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Preserving the Past in a Changing Climate: An Approach to Assess the Impact of Urban Flooding in Cultural Heritage Cities

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ABSTRACT

Urban floods are increasing due to the intensification of precipitation extremes in a changing climate and to the intensive expansion of urbanscapes. Therefore, flood hazards can potentially increase losses to historical buildings and cultural heritage. In this context, this study proposes a methodology to assess the impact of climate change on urban flooding at the district and building scale. The methodology is applied in the Santa Croce District, where an extensive collection of masterpieces of the city of Florence (Italy) is preserved and exposed, especially in the National Central Library. The flood hazard assessment is obtained by using a dual drainage hydraulic model to quantify the flooded area within the buildings due to the overflow of sewer systems. An ensemble of 34 climate model projections based on output from Phase 6 of the Climate Model Intercomparison Project (CMIP6) in two emission scenarios, or Shared Socioeconomic Pathways (SSP245 and SSP585) and two time windows (2021–2050, Near Future, and 2071–2100, Far Future) are considered as input of the model. The results show that the flood hazard will increase in all climate scenarios, especially in the SSP585 at the end of the century.

1 | Introduction

Urban floods result from intense storm events whose intensity overwhelms the urban drainage system capacity, causing inundation in built environments (Rözer et al. 2021). In recent decades, efforts in engineering have focused on understanding river flood risks and developing related management strategies (Herath and Wijesekera 2019). Indeed, while fluvial and coastal flooding are highly studied and management strategies are available, urban flood management remains underdeveloped (Hammond et al. 2015; Nicklin et al. 2019).

Urban floods may cause less immediate damage compared to river floods, but their higher frequency can result in cumulative damage over the years that equals or even surpasses that caused by fluvial flooding events (Acosta-Coll et al. 2018; Szewrański et al. 2018; Prokić et al. 2019). The intensification of extreme rainfall due to climate change (Kundzewicz et al. 2014; IPCC 2021; Papalexiou and Montanari 2019) is also placing attention on protecting cities from urban flooding. Indeed, the risk associated with urban floods is also increased due to urbanisation (Kaspersen et al. 2017; Bulti and Abebe 2020).

Flood risk analysis is usually done considering flood losses in monetary terms to find related mitigation measures (Salman and Li 2018). Potential flood losses related to the cultural heritage of ancient towns are intangible elements which cannot easily be expressed in monetary terms. Indeed, damages or losses to unique pieces of art or historical manuscripts represent a loss of cultural heritage, from which posterity will no longer benefit. Cultural heritage is exposed to a high risk (UNESCO, Managing disaster risks for world heritage 2010) since natural hazards are usually faced with an internal vulnerability due to the fragility of the materials inside the historical buildings or of the structure. Moreover, historical sites are usually close to rivers and coastlines, and this implies that one of the dangerous natural hazards for cultural heritage is flooding (Reimann et al. 2018). Indeed, the increasing frequency and magnitude of floods in Europe are impacting historical buildings and structures, wooden heritage, buildings' interiors and collections, archaeological sites and historical cities (Sesana et al. 2021). For this reason, methodologies to assess the impact of flood risk on cultural heritage or to assess the resilience of art cities to flood risk have been proposed (Lanza 2003; Arrighi 2021; Arrighi et al. 2022, 2023). Furthermore, there are studies that have analysed the impact of climate change on river flood hazards and flood losses in historical cities (Ranger et al. 2011; Lompi et al. 2021; Soriano et al. 2023). Nevertheless, river flood risk is not the only natural hazard impacting buildings in historical cities. Indeed, the impacts induced by rainstorms have been identified as one of the most critical factors undermining cultural heritage (Brimblecombe 2014). Most of the European cities are experiencing problems with urban flooding in the current climate, just with a 10-year event (Guerreiro et al. 2017). Moreover, Hosseinzadehtalaei et al. (2020) have shown an increase in the Intensity Duration Frequency curve (IDF) in most of Europe under climate change scenarios. Particularly, they show an increase for all the return periods and especially for short durations if spatial median values across the continent are considered. Therefore, cultural heritage preservation could encounter new challenges in the future (Carroll and Aarrevaara 2018), especially with the increasing impact of climate change on extreme rainfall and urban floods.

The impact of climate change on extreme precipitation is usually analysed with projections of Global Climate Models downscaled by Regional Climate Models. Recently, the impact of climate change on urban runoff has been analysed with high-resolution projections which can characterise the convection (Convection Permitting Model) (Reder et al. 2022). Very High-Resolution Projections under different CMIP5 IPCC scenarios over Italy have recently become available (Raffa et al. 2023). The projections with high spatial and temporal resolution belong to Phase 5 of the Climate Model Intercomparison Project (CMIP5), while hourly precipitation with a high spatial resolution based on output from Phase 6 is not available yet. CMIP6 is a new generation of GCM models based on Shared Socioeconomic Pathways (SSPs), an upgraded version of Representative Concentration Pathways (RCPs), which improves future scenario accuracy with respect to the CMIP5 (Eyring et al. 2016).
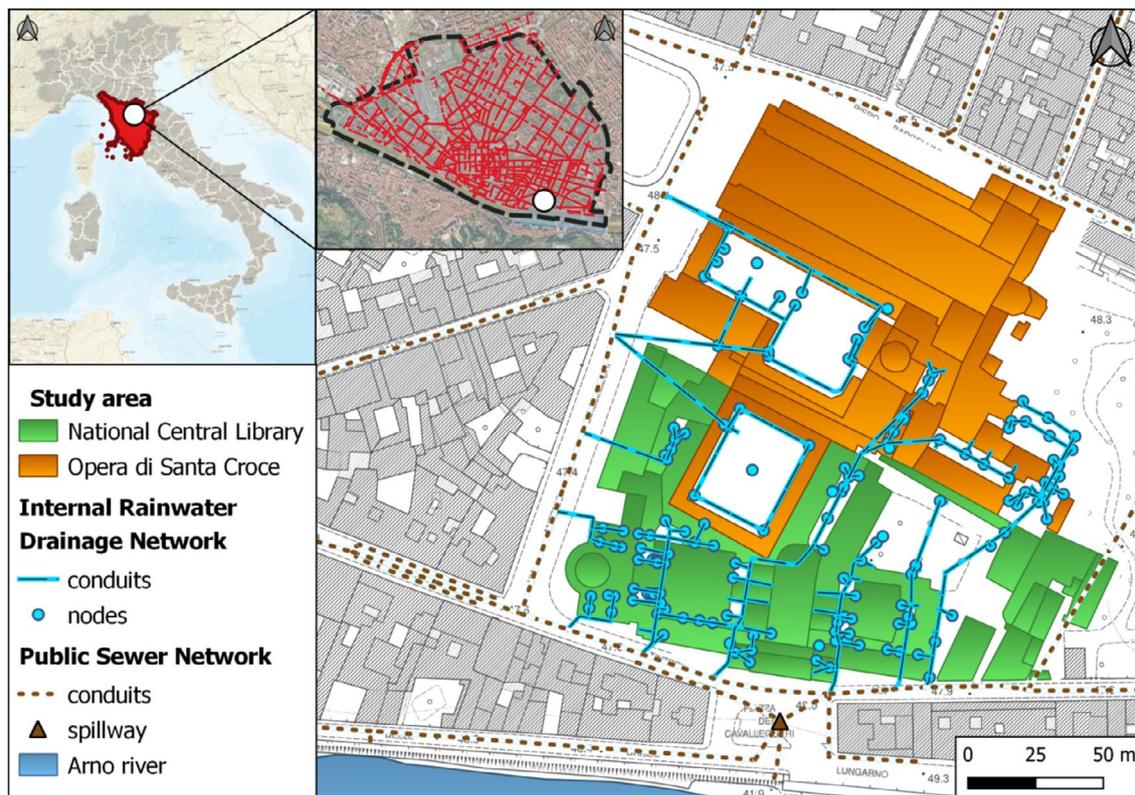
Since climate projections are always improving in time, this study introduced the elasticity of the urban catchment as a new concept for a rapid assessment of the climate change impact on urban floods. Indeed, the elasticity of the urban catchment represents the increase in flood volumes (FV) that are associated with climate change. Once the elasticity of the urban catchment is evaluated, just a rainfall frequency analysis of a new climate projection can allow the quantification of the FVs without using the hydraulic model again. Padulano et al. (2021) proposed something similar, assessing the possible impact of climate change on urban flood with a bottom-up procedure that associates urban flood features to the precipitation intensity, without climate change information in the flood modelling. In this case, the elasticity of the urban catchment is assessed to evaluate the changes in FV for events with a given return period. This is obtained by combining a frequency analysis of extreme rainfall in the current and future scenario with an ensemble of climate projections and the use of a 1D/2D hydrologic-hydraulic model to simulate the impact of climate change on urban floods. This study uses the CMIP6 information downscaled with a 0.25° resolution globally (Thrasher et al. 2022) to evaluate the impact of climate change on extreme rainfall and a high-resolution hydraulic model to assess the future urban flood hazard.

There are several rainfall-runoff models that are commonly used to model flood risk in urban catchments, such as LISFLOOD-FP (Hunter et al. 2005), SWMM (Huang and Jin 2019), Iber (Sañudo et al. 2020), SOBEK (Deltares 2022), MIKE URBAN (DHI 2022) and TUFLOW (BMT 2022) among others. Moreover, hazard mapping tools in urban areas exploiting fast DEM-based algorithms are available (Mediero et al. 2022). 2D hydrodynamic models are able to accurately simulate pluvial floods in complex urban areas, even if they may require high computational costs (Henonin et al. 2013). InfoWorks Integrated Catchment Modelling (ICM) by Autodesk Innovyze (Innovyze 2021) has been selected in this study. The model can simulate runoff propagation through two different routines: a 1D drainage network that describes discharge and water level within the conduits and a 2D model to evaluate the movement of the flooded water coming from the sewer network over the terrain. This model has also been largely used for flood risk assessment studies (Cheng et al. 2017; Costa et al. 2021; Ferguson and Fenner 2020; Guoru et al. 2019; Muhadi et al. 2017; Musa et al. 2016). Moreover, this software has been largely used to implement a 1D/2D coupled models to assess flood-prone areas in urban watersheds (Wolfs et al. 2018; Sidek et al. 2021).

The methodology proposed in this study is applied to a small urban watershed in the city centre of Florence, that is, the Santa Croce district, to assess the changes in the urban flood hazard which can cause losses in the cultural heritage. Indeed, two important historical buildings, the National Central Library and the Opera di Santa Croce, are placed in the analysed district. The location of the buildings is exposed to two different sources of flood risks: the river flood hazard from the Arno River (the area had been severely damaged by the famous flood in November 1966) and the urban flood hazard due to the surcharging of the sewer system. Particularly, the buildings have an internal rainwater drainage network, which collects the rainfall over their roof, that is connected to one public sewer network of the city.

The urban flood hazard assessment is carried out by simulating different scenarios to consider the impact of severe storms in the study area in the current and future climate. The considered

FIGURE 1 | Location of the study area, that is, the Santa Croce district in the city centre of Florence. The public sewer network of the district is shown in red in the top left corner, while the internal drainage network is shown in blue within the historical building of Santa Croce. In the bottom part of the figure, a triangle shows the flood spillway of the sewer network, as the Santa Croce is close to the Arno River.

scenarios are made by a combination of different return periods (10, 20, 50, 100 and 200-year rainfall event), time windows (historical; 2021–2050, Near Future [NF]; and 2071–2100, Far Future [FF]) and Shared Socioeconomic Pathways (SSP245 and SSP585).

The results show that climate change will increase the urban flood hazard in the study area, especially at the end of the century in both the SSPs. The study is organised as follows: a brief description of the study areas is given in Section 2; Section 3 presents the methodology, Section 4 shows the results and Section 5 presents the discussion of the main outcomes. Conclusions, limitations and future developments of the study are given in Section 6.
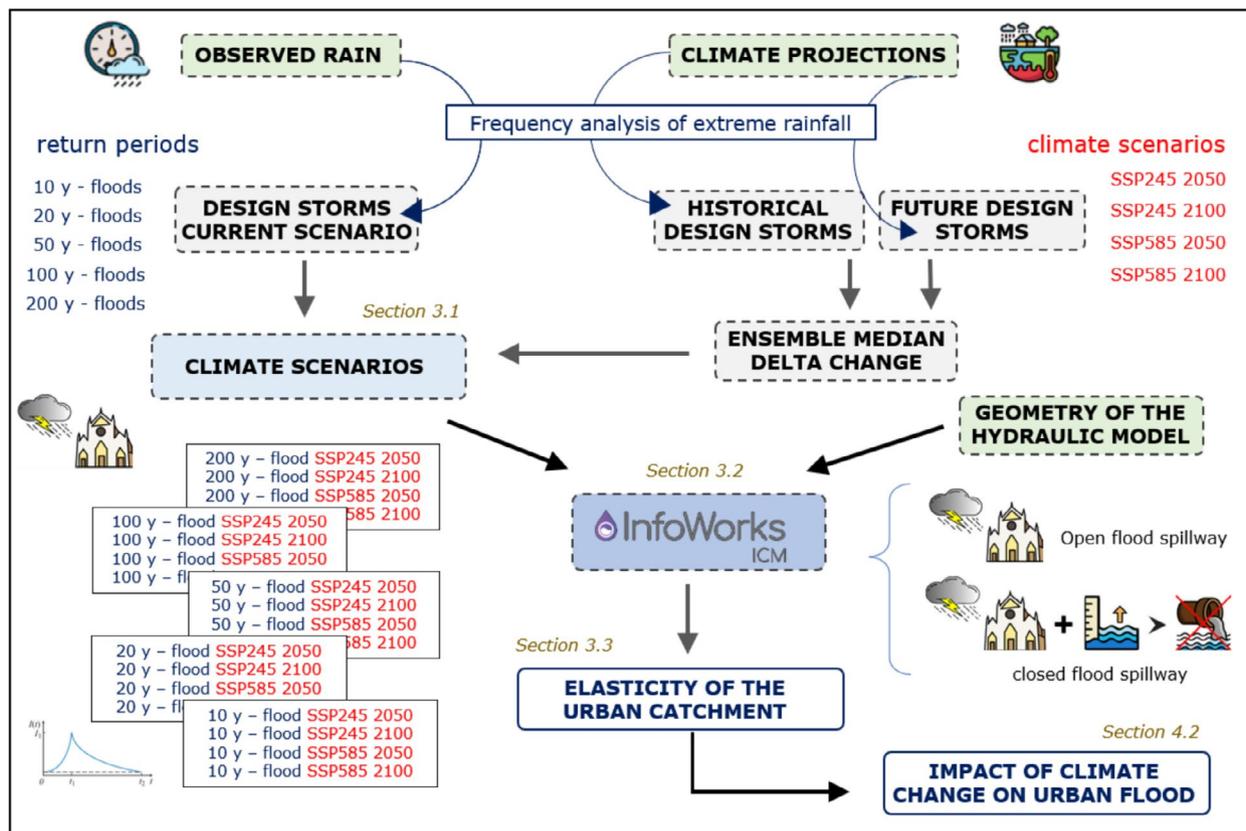
2 | Study Area

The city centre of Florence (Tuscany Region, Central Italy) represents a perfect case study to assess the impact of climate change on urban flood and cultural heritage, as a vast variety of cultural heritage is here susceptible to flooding. Florence holds a prominent place in Italy, designated as a UNESCO World Heritage Site for its wealth of museums, historic buildings and libraries safeguarding priceless manuscripts. Two historical buildings take place within the district chosen as a case study: the National Central Library, which is the largest in Italy, and the Opera di Santa Croce, a 13th-century complex. This area is situated in the southeastern part of Florence, adjacent to the Arno River. Inside the building, there is an

internal drainage network with lots of nodes that, in case of extreme events, can be flooded. Indeed, sometimes ancient buildings have internal downspouts as they cannot collect all the rainfall with external gutters. The area that is modelled in this study is represented in Figure 1, where the internal drainage network, its connections with the public sewer system, and the flood spillway close to the Arno River are shown. Particularly, the public sewer system (red in Figure 1) is modelled with a 1D hydraulic model and covers an urban catchment of $3.5\,km^2$. For the district of interest (around 3 ha) nested into the historic city centre, a 1D/2D dual drainage model has been implemented (Tamagnone et al. 2022).

3 | Methodology

The methodology elaborated in this study is schematized with the flowchart in Figure 2.

The inputs of the 1D/2D dual drainage model (climate scenarios) are generated with a frequency analysis of extreme rainfall in current and future scenarios (Section 3.1). Comparing the future and the historical scenarios of each climate model, a delta change is obtained. The ensemble of the climate projection is used to scale the hyetographs of the current scenario. The 1D/2D dual drainage model, already presented in Tamagnone et al. (2022), is described in Section 3.2. The model and the projections are used to derive the elasticity of the urban catchment (Section 3.3), to quantify how much FVs will change according to the intensification of the future

FIGURE 2 | Flowchart of the methodology. The impact of climate change on urban flood hazard is done by forcing future precipitation extremes in the InfoWorks model. The climate scenarios are obtained with a delta change approach from an ensemble of CMIP6 climate projections. (Icons made by Sittipat Tojarean, Freepik and Good Ware from www.flaticon.com).

extreme precipitation. The results of the model are expressed in terms of number of flooded nodes (FN) and total FV in each scenario (considering two SSPs, two time windows and five return periods). Moreover, all the scenarios are modelled with two different conditions in the hydrological-hydraulic model: (i) extreme short-duration event over the city in dry periods, that is, when the water level in the river is low; (ii) concurrence of an extreme storm over the city and high water levels in the Arno River. In the second scenario, the public sewer network is not able to discharge the stormwater through the emergency flood spillways.

3.1 | Climate Change Impacts on Extreme Rainfalls

To assess the impact of climate change on extreme rainfall, observed data and climate projections are considered. Several methodologies are available to assess the impact of climate change on rainfall quantiles. Probability distribution functions (PDFs) with time-dependent parameters can be used to fit the empirical frequency distribution of the annual maxima rainfall (Sarhadi and Soulis 2017), that is, using frequency analysis in non-stationary conditions, or a delta-change method can evaluate the difference in given rainfall quantiles in two different time windows. This latter method usually assumes stationarity in time windows with a time series length of 30 years. The delta-change method is used in this work. Therefore, a delta-change

is evaluated for each scenario (emission scenario and time windows in the future) as:

$$rP_T = \frac{P_T^{fut}}{P_T^{hist}} \tag{1}$$

where P_T^{fut} and P_T^{hist} are, respectively, the extreme rainfall with a daily duration in a given return period T in the future and in the historical period of each climate model. The projections that are used are historical and future projections for 1950–2100 based on output from Phase 6 of the Climate Model Intercomparison Project (CMIP6) downscaled with a 0.25° resolution globally (Thrasher et al. 2022).

Historical and future time windows in which rainfall quantiles are evaluated have a time series length of 30 years: 1985–2014, historical, 2021–2050, NF, and 2071–2100, FF. The future time windows consider two emission scenarios or Shared Socioeconomic Pathways (SSPs): SSP245 and SSP585. Several PDFs are fitted to the empirical frequency curve of the annual maxima rainfall in each of the five scenarios (historical, SSP245_NF, SSP245_FF, SSP585_NF and SSP585_FF). For each scenario, the best fitting is analysed with the maximum likelihood. Then, the fitting curve that results to be the best more times has been used to evaluate the delta changes for each scenario. Indeed, the use of the same PDF is important to compare the same quantiles in different scenarios.

Considering that five scenarios are evaluated for each of the 34 climate models, a total number of 170 scenarios have been analysed. Ultimately, the PDF chosen is the Generalised Extreme Value (GEV), representing the best fitting in 76% of the scenarios. Therefore, the delta change for a given return period T is obtained for each climate model and future scenario as:

$$rP_T = \frac{u_{fut} + \frac{\alpha_{fut}}{k_{fut}}\left\{1 - \left[-ln\left(1 - \frac{1}{T}\right)\right]^{k_{fut}}\right\}}{u_{hist} + \frac{\alpha_{hist}}{k_{hist}}\left\{1 - \left[-ln\left(1 - \frac{1}{T}\right)\right]^{k_{hist}}\right\}} \qquad (2)$$

where u, α and k are the location, the scale and the shape parameters of the GEV distribution assumed to be constant over time in the historical and future time windows in the extreme frequency analysis of extreme rainfall. A delta change greater than one is associated with an intensification of the extreme events with the delta change T, and vice-versa.

Then, the ensemble median of all the delta changes in a given scenario is used to scale the hyetograph of the current scenario to force the hydraulic model.

The input of the hydraulic model, described in the next session, is short and intense storm events, which may lead to the overwhelming of the drainage system, causing urban floods. Therefore, extreme rainfall with hourly duration and different return periods has been obtained from the Intensity–Duration–Frequency (IDF) curves commonly used in the Tuscany Region (Caporali et al. 2018). The IDFs are built using a Regional Frequency Analysis approach. Specifically, they are evaluated by combining a growth factor for statistically homogeneous areas within the region obtained with a Two-Component Extreme Value (TCEV) distribution and an index rainfall. The temporal distribution of storm events is considered using hyetographs with a Chicago shape, as in Tamagnone et al. (2022).

3.2 | Hydraulic Model

All the details regarding the development of the hydraulic model can be found in Tamagnone et al. (2022), while in this section just a summary of the most important aspects of the model is provided.

InfoWorks ICM v2021.7, an Autodesk Innovyze product, has been used to assess the impact of climate change on urban flooding. The model is a hydrological-hydraulic model which simulates both the bidimensional water fluxes over the terrain and the pressurised flow in the conduits. In this study, the 1D engine calculates the discharge and water levels in the conduits and assesses which nodes in the drainage network are flooded. Then, the 2D engine is used to simulate the flood propagation over the terrain within and outside the buildings of the district of interest. Model parameters were available thanks to Publiacqua S.p.A. (Florence's Integrated Water System), which has a calibrated model of the public sewer system, to which the internal drainage network of the

national library is connected. The topography of the hydraulic model is described with a Digital Terrain Model (DTM) for both the district and the internal part of the building. Moreover, the geometry of the public sewer network, as well as the internal drainage system of the building, has been included in the model. The DTM used for the external part of the district in Florence has been downloaded from Open Data of the Tuscany Region and it has a resolution of 1 m (Regione Toscana 2022). On the other hand, the historical buildings in the district do not have recent technical drawings. For this reason, an extensive field campaign of measurements was conducted to update the information obtained from the historical archives to obtain all the technical specifications of the internal sewer network and the internal DTM. These efforts enabled the geolocalisation of the conduits and the manholes of the internal pipe network and the creation of the floor altimetry of the national library (green in Figure 1). All the extreme rainfall scenarios described in the previous section are analysed in two different hydraulic configurations to assess possible concurrences of an urban flood in Florence with high water levels in the Arno River. Indeed, the location of the historical buildings on the right bank of the Arno River could imply the impossibility of the sewer network using the emergency flood spillways to reduce the excess of stormwater. This condition is particularly relevant, as a hydrometer in the vicinity of the spillway (Firenze Uffizi, Lat 43.768°; Lon 11.255°) has revealed how the spillway is closed on average three times per year, due to the frequent variations of river water levels.
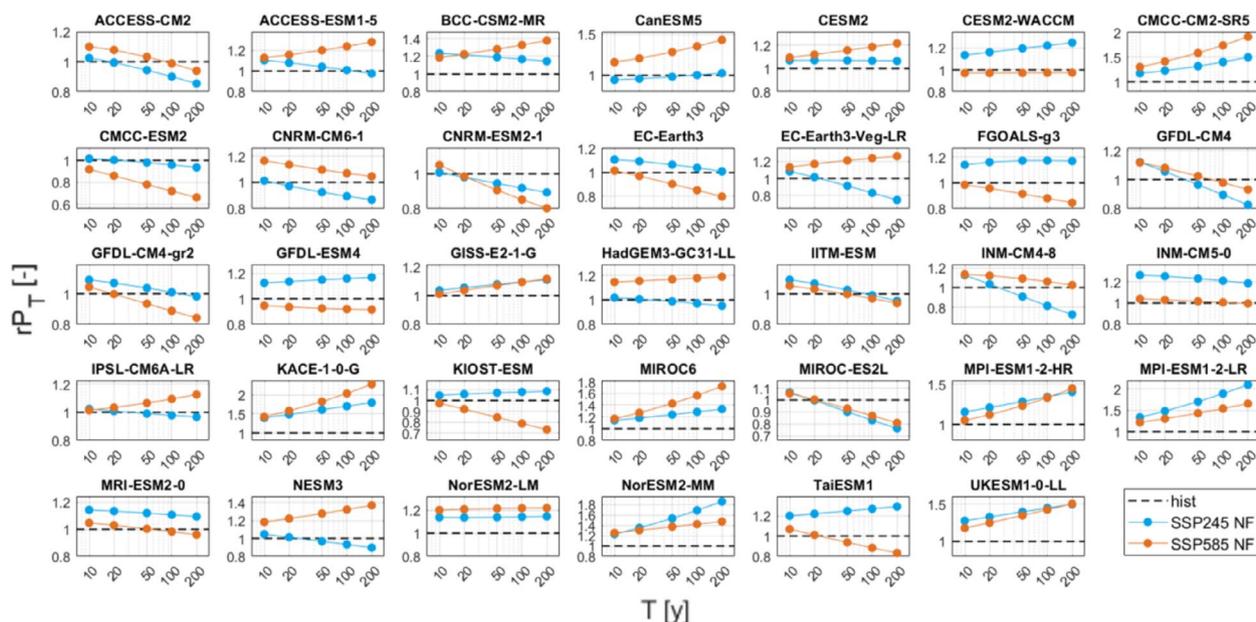
3.3 | Elasticity of the Urban Catchment

The concept of elasticity of a river basin is used in hydrological practice to assess how variations of flood peaks are associated with changes in precipitation quantiles. Indeed, elasticity is defined as the ratio between the relative change in discharge and the relative change in precipitation (e.g., Sankarasubramanian et al. 2001). Therefore, if the flood frequency curve is proportional to the rainfall frequency curve, the elasticity is unity, while if the first one is steeper than the other, elasticity is greater than one (Breinl et al. 2021). Elasticity depends on the characteristics of the river basin, and it is estimated directly from precipitation and discharge observations (Bertola et al. 2021) to assess the impact of climate change by just analysing changes in the rainfall frequency, assuming that the elasticity of the river basin is constant over time.

However, the elasticity does not give any measure of the increased risk in a given river basin, as the increase in the flood frequency curve is not directly linked to damages, that is, the increased discharge can anyway be contained in the river without generating a flood.

In this study, the elasticity of the urban catchment is introduced (Equation 3) to understand how changes in precipitation quantiles drive changes in the FVs from the sewer system and, therefore, damage to the cultural heritage.

$$\varepsilon_{UC} = \frac{rFV}{rP_T^{fut}} = \frac{\frac{FV_T^{fut}}{FV_T^{hist}}}{\frac{P_T^{fut}}{P_T^{hist}}} \qquad (3)$$

FIGURE 3 | Delta changes of precipitation quantiles for each climate model in the Near Future (NF), that is, 2021–2050 time window. The Shared Socioeconomic Pathways are identified with different colours: Cyan for the SSP245 and orange for the SSP585.

In this case, the elasticity is not comparing quantiles of precipitation with quantiles of discharge but changes in precipitation quantiles with total FV change rFV, to give a measure of the increasing hazard for a given return period T. Therefore, the elasticity of the urban catchment can be used to assess future changes in FVs only by analysing the impact of climate change on rainfall quantiles from other projections. For this reason, ϵ_{UC} is different from the traditional elasticity as it is not done just with observations, as a hydraulic model is needed to quantify the FVs. However, since urban catchments have most of the surface impermeable, ϵ_{UC} does not depend on initial soil moisture conditions, but just on the geometry of the sewer system and on this maximum drainage capacity. For this reason, ϵ_{UC} can be easily assumed to be constant in time if changes in the geometry of the sewer are not made.

4 | Results

This section is divided into two parts: first, the results regarding the input of the hydraulic model show the impact of climate change on extreme rainfall; second, the results of the hydraulic model are shown to assess the urban flood hazard in the district.
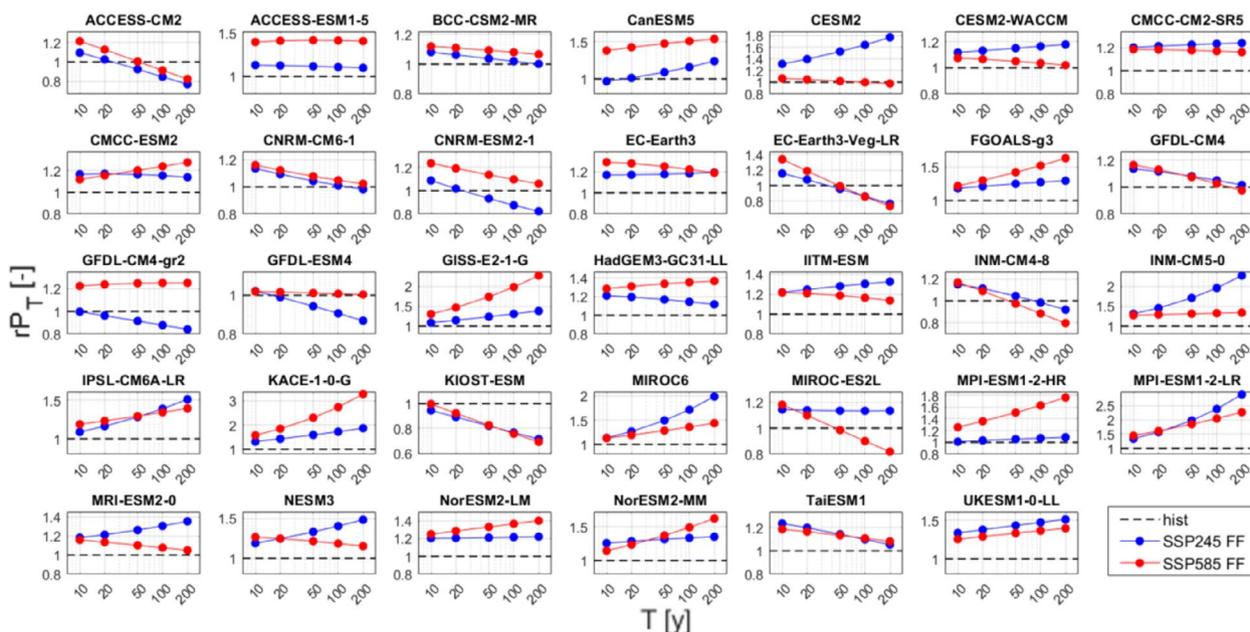
4.1 | Climate Scenarios

In this section, the results of the climate scenarios are described. In the next two figures, the delta changes for different rainfall quantiles rP_T are shown for each climate model for the NF, that is, 2021–2050 time window (Figure 3) and the FF, that is, 2071–2100 (Figure 4). In the figures, the dashed horizontal black lines represent no changes between the future and the historical periods. If a dot is in the upper part of the subplot, over the black dashed line, the rP_T is greater than one and the rainfall quantile is greater in the future than in the historical period. If a dot is in

the lower part of the subplot, under the black dashed line, rP_T is smaller than one and the rainfall quantile will decrease in the future. Even if the delta changes are different for all the climate projections, some patterns can be detected. The precipitation extremes are expected to increase more in the FF than in the NF for both the SSPs. Indeed, an increase of the rainfall extreme for all the return periods is expected for 29 climate models in the FF (Figure 4) and for 17 climate projections in the NF in the SSP585 (Figure 3), while 26 climate models have rP_T greater than one for all the return periods in the FF of SSP245 (Figure 4) and 18 in the NF.
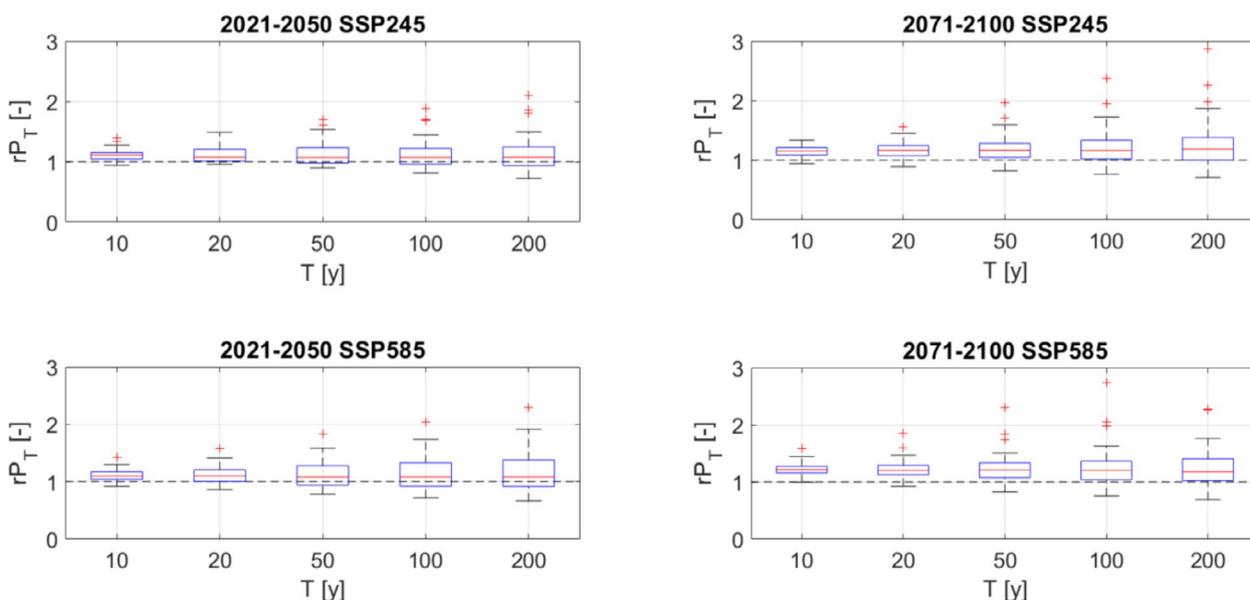
Moreover, changes are expected to be higher in the SSP585 than in the SSPS245. This can be seen especially in Figure 4, where 15 climate models show delta changes greater in the SSP585 for all the return periods, that is, the red line is completely over the blue one in 15 subplots, while just in seven scenarios the SSPS245 shows to be more extreme than the SSP585.

Nevertheless, a complete overview of the impact of climate change on extreme rainfall is possible only by comparing all the climate models together with an ensemble. The results are shown in Figure 5, where the ensemble of the delta changes of precipitation quantiles is shown in the first row for the SSP245 and in the second row for the SSP585, while the columns represent the future time window, 2021–2050 the first one and 2071–2100 the second one. Figure 5 shows how the magnitude of extreme precipitations in the study area will increase regardless of their frequency, as the median values of the boxplot tend to have the same delta change for all the return periods in all the scenarios. The reason behind these results could be associated with changes in the scale parameter only, with the tail of the distribution that will not be affected by climate change.

The median values of the boxplots in Figure 5 are also shown in Figure 6, to compare the signal driven by the ensemble of all the climate models in the different scenarios (SSPs and time

FIGURE 4 | Delta changes of precipitation quantiles for each climate model in the Far Future (FF), that is, 2071–2100 time window. The Shared Socioeconomic Pathways are identified with different colours: Blue for the SSP245 and red for the SSP585.

FIGURE 5 | Ensemble of the delta changes of precipitation quantiles. The rows represent Shared Socioeconomic Pathways (SSP245 and SSP585), and the columns represent future time windows (Near Future, 2021–2050, and Far Future, 2071–2100).
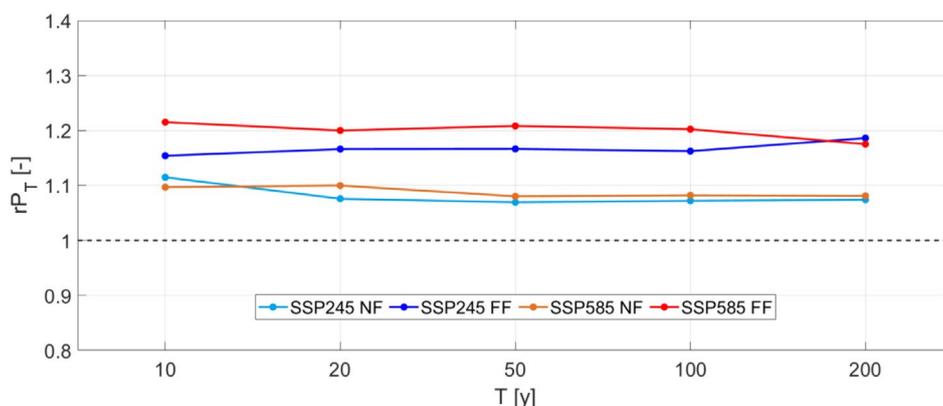
windows). Figure 6 clearly summarises all the results shown in the previous plots: the changes will be greater in the FF for both the SSPs; the changes seem to have a scaling factor of 10% in the NF and 20% in the FF regardless of the frequency of the extreme events.

4.2 | Urban Flood Hazard Assessment

This section shows the results of the hydraulic model with all the climate scenarios. InfoWorks ICM can also provide discharges and water depths in each pipe and node of the domain. However, since the focus of the study is the assessment of the urban flood

hazard, the results are expressed in terms of the water depth of the flooded area. Figure 7 shows the flooded areas and water depths inside the National Library building due to the surcharge of the internal drainage network in the most critical scenario, that is, with the concurrence of extreme rainfall over the city and high water level in the Arno River.

Indeed, as can be seen in Figure 1, and as already described in Section 2, inside the building, there is an internal drainage network with a number of nodes that, in case of extreme events, can be flooded. Particularly, the figure shows the flood maps for the 200 year-rainfall event in the five considered scenarios (current, NF and FF for the SSP245 and SSP585). It is clear how

FIGURE 6 | Median values of delta changes of precipitation for the different return periods (10, 20, 50, 100 and 200 years), emission scenarios (SSP245 and SSP585) and future time windows (Near Future, 2021–2050, and Far Future, 2071–2100), considering the ensemble of all the climate projections.

climate change will affect and increase urban floods in the study area in the future, as higher water depths are expected inside the building especially in the FF, with possible impact on the cultural heritage stored inside. A complete overview of the result is available in Figure 8, where all the scenarios are compared in terms of the number of FN and the total FV, which is the sum of the surcharge water that comes out from each node, in each scenario.

The results are displayed for the different return periods T (10, 20, 50, 100 and 200 years) in a logarithmic scale. The two critical scenarios are displayed by circles for the scenario with open flood spillways (i.e., with extreme rainfall over the city and a low water depth in the river), while crosses represent the scenario with closed spillways (i.e., concurrence of extreme rainfall over the city and high water level in the river).
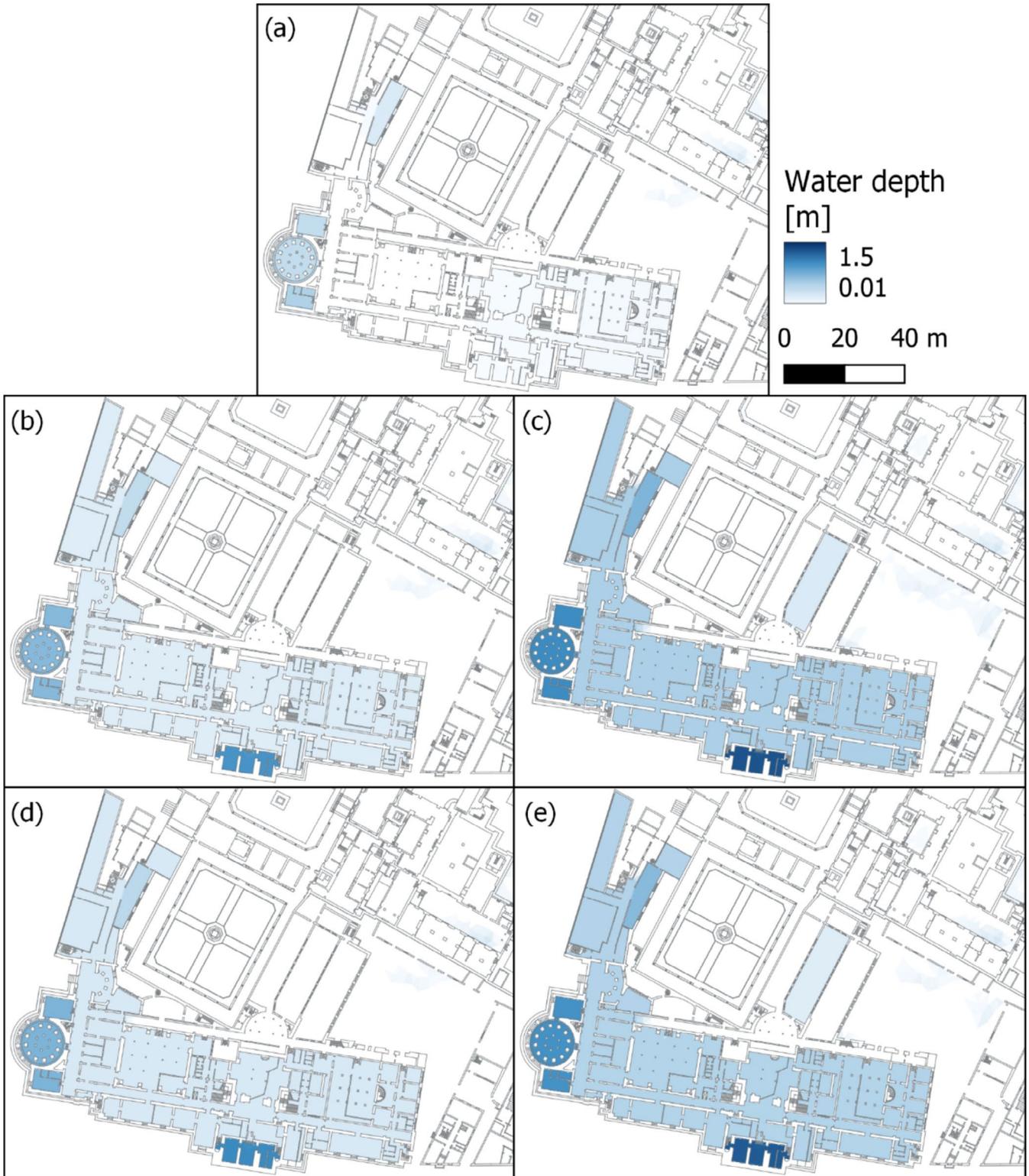
Figure 9 shows the elasticity of the urban drainage system, that is, how much the FVs change (rFV) with respect to variation of the rainfall, quantiles (rP) for each return period (10, 20, 50, 100 and 200 years). The solid red lines show the elasticity of the urban catchment for the scenario with the closed flood spillway, while the dashed light blue lines show the result for the open flood spillway scenario.

5 | Discussion

The impact of climate change on extreme rainfall will likely affect urban flood risk in the city of Florence in all future emission scenarios and time windows. Indeed, delta changes of precipitation quantiles greater than one result from the ensemble of the climate projections (Figure 6) in both the SSPs and time windows, near and FF. The results are in line with (Hosseinzadehtalaei et al. 2020) which found an increase in extreme precipitation for all the scenarios (RCPs) and return periods in the CMIP5 on average in Europe. The increase in rainfall quantiles will be higher in the FF (2071–2100) with respect to the NF (2021–2050) for both SSPs. The increases are generally slightly higher in the SSP585 than in the SSP245 in the near and FF. This result is expressed with the median values of the delta changes after the ensemble of all the climate projections. Uncertainty may affect these results as different

expected changes in the rainfall quantiles are found for each climate model. Nonetheless, half of the climate projections (17 over 34) agree with a general intensification of extreme rainfall, that is, for all the quantiles, in both the SSPs in the NF (Figure 3). At the same time, 24 climate models have the same direction (increase) of the extreme rainfall for all the return periods in both the SSPs in the FF (Figure 4). The other models show an increase or decrease of delta changes in extreme precipitation depending on the considered quantiles, sometimes showing an intensification of the less frequent (or the more rare) extreme precipitation.
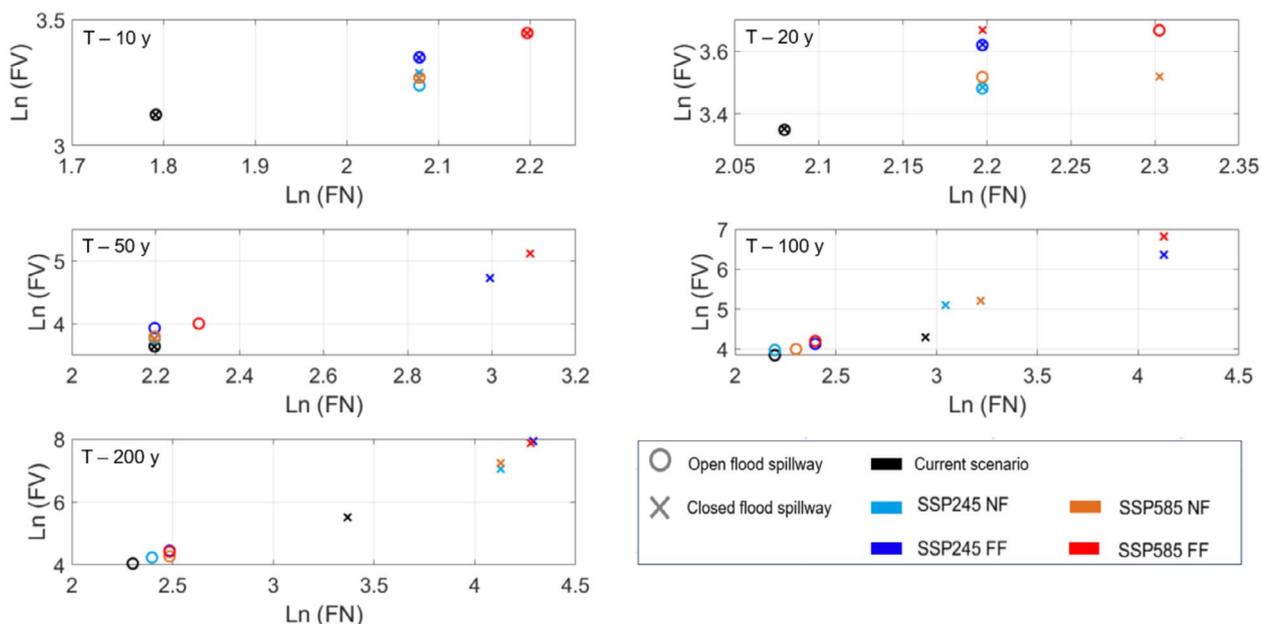
Since climate change tends to increase all the rainfall quantiles, an increase in the urban flood hazard in the future is also expected (Figures 7 and 8). Figure 7 shows how greater water depths and flooded areas will be expected in the future with respect to the current scenario for the same return period. This can have an impact on the cultural heritage that is safeguarded inside the building if some adaptation measures are not going to be taken. The water entering the building may have a direct and indirect impact on the damages to which the cultural heritage is exposed. First, the vast flooded area implies the relocation of a larger number of manuscripts to higher shelves, reducing the storing capacity of the site, and/or the wrapping into waterproof shields, with a consistent financial investment by managers. Second, more water in the building would destabilise the controlled environment of the Library, drastically increasing the level and persistence of humidity in the building, which is one of the main threats to mining the preservation of paper-based material. In this context, adaptation strategies to reduce the possible impact of climate change are necessary. Even if Low Impact Development or Nature Based solutions can represent a solution to reduce urban flood peaks (Pampaloni et al. 2024; Sun et al. 2021), these cannot be easily adopted in cultural heritage cities such as Florence (Pacetti et al. 2022), due to architectural constraints. Figure 8 shows that the smallest FVs for the less extreme event (10, 20 and 50 years) are expected in the current scenario, even with the concurrence of high water levels in the river (closed flood spillway scenario). This implies that the impact of climate change on extreme precipitation with smaller return periods will cause an increase in urban flood in the dry periods, that is, when storms are usually concentrated over the city and do not involve the Arno River, leading to FVs that are
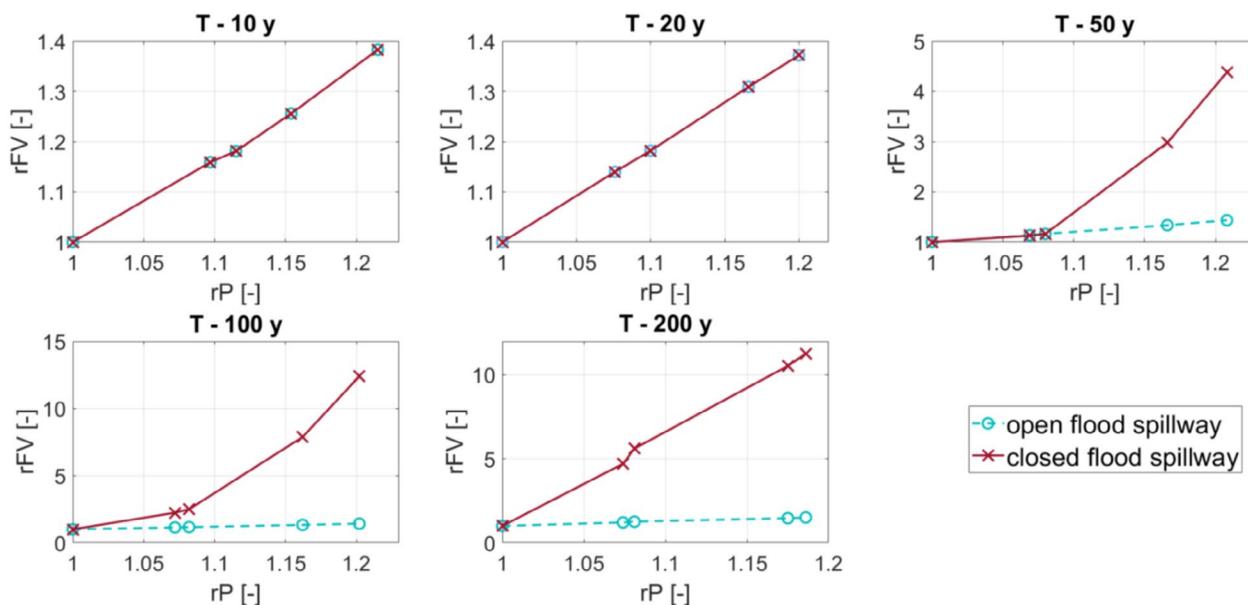
FIGURE 7 | Flooded area and water depth inside the National Library building due to the surcharge of the internal drainage network for the 200 year-rainfall event in the different scenarios: (a) current scenario, (b) SSP245 in the Near Future (2021–2050), (c) SSP245 in the Far Future (2071–2100), (d) SSP585 in the Near Future (2051–2050) and (e) SSP585 in the Far Future (2071–2100).

higher than in the concurrence of the two events (urban and river flood) in the current scenario. Indeed, the upper part of Figure 8 shows how higher FVs are expected in the open flood spillway scenario than in the current scenario with the concurrence of high water levels in the river. On the contrary, the closed flood spillway scenario for the highest return period (100 and 200 years) shows larger FVs even in the current scenario. Accordingly, climate change will increase the FV also for higher return periods, especially at the end of the century for both the SSPs. The increase in urban FVs under CMIP6 projections in all the SSP scenarios agrees with the findings of other studies in other climate conditions (Wang et al. 2023; Liu et al. 2023).

FIGURE 8 | Flood volume (FV) and number of Flooded Nodes (FN) in each scenario. Icons represent the concurrence of the urban flood with high water levels in the Arno River: Circles represent the scenario with open flood spillways, while crosses the one with closed flood spillways; colours are attributed to different scenarios: Black for the current scenario, cyan (Near Future, i.e., 2021–2050) and blue (Far Future, i.e., 2071–2100) for the SSP245 and orange (Near Future, i.e., 2021–2050) and red (Far Future, i.e., 2071–2100) for the SSP585.

FIGURE 9 | Elasticity of the urban catchment or how changes in precipitation quantiles (rP) are reflected in changes in total FV (rFV) for each return period (10, 20, 50, 100 and 200 years). The solid lines with crosses show the elasticity of the urban catchment for the scenario with the closed flood spillway, while the dashed lines with circles show the result for the open flood spillway scenario.

The latest results are better described by introducing the concept of the elasticity of the urban catchment, that is, how an increase in precipitation quantiles drives changes in total FVs in the study area. Padulano et al. (2021) proposed a similar approach, finding relationships between urban flood features and precipitation intensity. In this study, the elasticity of the urban catchment associates variation in the FVs for a given rainfall quantile to its intensification under climate change conditions. Therefore, the elasticity of the urban catchment varies for each return period as it is shown in Figure 9. It is evident how the two scenarios (open

and closed flood spillways) diverge for the 50-year storm event. Indeed, for small return periods (10 and 20 years) the variation of FVs with respect to changes in precipitation quantiles does not change in the two scenarios. This means that for smaller return periods, the concurrence of high water in the river does not change the urban flood hazard in the district.

If a 50-year storm event is considered, small variations of the precipitation quantile drive the same variation of FV in the two scenarios (open and closed flood spillway), while for bigger changes

in the extreme precipitation with this return period the elasticity of the urban catchment starts to diverge in the two scenarios. Even if the urban flood associated with the 100- and 200- years precipitation can be potentially affected by a huge uncertainty, the results show how changes in the flood volume will be much higher in the closed-flood spillway scenario. In these latter cases, the concurrence of the Arno River flood increases the FV in the Santa Croce district, exacerbating the damages to the monumental complex.

Limitations of this study are the consideration of daily delta changes to scale sub-daily hyetograph and the evaluation of the changes without a bias correction of the projections with observations. Nevertheless, it has been observed in several studies that extreme precipitation in shorter durations increases even more than daily precipitation under global warming (Fowler et al. 2021; Hosseinzadehtalaei et al. 2020; Berg et al. 2013). For this reason, it is likely that the impact of climate change on urban flooding in the study area in the future may even be underestimated. Moreover, bias correction methods can alter the statistical properties of GCM model outputs to fit GCM outputs to observations in the control period. Therefore, the expected changes predicted in the future could also change, modifying change signals predicted by GCMs. Quantile mapping bias correction methods are useful in modelling extreme events in long-term hydrological models to maintain coherence with discharge observations in the river. In this case, the 1D/2D dual drainage model simulates the urban flood in the sewer system with a single-event temporal scale and only the changing signal is used. However, future developments of this study could consider the use of sub-daily rainfall projections of the CMIP6 when they become available to analyse the impact of climate change on the elasticity of the urban catchment.

6 | Conclusions

This study shows the impact of climate change on urban floods in one of the districts in the city centre of Florence (Santa Croce). The methodology is based on using the climate projection from Phase 6 of the Climate Model Intercomparison Project (CMIP6) in two emission scenarios (SSP245 and SSP585) and two time windows (2021–2050, NF, and 2071–2100, FF) to force a 1D/2D dual drainage model, evaluating the FVs. The urban flood hazard in the Santa Croce district is expected to increase in all future scenarios (SSPs and time windows), highlighting the necessity of mitigation measures to face the possible future impact of climate change on the cultural heritage of the city. The study shows the great potential of conducting studies at the building scale to better quantify losses to the cultural heritage. Moreover, it introduces the elasticity of the urban catchment as a measure to assess how changes in precipitation quantiles driven by climate change can directly impact FVs. The results found in the city of Florence cannot be representative of other cities, but the simplicity of the applied methodology can be replicated in other case studies to assess the impact of climate change on urban floods with the latest available projections.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data available on request from the authors.

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