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PROTECTING HERITAGE CITIES FROM PLUVIAL FLOODING: THE SANTA CROCE DISTRICT IN FLORENCE

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Abstract

Nowadays we live in an era deeply influenced by climate changes and meteorological instability. The undergoing exacerbation of climate extremes – such as rainstorms, floods, and surges – is endangering what humankind built during the course of history. Besides the risk for human lives and assets losses, natural calamities are increasingly threatening the cultural heritage safeguarded in ancient cities. The damage to unique pieces of art, manuscripts and relics reflects a loss of heritage from which posterity will no longer benefit. In this framework, the present study intends to investigate the hazard related to pluvial flood to which the cultural heritage preserved in the National Library, and religious and museum complexes of Santa Croce (Florence, Italy) is exposed. The flood-related hazard assessment is accomplished by implementing a 1D/2D hydraulic model, to simulate the interactions between all hydraulic phenomena occurring both in the sewer system and on the surface. The outcomes reveal the critical nodes of the drainage network, the most prone areas to be flooded and how to prioritise rescue actions in case of extreme rainfall events. These insights will drive the choice of appropriate technical solutions in a context where planning structural defence works are hardly compatible within historical sites.

Keywords: Pluvial flooding; Flood hazard assessment; Hydraulic modelling; Cultural heritage; Historical buildings

1. INTRODUCTION

During the past decades, engineering and natural sciences strived for understanding the risk of coastal and river flooding as well as developing risk management strategies and policies (Herath and Wijesekera, 2019). Nowadays, in an era governed by continuous climate warm-up and unstoppable urbanisation, the increase in intensity and frequency of extreme rainfall events is directing the attention of decision-makers on defending cities from pluvial flooding (IPCC, 2021; Kundzewicz et al., 2014; Papalexiou and Montanari, 2019). Pluvial floods are directly induced by extreme rainstorms whose intensity exceeds the capacity of the urban drainage system causing the inundation of streets and buildings before the stormwater reaches the receptor water channel (Rözer et al., 2021). These occurrences have been defined by Houston et al. (2011) as an 'invisible hazard' that increasingly weighs on the budget of direct flood losses, raising the costs incurred by flood damages. Indeed, numerous cities around the world have been more frequently impacted by pluvial floods in recent years. For instance, catastrophic rainstorms affected the city of Beijing in 2012 causing estimated economic damage of almost USD 2 billion (Wang et al., 2013), or the heavy rains that hit German communities in summer 2021 (Fekete and Sandholz, 2021). Such events may be even more disruptive in developing countries, undermining their economy, environment, and fundamental resources (Asiedu, 2020).

Most of the current research on flood risk focuses on the monetary entity of losses and benefits related to mitigation measures (Salman and Li, 2018). To move towards a holistic evaluation, there is a need to incorporate intangible components that cannot be directly translated into monetary values. Besides the tangible losses, the costs might exponentially increase when the intangible share is considered, such as the potential loss of cultural heritage held in ancient towns. The cultural heritage describes the cultural and historical identity of a nation, which implies that its protection is compulsory, in order to preserve the legacy of our ancestors (Minea, 2019). The cultural heritage may be exposed to a series of risks, triggered by a variety of human factors and/or natural hazards. The UNESCO (Managing disaster risks for world heritage, 2010) reports that sources of hazard to cultural heritage might come from internal and external causes. The internal cause is represented by the internal fragility of the structure or materials and their sensitivity to the surrounding environment. The external causes are the disturbance or damage to cultural heritage caused by natural calamities (such as floods, hurricanes, wildfires), destructive sabotage, or wars. The study of Reimann et al. (2018) states that floods are one of the most threatening hazards for cultural heritage, due to the location of historical sites and buildings in the proximity of rivers or coastlines; areas representing a fundamental source of clean water for ancient civilizations. Concerning this statement, while risk management and mitigation strategies for fluvial and tidal flooding have been defined over the last decades, effective strategies to deal with the climate-related increasing pluvial flood hazard have not been extensively developed (Hammond et al., 2015). Consequently, looking at the upsetting forecasts and climate change potential impacts, the management and preservation of cultural heritage will face new challenges in the next future (Carroll and Aarrevaara, 2018).

Focusing on pluvial floods, the rainstorm-related effect has been sorted as the most critical factor in damage to heritage (Brimblecombe, 2014). Thus, a high level of protection against this natural hazard is required. Protective strategies are based on predicting the magnitude and extent of flow through flood hazard analyses, including potential socioeconomic consequences and cultural heritage loss to understand the impacts of flooding on the ancient cities (Lanza, 2003).

Considering these issues, the present study investigates the hazard related to pluvial flood to which the cultural heritage located in the most vulnerable areas of Santa Croce district (Florence, Italy) is exposed. The district hosts some of the most important buildings of the city: the National Central Library of Florence (BNCF) and the Opera di Santa Croce (OSC). The geographical location of this monumental complex makes the cultural heritage guarded inside of it dangerously exposed to multiple sources of flood hazard. As the first, river flooding due to the proximity to the Arno River (this area has been already harshly damaged by the catastrophic flood in 1966). Secondly, surcharging and overflowing by sewage since the Internal Rainwater Drainage Network (IRDN) of the buildings is directly linked to one of the main sewer conduits of the city (the Chiesi sewer pipe - named as the designer engineer Flaminio Chiesi). Then, overland runoff flowing down from the upper basin to the river. Considering this framework, the pluvial flood hazard assessment is performed using a 1D/2D dual drainage model specifically implemented to simulate all hydraulic phenomena occurring within the sewer network and their impacts on the surface. The hydrodynamic model is able to combine the features of 1D and 2D models, where a one-dimensional drainage network model is fully integrated with a two-dimensional overland flow model. Among different rainfall-runoff models typically used for urban catchment studies – such as SWMM (Huang and Jin, 2019), Iber (Sañudo et al., 2020), LISFLOOD-FP (Hunter et al., 2005), MIKE URBAN (DHI, 2022), TUFLOW (BMT, 2022), SOBEK (Deltares, 2022) – InfoWorks Integrated Catchment Modeling (ICM) by Innovyze (Innovyze®, 2021) has been chosen for this study. It is a mathematical software that provides an integrated modelling platform suitable for performing a wide range of hydraulic and hydrological studies, enabling engineers to bring together natural hydrology and manmade artefacts into a single model. This software was widely adopted for flood hazard/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) and implementing 1D/2D coupled models of urban catchments (Sidek et al., 2021; Wolfs et al., 2018).

The pluvial flood hazard assessment contemplates different scenarios designed to evaluate the impact of hydrometeorological extremes on the study area and each possible concatenation of consequences or failures of the drainage system. Thus, two different implementations were carried out in this study aiming to concern with (1) forcing represented by only extreme rainfall events occurring in dry periods, (2) the concurrence of extreme rainfall events and high-water levels in the Arno River. This latter condition implies the impossibility of the Public Sewer Network (PSN) to discharge the excess stormwater through the emergency spillways.

The scenarios stretch up to catastrophic precipitations with a return period of 200 years and short durations characteristic of pluvial flooding (less than 3 hours); those which undermine the drainage capacity of the sewage network.

The simulation outcomes reveal that most of the IRDN’s conduits were oversized during the design in order to safely evacuate the stormwater, even for high-intensity rainfall events. The flood hazard derives from the high water stage which may stand in the PSN, in worst scenarios, and produce a backwater effect into the IRDN, especially beneath the BNCF, determining intrusion of sewage flow into the building.

The structure of the paper is organised into four parts. The first section shows a brief contextualization describing the study case. The second part reports the materials, meaning the numerical model and its input data, and describes the methodologies used in the research discussed here. Section three sets out results and argues the discussions related to the outcomes. In the last section, conclusions and future perspectives are drawn.

2. MATERIALS AND METHODS

In this paper a series of acronyms have been used and repeated, therefore for clarity are summarised in Table 1.

Table 1. The glossary of acronyms utilised in the text.

ACRONYMS	FULL NAMES
SCD	Santa Croce District
BNCF	National Central Library of Florence
OSC	Opera di Santa Croce
IRDN	Internal Rainwater Drainage Network
PSN	Public Sewer Network

2.1 Study area

Italy holds most of the world's cultural heritage but it has a territory widely subject to high hydrogeological risk. More than 90% of the municipalities are at risk from landslides and/or floods, almost 17% of the national territory is classified as highly dangerous and more than 7 million people live in vulnerable territories (ISPRA, 2020). One of the areas subject to the highest risk is the Tuscany Region. Its capital, the city of Florence, is one of the most important cities on the national scene. The historical city centre of Florence has been listed by UNESCO as a World Heritage Site for the richness of its cultural heritage. The numerous museums, ancient palaces, religious buildings, and libraries are collectors of unique and inestimable pieces of art, manuscripts, and relics. The Santa Croce district hosts some of the most important buildings of the city: the National Central Library of Florence - the largest in Italy and one of the most important in Europe - and the Opera di Santa Croce. The Opera di Santa Croce is a hub that conserves more than four thousand unique works of art placed in a monumental complex that dates back to the 13th century. Whereas the National Central Library of Florence hosts a vast collection of books, among newspapers and rare manuscripts, that encompass 8 million volumes. The area is located in the southeast corner of the downtown next to the right bank of the Arno River.

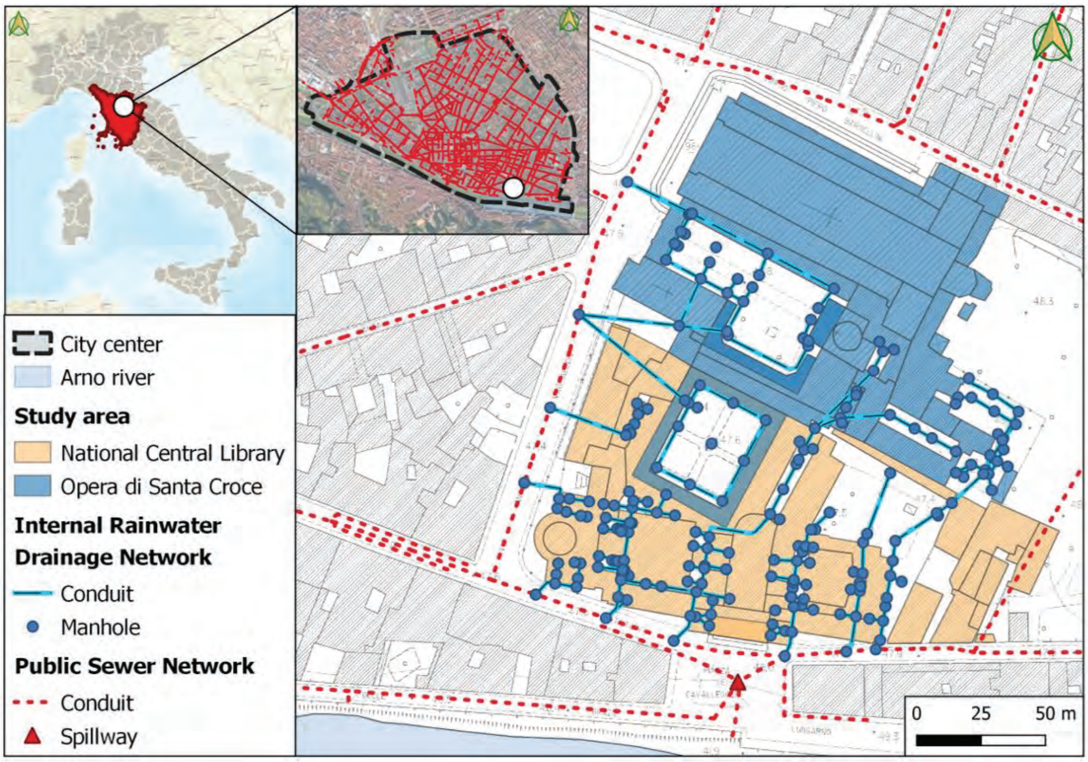

Figure 1. The geographical framework of the study area and sewer network. Top left: the PSN of the whole city centre of Florence (red lines). Enlargement: the IRDN within the monumental complex of Santa Croce and where it is connected to the PSN. It also shows the location of the emergency spillway.

2.2 Hydraulic model

The hydrological-hydraulic model of the sewer network was set up to investigate the impact-related hazard of extreme rainfall events. To achieve the purpose, the InfoWorks ICM (Integrated Catchment

Modelling) v2021.7 software has been chosen. The model allows simultaneously simulating bidimensional overland fluxes and pressurised pipe flow in order to accomplish a comprehensive simulation of all hydraulic phenomena occurring within the sewer network and their impacts on the surface. In this study, InfoWorks ICM operates as a 1D engine to forecast the water level and surcharge conditions in the drainage network. Moreover, in case of overflowing from manholes, the combined 2D engine computes the flood propagation within the monumental complex. Considering that the complex is deeply nestled into the urban fabric of the city and, additionally, to reduce the uncertainty of numerical simulations, the model calculates the propagation of the flow through the entire sewer network of the city (Figure 1). Model's parameters were retrieved from the already implemented and calibrated PSN shared by the Integrated Water System managers of the city of Florence, the Publiacqua S.p.A., to which the IRDN is directly connected.

Hydraulic analyses carried out in this study focused on short and high-magnitude rainfalls that lead to pluvial flood events. Thus, extreme rainfall events have been set as inputs for hydraulic simulations. Different hyetographs of high return periods (Tr) were generated from the Intensity–Duration–Frequency (IDF) curves freely available from the online portal of the Hydrological Service of the Tuscany Region (Settore Idrologico e Geologico Regionale, 2022). As shown in Figure 2, hyetographs range from 30 mins to 3 hours of duration, from 130 mm/h to 360 mm/h of intensity. Moreover, in order to investigate how the temporal distribution of precipitation might affect the discharge capacity of the sewer network, hyetographs have been built with a triangular and Chicago shape. Along with the text, the scenarios in which extreme precipitations are used as unique forcing threatening the study area will be identified with the acronym HF (Hydrometeorological Forcing).

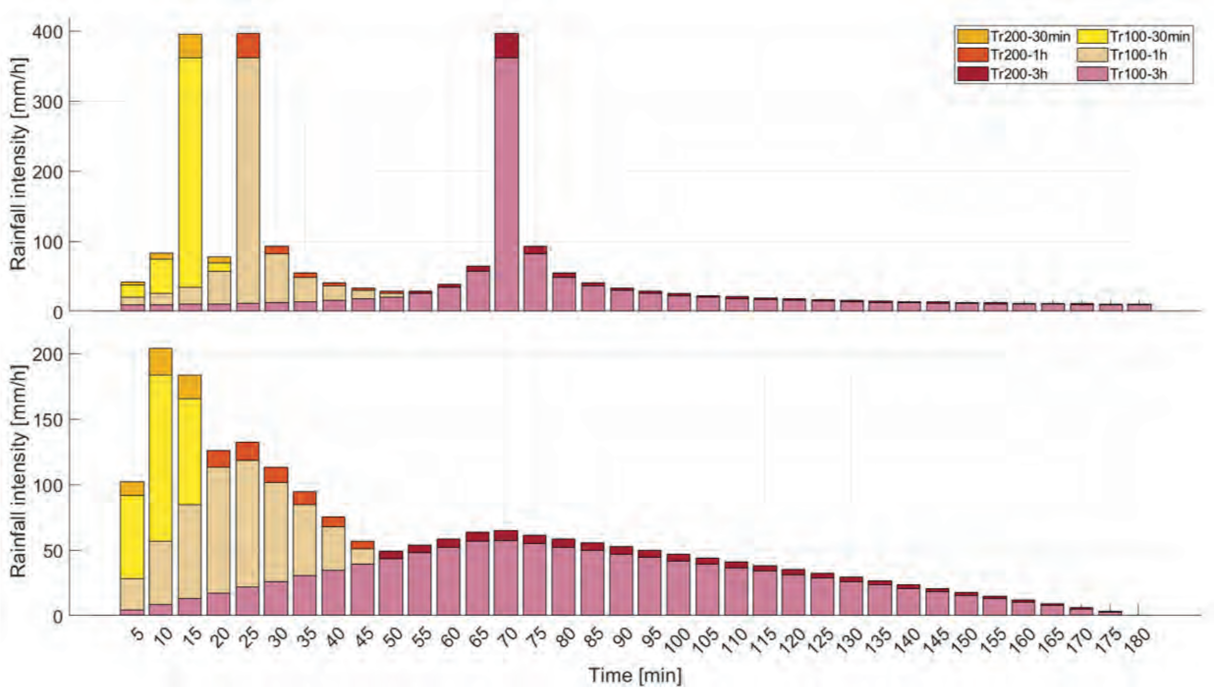

Figure 2. Hydrometeorological forcing used as input in the hydraulic model with return period of 100 and 200 years. Top: hyetographs generated using the Chicago formulation (they will be identified with a subscript C). Bottom: hyetographs generated following a triangular distribution (they will be identified with a subscript T).

Besides the hydrometeorological forcing generated, different scenarios were designed to furtherly evaluate possible concatenation of consequences or failures of the drainage system. Concerning the closeness of the study area with the Arno River, a critical scenario is designed to contemplate the concurrence of an extreme rainfall event and high-water level in the river. This condition implies the impossibility of the PSN to discharge the excess stormwater directly into the river through its emergency spillways. The scenarios related to these worst conditions will be identified with the acronym SC (Spillway Closed).

2.3 Geometric data

The hydraulic model integrates different layers of information: the Digital Terrain Model (DTM) of the study area and buildings interior, the public sewer network, and the internal rainfall collection system of the district. The DTM of the city of Florence is stored and freely available with a high-resolution resolution of 1 metre on the Regional webgis (Regione Toscana, 2022). It has been used to retrieve the ground level information of the external areas (yards and cloisters). Since the historical buildings in the study area have been built more than a century ago, especially the Opera di Santa Croce is a monumental complex that dates to the 13th century, there are no updated technical drawings. Thus, a detailed campaign of field surveys and consultation of several historical archives have been carried out to retrieve the geometrical specifications of the IRDN (Figure 3). These activities allowed geolocalizing the IRDN's features, such as manholes and conduits, and drawing the sewer profiles. Moreover, the DTM of the BNCF interior, meaning the altimetry of floors, has been created in order to set the elevation of each internal manhole and computational mesh.

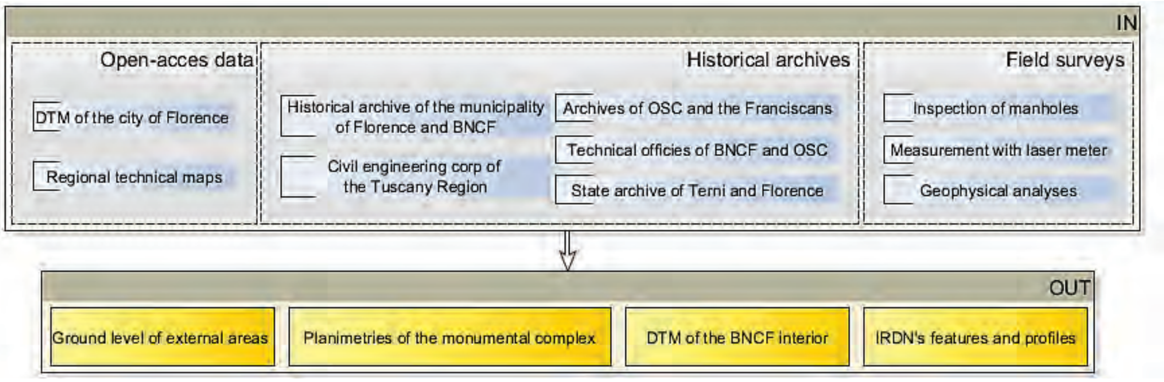

Figure 3. Sources of the geometric data and resulting elaborations.

3. RESULTS AND DISCUSSIONS

Results extrapolated from the hydraulic model have been examined and the flood hazard has been analysed in terms of the total amount of Flood Volume (FV) overflowed from the manholes into the study area and the number of flooded manholes, i.e. nodes of the network (FN), for the different scenarios.

3.1 Pluvial flood hazard assessment – Hydrometeorological Forcing scenarios

The HF scenario intends to simulate the behaviour of the sewer network under the pressure of extreme rainfall events. The results analysed are summarised in Figure 4 (top graph). What stands immediately out in the graph is that there is a different response of the network if Chicago or Triangular hyetograph is analysed. Indeed, the number of flooded nodes is higher when Chicago hyetographs are simulated. The extreme, but short, rainfall impulse surcharges the head of the IRDN – meaning the small manholes closest to the gutters – exceeding their capacity. This mainly affects those manholes placed in external courtyards, leading to slight overflow from the manholes. Comparing all simulation outcomes concerning Chicago hyetographs there is a slight difference among them, both in terms of FV and number of flooded nodes. This means that in the case of impulsive rainfall the duration of the event does not have an effect on the drainage capacity but impacts only depend on the rainfall intensity. Conversely, considering Triangular hyetographs, where the rainfall volume is more distributed over time, varying the rainfall intensity, there is a consistent difference among simulated rainstorms. Long downbursts, duration of 3 hours, do not surcharge the network and conduits are able to carry stormwater to outlets. For shorter durations, the number of flooded nodes and FV increase proportionally with the rainfall intensity. Figure 4 also shows that FV and FN are not always directly correlated. For example, the FV overflowed from 6 manholes for the event Tr200-30minT is equal to the one obtained for the event Tr100-1hC where the FN are 10. The simulation outcomes reveal that most of the IRDN's conduits were oversized during the design to safely evacuate the stormwater, even for high-intensity rainfall events. Only the sub-network of some external courtyards reaches the state of surcharge and a slight overflow from the manholes occurs. In case of extreme rainfall events, the pipes of the PSN around the study area reach a critical state in which are mostly filled. This produces a backwater effect into the IRDN, especially beneath the National Central Library, that reduces its discharge capacity but without determining the risk of intrusion of sewage flow into the building. Concerning the considered scenario in which the only forcing are extreme precipitations, the IRDN is sufficient to divert the stormwater towards its outlets avoiding the threat of damages to the cultural heritage guarded inside.

3.2 Pluvial flood hazard assessment – Spillway Closed scenarios

The SC scenario aims to assess the hazard of flooding of the monumental complex of Santa Croce in the harsh causality of contemporaneous presence of extreme rainfall events and high-water stage of Arno River. As aforementioned, this condition obstructs the release of surplus stormwater out of the PSN into the river, causing further surcharging in the sewer network. The higher water levels into the conduits exacerbate the backwater effect towards the IRDN raising the water surface to the pavement quote inside buildings. Simulation outcomes are displayed in Figure 4 (bottom graph).

In terms of the amount of FV, the first event that induces the overflowing of manholes flooding the interior rooms of the BNCF is the Tr100-3hC. The number of flooded nodes rises to 21 nodes since the water level in the IRDN overcomes the ground elevation of the lower left-side of the building (the side of the building called Tribuna Dantesca). The overflowing produces a water level inside of the interior spaces of 10 cm. This might not directly damage the books stored inside but the water and impurities carried by the sewage could affect the interior atmosphere of the rooms, such as boosting the moisture degree, indirectly damaging them. The water level in this side of the building increases as the severity of the rainstorm simulated increases, ranging from 20 cm, for the event Tr200-1hT, to 50 cm, for the event Tr200-3hC. This latter event, the worst simulated, also lead to the overflowing of the conduits along the right-side of the BNCF. For this reason, the number of FN consistently rises up (almost 32% of the manholes within the BNCF) and it produces the highest FV simulated. In this catastrophic condition, even if with an irrelevant water depth of a few centimetres, the 74% of the whole interior surface of the BNCF results inundated. Moreover, the water surface in most of the IRDN's conduits rises to 45.79 m a.s.l., just 1 cm below the elevation of most of the interior pavements of the BNCF. This outcome highlights how this scenario represents a threshold condition beyond which higher intensity precipitation or additional perturbation into the sewer system would cause severe flooding with remarkable direct damage to cultural heritage.

In summary, considering all scenarios simulated, only the underground floor of the BNCF is at risk of flooding. Particularly, books and ancient newspapers stored on lower shelves in the left-side of the library might be severely damaged by stormwater. On the contrary, due to the distance from the PSN, the OSC does not result subjected to a higher level of flood hazard. Indeed, a few manholes get surcharged, and overflow occurs. Since all manholes of the historical complex of OSC are placed outside, minor flooding occurs only in courtyards and car parks without threatening the cultural heritage safeguarded inside of the building.

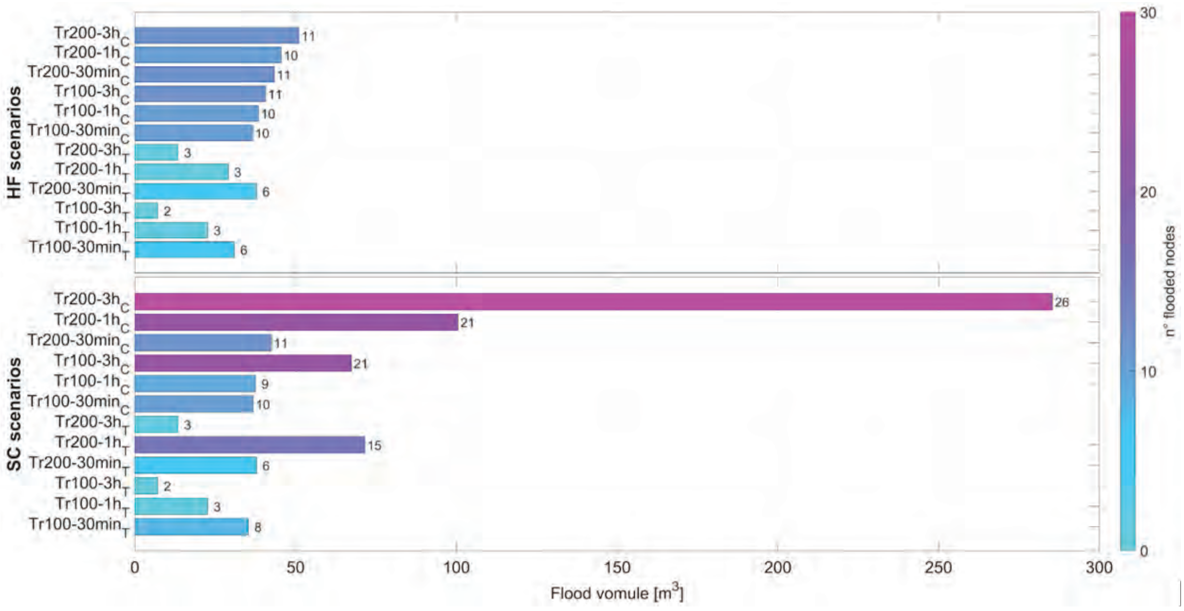

Figure 4. Flood volume overflowed from the surcharged manholes. Top: flood volume for the HF scenarios. Bottom: flood volume for the SC scenarios. Colouring and numbering: number of flooded manholes (nodes of the network).

4. CONCLUSIONS

Extreme rainfall events have been identified as one of the most critical hazards able to damage the cultural heritage. In this work, a pluvial flood hazard assessment for one of the most valuable areas of the art city of Florence (Italy) is presented. The assessment comprehends the evaluation of the stormwater propagation within the drainage system of the study area and the entire public sewer network of the city. Moreover, overland flow movements into the historical complex have been computed for those scenarios in which the sewer network get surcharged, and it overflows.

The results coming from the hydraulic model reveal that most of the IRDN was properly designed and it can safely discharge stormwaters out of the buildings. This is even more evident looking at the conduits' sizes beneath the BNCF which are comparable to the ones of the PSN.

The risk for the cultural heritage safeguarded into the BNCF to be flooded is sharply related to the capability of the PSN to efficiently carry the excess of stormwater. Indeed, in the case of the PSN surcharge, the water level inside of the conduits may significantly rise causing the flooding of the interior spaces of the library complex. Therefore, technical strategies for reducing the flood hazard of this area should be focused on the linkage between IRDN and PSN.

Considering the small scale and level of detail of the presented analysis, this study makes a step forward in the comprehensive investigation of flood hazards to which historical buildings and the cultural heritage safeguarded inside are exposed. The methodology proposed would stimulate the use of approaches based on hydraulic and hydrological models to cultural heritage protection.

The results of this study are beneficial for both the Water Managers, enhancing the level of knowledge of the sewer network functioning, and Site Managers, improving the effectiveness of their hazard management and emergency plans.

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