM-DAT Database." *Tourism Economics* 30, no. 4: 900–923. https://doi.org/10.1177/13548166241229319.

Bowitz, E., and K. Ibenholt. 2009. "Economic Impacts of Cultural Heritage—Research and Perspectives." *Journal of Cultural Heritage* 10, no. 1: 1–8. https://doi.org/10.1016/j.culher.2008.09.002.

Cassar, M., and R. Pender. 2005. "The Impact of Climate Change on Cultural Heritage: Evidence and Response." Triennial Meeting (14th), The Hague, 12-16 September 2005: preprints, 610–616.

CHCfE. 2015. "Cultural Heritage Counts for Europe." In *Kansas Agricultural Experiment Station Research Reports*. International Cultural Centre. https://doi.org/10.4148/2378-5977.7527.

Cocola-Gant, A. 2023. "Place-Based Displacement: Touristification and Neighborhood Change." *Geoforum* 138: 103665. https://doi.org/10.1016/j.geoforum.2022.103665.

Di Baldassarre, G., S. Saccà, G. T. Aronica, S. Grimaldi, A. Ciullo, and M. Crisci. 2017. "Human-Flood Interactions in Rome Over the Past 150 Years." *Advances in Geosciences* 44: 9–13. https://doi.org/10.5194/adgeo-44-9-2017.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J. L. Salinas, and G. Blöschl. 2013. "Socio-Hydrology: Conceptualising Human-Flood Interactions." *Hydrology and Earth System Sciences* 17, no. 8: 3295–3303. https://doi.org/10.5194/hess-17-3295-2013.

di Firenze, C. 2021. "Archivi del Turismo." il 20 gennaio 1932, dei visitatori è in crisi. https://www.cittametropolitana.fi.it/archivi-provinciali/archivi-del-turismo/#:~:text=Quando.

Dube, K., and G. Nhamo. 2020. "Evidence and Impact of Climate Change on South African National Parks. Potential Implications for Tourism in the Kruger National Park." *Environmental Development* 33: 100485. https://doi.org/10.1016/j.envdev.2019.100485.

Fatorić, S., and E. Seekamp. 2017. "Are Cultural Heritage and Resources Threatened by Climate Change? A Systematic Literature Review." *Climatic Change* 142, no. 1–2: 227–254. https://doi.org/10.1007/s10584-017-1929-9.

Galloway, G., G. Seminara, G. Blöschl, M. Garcia, A. Montanari, and L. Solari. 2017. *Saving a World Treasure: Protecting Florence From Flooding*. In Report (November). Firenze University Press. https://doi.org/10.36253/978-88-6453-678-1.

Galloway, G. E., G. Seminara, G. Blöschl, M. H. García, A. Montanari, and L. Solari. 2020. "Reducing the Flood Risk of Art Cities: The Case of Florence." *Journal of Hydraulic Engineering* 146, no. 5: 1–7. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001741.

García-Hernández, M., M. de la Calle-Vaquero, and C. Yubero. 2017. "Cultural Heritage and Urban Tourism: HISTORIC CITY CENTRES UNDER PRESSURE." *Sustainability* 9, no. 8: 1346. https://doi.org/10.3390/su9081346.

Genc, K., O. Turkay, and S. Ulema. 2022. "Tourısm Gentrıfıcatıon: Barcelona and Venıce." *Turismo y Sociedad* 31: 125–149. https://doi.org/10.18601/01207555.n31.06.

Genova, J., R. Caimanque, and T. Kopelman. 2020. "Learning From Disaster: Building City Resilience Through Cultural Heritage in New Orleans."

GFDRR. 2020. "Resilient Cultural Heritage Learning From the Japanese Experience."

Gizzi, S. 2021. "Climate Change, Natural Disasters and Their Effect on Historic Centers." In *Smart Innovation, Systems and Technologies*, vol. 178. Springer International Publishing. https://doi.org/10.1007/978-3-030-48279-4_182.

Heinzlef, C., V. Becue, and D. Serre. 2020. "A Spatial Decision Support System for Enhancing Resilience to Floods: Bridging Resilience Modelling and Geovisualization Techniques." *Natural Hazards and Earth System Sciences* 20, no. 4: 1049–1068. https://doi.org/10.5194/nhess-20-1049-2020.

IRPET. 2019. "Rapporto sul turismo in toscana." http://www.irpet.it/wp-content/uploads/2019/06/rapporto_turismo_toscana_2019-1.pdf.

Istituto Centrale di Statistica. 1966. "annuario statistico italiano."

Jigyasu, R. 2016. "Reducing Disaster Risks to Urban Cultural Heritage: Global Challenges and Opportunities." *Journal of Heritage Management* 1, no. 1: 59–67. https://doi.org/10.1177/2455929616649476.

Kumar, N., V. Poonia, B. B. Gupta, and M. K. Goyal. 2021. "A Novel Framework for Risk Assessment and Resilience of Critical Infrastructure Towards Climate Change." *Technological Forecasting and Social Change* 165: 120532. https://doi.org/10.1016/j.techfore.2020.120532.

Kumar, P. 2020. "Crowdsourcing to Rescue Cultural Heritage During Disasters: A Case Study of the 1966 Florence Flood." *International Journal of Disaster Risk Reduction* 43: 101371. https://doi.org/10.1016/j.ijdrr.2019.101371.

Lam, D., C. Thompson, J. Croke, A. Sharma, and M. G. Macklin. 2017. "Reducing Uncertainty With Flood Frequency Analysis: The Contribution of Paleoflood and Historical Flood Information." *Water Resources Research* 5, no. 3: 2. https://doi.org/10.1111/j.1752-1688.1969.tb04897.x.

Li, B., C. Fan, Y. H. Chien, C. W. Hsu, and A. Mostafavi. 2024. "Mobility Behaviors Shift Disparity in Flood Exposure in U.S. Population Groups." *International Journal of Disaster Risk Reduction* 108: 104545. https://doi.org/10.1016/j.ijdrr.2024.104545.

López-Gay, A., A. Cocola-Gant, and A. P. Russo. 2021. "Urban Tourism and Population Change: Gentrification in the Age of Mobilities." *Population, Space and Place* 27, no. 1: 1–17. https://doi.org/10.1002/psp.2380.

Lucchesi, F., M. De Silva, G. Del Chiappa, et al. 2009. "La periodizzazione della crescita urbana. una banca dati dei sedimi edificati derivati dalla CTR toscana." Atti 13a Conferenza ASITA.

Marzeion, B., and A. Levermann. 2014. "Loss of Cultural World Heritage and Currently Inhabited Places to Sea-Level Rise." *Environmental Research Letters* 9, no. 3: 034001. https://doi.org/10.1088/1748-9326/9/3/034001.

McClymont, K., D. Morrison, L. Beevers, and E. Carmen. 2020. "Flood Resilience: A Systematic Review." *Journal of Environmental Planning and Management* 63, no. 7: 1151–1176. https://doi.org/10.1080/09640568.2019.1641474.

Merz, B., F. Elmer, and A. H. Thieken. 2009. "Significance of "High Probability/Low Damage" Versus "Low Probability/High Damage" Flood Events." *Natural Hazards and Earth System Sciences* 9, no. 3: 1033–1046. https://doi.org/10.5194/nhess-9-1033-2009.

Min, J., K. C. Birendra, S. Kim, and J. Lee. 2020. "The Impact of Disasters on a Heritage Tourist Destination: A Case Study of Nepal Earthquakes." *Sustainability (Switzerland)* 12, no. 15: 1–12. https://doi.org/10.3390/su12156115.

Mohanty, M. P., and S. P. Simonovic. 2021. "Understanding Dynamics of Population Flood Exposure in Canada With Multiple High-Resolution Population Datasets." *Science of the Total Environment* 759: 143559. https://doi.org/10.1016/j.scitotenv.2020.143559.

Nair, B. B., and M. R. Dileep. 2020. "A Study on the Role of Tourism in Destination's Disaster and Resilience Management." *Journal of Environmental Management and Tourism* 11, no. 6: 1496. https://doi.org/10.14505/jemt.11.6(46).20.

Osservatorio Turistico di Destinazione. 2015. "Progetto regionale Toscana Turistica Sostenibile e Competitiva."

Paprotny, D., A. Sebastian, O. Morales-Nápoles, and S. N. Jonkman. 2018. "Trends in Flood Losses in Europe Over the Past 150 Years." *Nature Communications* 9, no. 1: 1985. https://doi.org/10.1038/s41467-018-04253-1.

Romão, X., and E. Paupério. 2021. "An Indicator for Post-Disaster Economic Loss Valuation of Impacts on Cultural Heritage." *International Journal of Architectural Heritage* 15, no. 5: 678–697. https://doi.org/10.1080/15583058.2019.1643948.

Romão, X., E. Paupério, O. Monserrat, T. Rousakis, and P. Montero. 2020. "Assets at Risk and Potential Impacts: 3.6–Cultural Heritage." In *Science for Disaster Risk Management 2020: Acting Today, Protecting Tomorrow*, edited by A. V. Casajus, F. M. Marin, K. Poljanšek, and I. Clark, 503–525. European Union.

Rosselló, J., S. Becken, and M. Santana-Gallego. 2020. "The Effects of Natural Disasters on International Tourism: A Global Analysis." *Tourism Management* 79: 104080. https://doi.org/10.1016/j.tourman.2020.104080.

Scaini, C., A. Tamaro, B. Adilkhan, et al. 2024. "A New Regionally Consistent Exposure Database for Central Asia: Population and Residential Buildings." *Natural Hazards and Earth System Sciences* 24, no. 3: 929–945. https://doi.org/10.5194/nhess-24-929-2024.

Spennemann, D. H. R., and K. Graham. 2007. "The Importance of Heritage Preservation in Natural Disaster Situations." *International Journal of Risk Assessment and Management* 7, no. 6–7: 993–1001. https://doi.org/10.1504/IJRAM.2007.014670.

Tanaka, R., H. Kato, and D. Matsushita. 2023. "Population Decline and Urban Transformation by Tourism Gentrification in Kyoto City." *Sustainability* 15, no. 3: 2247. https://doi.org/10.3390/su15032247.

Tanoue, M., Y. Hirabayashi, and H. Ikeuchi. 2016. "Global-Scale River Flood Vulnerability in the Last 50 Years." *Scientific Reports* 6: 1–9. https://doi.org/10.1038/srep36021.

Tellman, B., J. A. Sullivan, C. Kuhn, et al. 2021. "Satellite Imaging Reveals Increased Proportion of Population Exposed to Floods." *Nature* 596, no. 7870: 80–86. https://doi.org/10.1038/s41586-021-03695-w.

Tong, S., C. Wu-Qun, B. Qiu-Yu, M. Xiao, and L. Dong. 2021. "Analysis on Historical Flood and Countermeasures in Prevention and Control of Flood in Daqing River Basin." *Environmental Research* 196: 110895. https://doi.org/10.1016/j.envres.2021.110895.

UNDP. 2013. "PDNA Guidelines-Volume B: Culture." 1–57.

UNISDR. 2015. "Sendai Framework for Disaster Risk Reduction 2015–2030."

United Nations. 2005. "International Strategy for Disaster Reduction Hyogo Framework for Action 2005-2015: Building the Resilience of Nations." World Conference on Disaster Reduction (A/CONF.206/6), 25.

Viglione, A., R. Merz, J. L. Salinas, and G. Blöschl. 2013. "Flood Frequency Hydrology: 3. A Bayesian Analysis." *Water Resources Research* 49, no. 2: 675–692. https://doi.org/10.1029/2011WR010782.

Yang, J., F. Castelli, and Y. Chen. 2014. "Multiobjective Sensitivity Analysis and Optimization of Distributed Hydrologic Model MOBIDIC." *Hydrology and Earth System Sciences* 18, no. 10: 4101–4112. https://doi.org/10.5194/hess-18-4101-2014.