The Interlink Between Urban Growth and Flooding: Lessons from the City of Bari (Italy)

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Abstract. Urban growth, combined with the intensification of extreme rainfall events driven by climate change, has significantly altered the natural hydrological dynamics responsible for flood events, leading to an increased risk in urban areas. Indeed, the increase of impermeable surfaces, along with the inadequacy of urban drainage systems, can cause significant damage during heavy and short-duration rainfall events. These phenomena are also characterized by their localized nature, affecting specific urban or peri-urban areas that are often not recognized as floodable areas. This evolution in flood dynamics within increasingly urbanized contexts has highlighted the inadequacy of existing mitigation measures, which were originally conceived to address different types of flood risks. Therefore, it is crucial to design mitigation strategies that acknowledge the specific characteristics of these phenomena and integrate them into new urban development models and take into account citizens' risk perception. To this end, understanding territorial evolution is essential for identifying new areas of hydraulic vulnerability that have not yet been recognized or sufficiently studied. In this context, the present study aims to investigate the relationship between urban growth and hydraulic vulnerability through an integrated methodological approach, based on Geographic Information Systems (GIS) and survey-based risk perception analysis. The proposed methodology was applied to the case study of Bari (southern Italy), a coastal city whose metropolitan area is crossed by several episodic streams. The results identify new potentially vulnerable zones that escape traditional risk delineation methods, highlighting critical issues in urban development practices that have evolved without adequate consideration of the hydraulic morphology of the territory.

Keywords: Urban Floods · Urban Planning · Risk Management

1 Introduction

Urban expansion is one of the most significant territorial transformations of recent centuries, profoundly influencing – among others - ecosystems and hydrological dynamics. Increase of urban population, coupled with rapid infrastructural development, have drastically altered natural processes such as infiltration, runoff, and groundwater recharge,

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leading to increased hydraulic risk and declining in water quality (De Roo et al., 2001) [1]. As an example, the transition from natural or semi-natural landscapes to artificial and impermeable surfaces reflects in the reduction of soils infiltration capacity, leading to an increased surface runoff that should be generally channeled into drainage systems.

It is well known that cities generally develop in a fragmented and stratified way, incorporating areas that were once designated for natural water flow, such as river floodplains and ancient drainage channels [2, 3]. In fact, urban expansion has increasingly occupied natural retention and attenuation basins, decreasing their absorption capacity and exacerbating the risk of pluvial flooding [4]. This process has led to the rise of floodable areas even in places that were historically not susceptible to river flooding, with the coexistence of multiple type of floods in the same urban areas, which make difficult investigate causes and design mitigation measures [5, 6].

Concerns are then arising about the efficiency of current hydraulic mitigation measures also in the light of changes in extreme rainfall dynamics due to climate change, stressing need of revisiting traditional design techniques [7, 8]. These characteristics, combined with fragmented urban and infrastructural planning that often overlooks the need for natural drainage spaces and interconnections between urbanized areas and existing waterways, have intensified ground-level impacts, presenting a silent yet growing threat to cities [9]. In fact, many hydraulic mitigation infrastructures were designed without accounting for the continuous expansion of impermeable surfaces and evolving flood dynamics. This has created a paradoxical situation where areas previously not considered at risk of hydrogeological hazards now experience sudden flooding, causing significant damage to infrastructures and human activities [10, 11].

In recent years, scientific research has increasingly focused on developing strategies to mitigate the effects of urbanization on water systems, particularly concerning pluvial flooding risks. Sustainable urban drainage systems, integration of green infrastructures, and stormwater management are becoming effective tools for supporting the control of surface runoff generation and reducing the impacts of heavy rainfall events in urban areas [12]. To increase their efficiency, these measures should be complemented by more informed spatial planning that recognizes the hydrological and hydraulic histories of the area and preserves spaces for natural water management.

However, despite technological and scientific advances, defining effective integrated flood risk management strategies is still a challenge for communities and institutions [12, 13]. In this framework, the investigation of people's risk perception received considerable attention in last decades, because of the influence it can exert on people's response and decision-making during a flood emergency, even exacerbating the effects over those naturally expected [15–17].

This study presents a methodology that combines the analysis of the historical evolution of urban landscapes with an assessment of local residents' perception of flood risk. By integrating these two dimensions, the approach offers a more comprehensive and multidimensional understanding of urban flooding, serving as a valuable complement to conventional technical and hydrological analyses. The methodology aims to reveal the complex interplay between urban development, the physical vulnerability of the territory, and societal awareness of flood risk. Ultimately, the goal is to support more informed and participatory spatial planning processes ones that integrate both technical

and socio-cultural perspectives and are better equipped to respond to the challenges posed by climate change and ongoing urban expansion. The paper is structured as follows: in Sect. 2 the case study is introduced, together with an overview about the most relevant river flood events that here occurred; in Sect. 3 the methodology and the material used for this study are described, while in Sects. 4 and 5 the main results and implications of the proposed analysis are discussed. Finally, the paper ends with an overview about the most significant conclusions of the study.

2 Case Study

2.1 The City of Bari (Southern Italy)

The city of Bari is located in the eastern coast Italy and is among the most important cities of Southern Italy, due to its key role in the industrial and financial sectors.

The hydrogeological system of Bari is strongly influenced by the karst nature of the region, characterized by a calcareous substrate that facilitates the rapid infiltration of rainwater and the formation of important underground aquifers [18]. This system consists of a superficial aquifer, discontinuous and influenced by seasonal variations, and a deep aquifer, more stable and which acts as a strategic resource for water supply [19]. A distinctive feature of the landscape is the presence of natural episodic streams called *lame* (Fig. 1), whose drainage networks are not fully organized, due to the low frequency of events characterized by enough energy to shape the geomorphology.

Hence, all these streams are characterized by a permanent absence of flows and somewhere not recognizable riverbeds, but in correspondence of heavy rainfall events significant peak discharges can be observed [20–22]. They are depressions that historically served as drainage routes for rainwater, but have been increasingly compromised by urbanization [2, 23]. The expansion of built-up areas has altered their hydrological function, contributing to an increased risk of flooding, particularly in the urbanized sections of their catchments (Fig. 2) [2, 24].

The metropolitan area of Bari falls within a climatic regime typical of Mediterranean regions, characterized by intense rainfall events that vary in duration throughout the year [25]. Short-duration rainfall episodes (between 30 min and 2 h), often highly intense, occur predominantly between June and September, whereas longer-lasting events (up to 24–48 h) are more common during the winter months. This marked seasonal and temporal variability, combined with the high intensity of shorter events, creates favorable conditions for the onset of sudden flooding, with diverse dynamics and impacts across the urban landscape. Historical analysis of rainfall data conducted in Totaro et al. [25] identified more than 80 urban flooding episodes linked to specific extreme precipitation events, highlighting a strong correlation between local climatic patterns and hydraulic risk exposure.

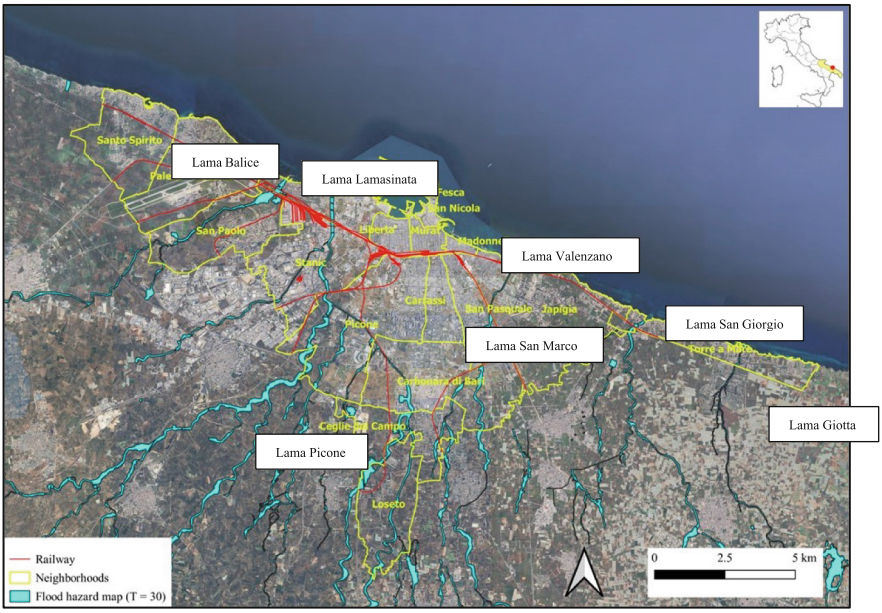

Fig. 1. The city of Bari with lame stream network and flood hazard maps

2.2 Flooding History

The history of the river floods that affected the city of Bari has been analysed in several scientific works [24, 26, 27], who described the main floods occurred in 1905, 1915, 1926 and 2005.

According to Mossa (2007) [24], each major flood that hit the city of Bari led to the implementation of engineering interventions aimed at protecting the territory, such as the construction of dikes and diversion channels. For example, the flood of 1915 prompted the construction of dikes along Lama Picone, considered at the time an effective solution to contain future floods. However, when another catastrophic event occurred in 1926, the barriers gave way and collapsed, triggering a devastating flood wave that submerged entire neighborhoods of the city. Following this tragedy, authorities recognized the need for broader and more integrated flood defense strategies, beyond simple pure hydraulic infrastructure. This led to the establishment of the Mercadante wood in 1928, located in the municipality of Cassano delle Murge. The reforestation project had a clear objective: to reduce hydrogeological risk by improving the soil's capacity to absorb rainwater and limiting runoff towards the coast [26]. The creation of the forest was accompanied by other strategic interventions, including the strengthening of the embankments, the diversion of Lama Lamasinata, and the construction of a new drainage channel to distribute water more effectively [28].

At the same time, improvements were made to urban infrastructure, including the enhancement of the sewer system to facilitate rainwater drainage and reduce water accumulation in vulnerable neighborhoods [2]. In addition, new urban planning regulations were introduced to prevent construction in high-risk areas. However, over time, many of



Fig. 2. Lama Giotta: example of urbanization close to the stream network

these regulations were ignored, leading to urban development that largely ignored the city's hydraulic safety [29].

However, the lack of maintenance of hydraulic infrastructure and poor land management made Bari vulnerable to flooding again, as demonstrated by the 2005 flood [27]. During the night between 22 and 23 October, an intense storm brought torrential rains, with almost 150 mm of rain falling in a few hours. The event caused the collapse of a road between Cassano delle Murge and Bitetto, resulting in the death of five people, as well as the derailment of a Eurostar train, resulting in multiple injuries. The water inundated several areas of the city, submerging homes, cars and industrial plants.

3 Methodology

The methodology used in this paper is articulated in two main steps, and namely: (i) GIS-based analysis aimed at the detection of urbanization trends over time, and (ii) detection of city landmarks that people perceive at flooding risk. In the following paragraphs all these steps are illustrated.

3.1 Evolution of Urbanized Areas Over Time

The historical evolution of the urbanization of the city of Bari has been reconstructed through collection and analysis of historical books and reports, photographical documentation and historical official cartography. The need of these three types of information is due to the lack of a consolidated analysis of the evolution of the urban texture of the city of Bari. To this aim, in particular we exploited:

(i) historical cartography (e.g. Military Geographic Institute) and orthophotos;
(ii) geological maps;
(iii) books and reports containing information about floods and urban fabric evolution;
(iv) Regional Technical Map of Puglia region;
(v) photographical documentation.

Combination of such data allowed to obtain a reliable description of the structure of the urban area of Bari during the last two centuries, together with useful insights about the dynamics of historical river floods events describes in Sect. 2.2.

3.2 Floodable Landmarks Perception Analysis

This step is aimed in the investigation of city landmarks perceived to be potentially subject to flooding by citizens. For this purpose, we collected data by disseminating survey with the methodology of snowballing sampling from July to September 2020 and, because of the restrictions imposed by the COVID-19 pandemic, it was diffused and shared only via online channels. Participants were asked with an open question to list streets, neighborhood or places that they perceive to be floodable after a rain events. As a results, a sample of 752 respondents has been collected. For a detailed discussion about the structure of the sample, the reader can refer to Santoro et al. [30].

4 Results

4.1 Urbanization Dynamics

The analysis of the evolution of the urbanization of the city took place in a GIS environment. In Fig. 3 is reported the urban evolution of the city of Bari as can be deduced from IGM cartography. The representation of the urban expansion was represented according to a temporal classification based on the 2011 Regional Technical Map, allowing to correlate the settlement dynamics with the stream network.

From a historical perspective, Fig. 3 illustrates four main phases of urbanisation. In 1869, the city was still extended not far from the historical settlement, close to the sea, with limited expansion. However, as it can be supposed from the analysis of a detailed geological map realized for the city of Bari [31] and historical information [24], at that time the evolution of the city already interested the mouth of the original path of the Picone lama, which crossed the Picone and Libertà neighborhoods flowing into the sea in the proximity of the city castle. In particular, historical photos [32] clearly show evidence of the Picone lama and crossing bridges in the homonymous neighborhood in the early ‘900.

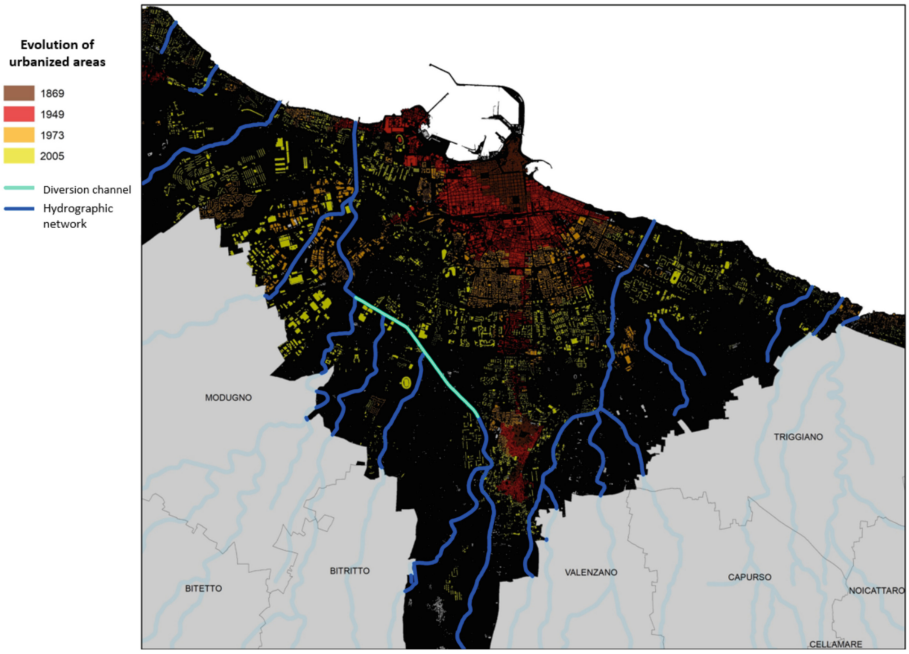

Fig. 3. Relationships between actual stream network and urban fabric development

As reported in Sect. 2.2, between 1905 and 1926 three major river flood events hit the city of Bari, causing victims and significant damage, leading to the design and building of hydraulic structures aimed in the protection of the city core. At the same time, the railway network was consolidated, splitting the city in two areas linked by underpasses that, with the increased diffusion of vehicles, become crucial points for urban mobility. In this context of renewed safety, induced by the coupled effect of the episodic nature of *lame* and of the hydraulic works, the urbanized area expanded significantly, reflecting a period of economic and population growth. As the decades passed, the process of expansion accelerated further: in 1973, there was a wider spread of urban fabric, favoured by industrialisation and infrastructure development. Finally, in 2005, more recent urbanisation extended towards the periphery and along the stream network, substantially changing the relationship between the city and its surroundings. This progression demonstrates a radial expansion of the urban fabric, with a strong initial concentration in the historic center and gradual growth towards the peripheral areas, often without adequate planning in relation to the hydro-geological conformation of the territory [26].

4.2 Landmark Detection

With respect to the results of the sample dissemination, it emerges how 14.4% of the respondents explicitly declared to not have any knowledge about potentially flooded areas. In the complementary 85.6%, only the 3.4% indicated *lame* as hazardous places.

Instead, the remaining part of the sample provided a reply with one or more options. Landmarks included general indications (e.g., streets, squares, underpasses) and specific streets and residential neighborhoods. In detail, Fig. 4 show landmarks indicated by respondents: among these, six out of the ten most popular landmarks belong to this category, and in 5 cases an explicit indication about their toponym is recorded. It is interesting to highlight how in the 63% of the cases underpasses were indicated as areas at risk.

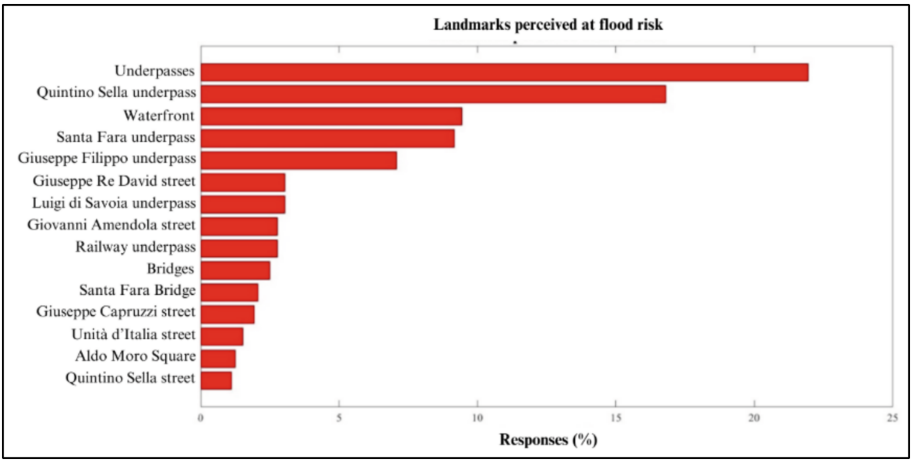

Fig. 4. *Frequency* of landmarks perceived at risk of flooding (only those with more than 1% of responses are reported)

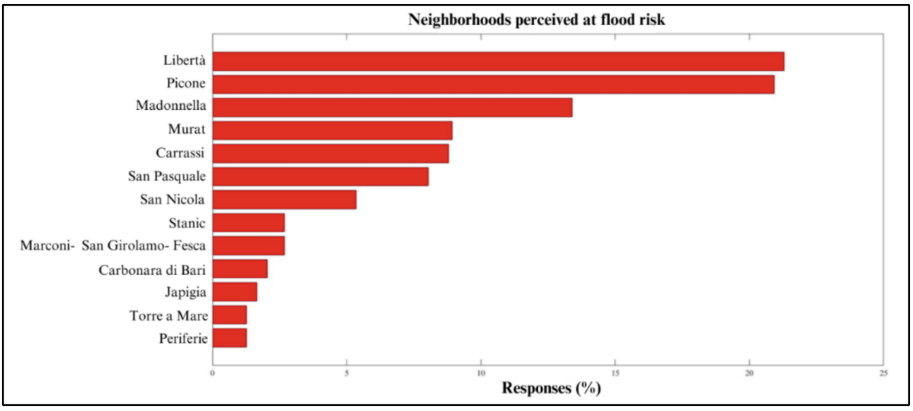

Fig. 5. Frequency of residential neighborhoods perceived at risk of flooding (only sites with more than 1% of occurrences are reported)

If moved to the neighborhoods (Fig. 5), the two top-rated options provided by respondents are the areas named Picone and Libertà (see Fig. 1), followed by Madonnella and

Murat. In all cases, this correspondence could be related to the presence of underpasses, which are crucial points in linking peripheral areas of the city with the city center.

Interestingly, Picone and Libertà neighborhoods are those were crossed by the original path of the Picone lama. From a hydraulic perspective, those landmarks clearly show how people perceive risk essential in response to pluvial flooding events, which generally exacerbate their effects in presence of moderate slopes or local depressions. Both conditions are typical of the urban area under investigation.

It is important to note that the data represented in this figure do not only reflect neighborhoods explicitly named by respondents, but also include those identified through specific reference points, such as streets or underpasses.

The results are quite clear: they reveal that neighborhoods located within the central urban area are widely perceived as vulnerable to flooding. The mention of specific landmarks—particularly underpasses and low-lying areas—helped to contextualize this perception, highlighting how certain features of the built environment contribute to water accumulation.

5 Discussion

The study of the evolution of urbanization is of paramount importance for understanding criticalities and relationships between citizens and the urban built environment. With respect to the specific case study of this paper, it emerges that urbanisation dynamics in the city of Bari has been characterised by a continuous tension between urban growth and hydraulic safety since its beginning, i.e., in the early ‘800. While on the one hand water diversion and containment works mitigated the risks due to river flooding, on the other the increase in concreting – especially in areas surrounding the stream network – changed the relationship between citizens and water. The results of Sect. 4.2 clearly describe how citizens’ risk perception reflects the modified hydraulic asset of the city. In fact, pluvial flooding events are nowadays the most common threat that affect the city. As shown in [26], a systematic analysis of flooding events news and contents derived from newspaper and social media confirmed how, in effect, landmarks indicated from survey respondents corresponds to areas subject to floods in the past. The analysed journalistic and social media sources show that intense and sudden rainfalls quickly turn roads into flowing water, with recurring ground effects such as flooded subways, stranded cars, traffic jams and damage to businesses. In particular, critical points in the city, such as road underpasses, are often flooded in few hours due to the failure of the urban drainage system and local topography, which struggles to dispose of the accumulated volume of water. An analysis of the events reported in recent years shows poor maintenance of the hydraulic infrastructure, evidenced by recurrent reports of clogged manholes and insufficient sewerage pipes. This problem is aggravated by the increasing soil sealing due to uncontrolled urban expansion, which has reduced the natural surfaces capable of absorbing rainwater. The combination of these factors amplifies the risk of flooding, transforming even medium-intensity rainfall into urban emergencies. Interestingly, these landmarks lie generally outside the officially designated flood-prone areas, as recognized by the Hydrogeological Risk Management Plan. This note sheds light on the need of taking in account also this type of floods during land planning, in order to increase resilience of urban areas to extreme events.

Another relevant aspect highlighted by the map of Fig. 3 is the relationship between the urbanisation of Bari and its neighboring municipalities, including Modugno, Bitritto, Valenzano, Capurso and Triggiano. This suggests that the city's growth did not occur in isolation, but was part of a broader process of metropolitan expansion, with significant implications for the management of land and water resources. The need for coordinated planning between different administrations has emerged several times throughout history, remarking how urban development need to be carried out with particular attention to hydrogeological risks [29]. Hydraulic protection cannot be based only on the construction of engineering works, but must be accompanied by careful urban planning and respect for the territory's natural characteristics [24].

These results are a sign that the measures taken so far have not been sufficient or that prevention has not been given the right priority. In order to prevent these events from continuing to create damage and inconvenience, a more strategic and proactive approach is needed, one that does not just react to emergencies but aims to prevent the hydrogeological risk from flooding with long-term solutions.

6 Conclusions

The analysis showed that uncontrolled urban expansion and progressive soil sealing have had a significant impact on the hydraulic vulnerability of cities, increasing the risk of flooding. The increasing occupation of areas once used for natural water runoff has led to an alteration of the natural hydrological dynamics, with a reduction in infiltration capacity and an increase in surface runoff. Pluvial and flash floods, which are often underestimated in comparison to river floods, occur quickly and with sudden effects, making their management and prevention even more complex.

The study demonstrated the effectiveness of a methodological approach based on a combination of risk perception analysis and GIS tools to analyse the evolution of urbanisation and its impact on hydrological dynamics. Integrating the analysis with flood events catalogue made it possible to gather detailed information on the frequency and effects of recent flood events, while GIS model-relation made it possible to correlate the growth of the city with the transformation of the hydrographic reticulum and the increased risk of flooding.

The case study of Bari provided a concrete example of how urban expansion can generate new hydraulic criticalities, often in areas that historically were not considered at risk. The city has suffered a significant number of episodes of pluvial flooding in recent decades, in areas not included in traditional hydraulic hazard maps. This highlights the need to constantly update land planning and management tools, integrating historical data and predictive models capable of identifying vulnerable areas.

In order to mitigate the impacts of urbanisation on water resources and urban security, integrated strategies that combine sustainable spatial planning, Nature-Based Solutions (NBS) and advanced urban drainage infrastructures become crucial. Tools such as Sustainable Urban Drainage Systems (SUDS) can be effective solutions to improve the hydraulic resilience of cities.

This study underline the importance of more careful land and water management in expanding cities, highlighting how the integration of digital analysis tools and innovative approaches to water management can offer effective answers to the challenges of

climate change and increasing urbanisation. A multidisciplinary approach, combining technology, research and strategic planning, will be essential to ensure the long-term water security and sustainability of urban areas.

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