Response to urban waterlogging control under different topographic conditions

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Abstract: In recent years, the acceleration of urbanization and the occurrence of intense rainfall have led to urban waterlogging, resulting in property damage and threats to human life. The development of flood resilient infrastructure systems is therefore crucial. However, achieving this goal can be challenging in high-density urban areas due to land resource constraints. This study proposes a framework based on local human wisdom that can withstand, absorb and recover from floods in a timely manner to enhance flood resilience in the urban design process. In this study, we analyzed the hydrological characteristics of Zhengzhou City and constructed a rainfall and flood security pattern using GIS and hydrological models. Corresponding blue-green solutions were determined for different topographic conditions. Finally, a macro-scale rainfall and flood mitigation program was designed and its effectiveness was evaluated using the Storm Water Management Model (SWMM). The results show that the Blue-Green program created 40,000 cubic meters of rainwater storage, resulting in significant economic benefits for the community. This approach can improve the flood resilience of inland cities, particularly in response to heavy rainfall and river flooding.

Keywords: urban waterlogging; topographic conditions; flood resilience; Blue-Green solutions; SWMM

1.Introduction

With increasing urbanization and impervious underlying surface, the risk of urban waterlogging has increased significantly (N. Q. Zhou & Zhao, 2013). The frequent occurrence of extreme weather events and the rising threat and impact of climate variability on cities have made urban waterlogging a major concern in many highly urbanizing areas (Hammond, Chen, Djordjević, Butler, & Mark, 2013; Liu et al., 2023). Urban waterlogging disasters cause huge economic loss and pose a serious threat to people's lives. For example, Beijing was hit by a torrential rainstorm in 2012, resulting in 79 deaths, affected 1.602 million people and resulted in loss of more than US$ 1.64 billion (T. Xu et al., 2021); in 2014, Shenzhen suffered the strongest rainstorm since 2008, with economic loss of more than US$ 11 million (Q. Zhang, Wu, Zhang, Dalla Fontana, & Tarolli, 2020). Urban waterlogging has now become a serious obstacle to sustainable urban development and has attracted widespread attention worldwide (da Silva, Alencar, & de Almeida, 2022; Ward et al., 2017). To address this growing challenge, improving urban resilience and enhancing urban waterlogging risk management has become a new topic in many research fields (Liu et al., 2023; Sharifi & Yamagata, 2014).

The development of flood-resistant infrastructure systems is critical. However, achieving this goal in high-density urban areas can be challenging. On the one hand, traditional urban water control infrastructure, such as retention ponds or pumping stations, take up a lot of land and result in a waste of money. They are usually designed with one function in mind: to store rainwater when it rains, or to drain excess rainwater, but they are not designed for dry days (Cheng, Qin, Fu, & He, 2020). On the other hand, land resource constraints could make it difficult to build infrastructure in high-density urban areas. Therefore, in densely populated urban areas, there is a contradiction between the space required for waterlogging management and the scarcity of space (Q. Zhang et al., 2020). In recent studies, scientists have proposed many new ways to reduce urban waterlogging. The relative concepts include Sustainable Drainage System, Sponge City Construction, Water Sensitive Urban Design, and Low Impact Development (Nguyen, Ngo, Guo, & Wang, 2020; M. Wang et al., 2023; Mo Wang et al., 2023; H.

Zhou, Li, Zhao, & Ding, 2021). These theories and techniques suggest that the problem of urban waterlogging management can be partially solved through adaptive initiatives using nature-based solutions (C. Xu, Jia, Xu, Long, & Jia, 2019). However, relying solely on flood prevention to mitigate disasters will make cities more vulnerable (Liao, Le, & Nguyen, 2016).

Taking the heavy rainstorm that occurred in Zhengzhou City on 20 July 2021 as an example. This study first analyzed the hydrological characteristics of Zhengzhou City and constructed the rainfall and flood security pattern using GIS and hydrological models. On this basis, the corresponding Blue-Green solutions was determined for different topographic conditions. Finally, macro-scale rainfall and flood mitigation scenarios were developed and their effectiveness was evaluated using the SWMM. In order to promote urban flood resilience in high-density urban areas, this paper proposes a Blue-Green solutions for improving flood resilience in the urban design process, based on a framework that relies on local human ingenuity and is able to resist, absorb and recover from floods in a timely manner. This is an example of a flood adaptation paradigm and offers lessons for modern cities. This study provides a theoretical and practical reference for the government and urban planners for urban waterlogging prevention and management.

2. Study area

Zhengzhou is the capital of Henan Province, China, with a population of 12.74 million at the end of 2021 and a total urban area of 7,567 square kilometers. The general topographical trend of Zhengzhou is high in the southwest and low in the northeast, with a temperate continental monsoon climate (Fig.1). There are 124 rivers of various sizes within the Zhengzhou Municipality, spanning the two major river basins of the Yellow River and the Huaihe River. The average annual rainfall is 632.4 millimeters, and the average annual number of rainy days is 78. Rainfall is concentrated from June to August each year, with the heaviest rainfall occurring in August. On 20 July 2021, in less than an hour, Zhengzhou was hit by an extreme 1,000-year storm event in which 201.09 mm of rain, exceeding the historical extreme of meteorological observation records in mainland China, left large areas of the city under up to almost a meter of water (Fig.2). The heavy rainstorms affected 13,664,300 people, with direct economic losses of up to US$12.255 billion, and 398 people were killed or missing in Henan Province as a result of the disaster.

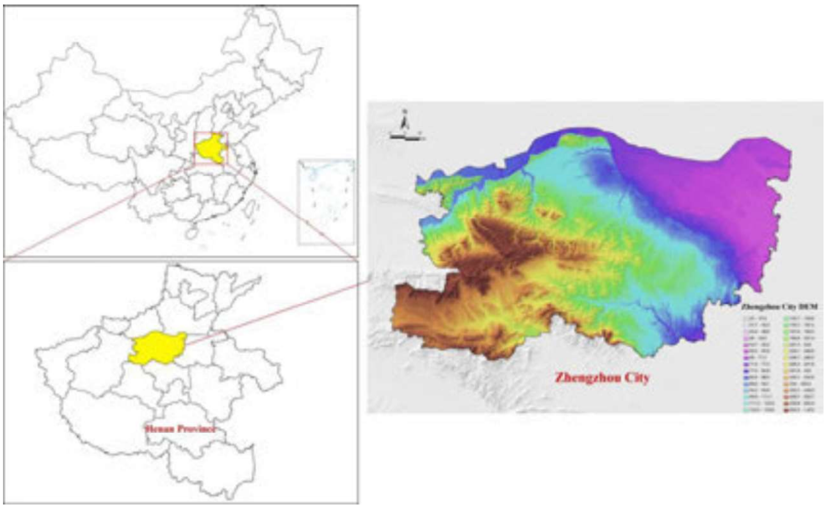

Fig. 1. Study area.

Fig. 2. Waterlogging damage image of Zhengzhou City on July 21, 2021.

3. Data and methods

3.1. Data source and pre-processing

The data used in this study include historical hydrological data, rainfall data, topographic data, and data from the Third National Land Survey in the study area. The data resources are summarized in Table 1.

Table 1

The data and variables used in this study.

Category	Data	Data resource	Abbreviation	Unit
Historical hydrological	Rainfall intensity (2000-2020)	http://ha.cma.gov.cn/	RI-2020	mm/d
	Rainstorm intensity formula (2021)	http://ha.cma.gov.cn/	q	L/s·ha
	Runoff coefficient	http://ha.cma.gov.cn/	y	R/P

	Catchment area	https://www.zhengzhou.gov.cn/	F	m^2
Rainfall data	Rainfall intensity (2021)	http://ha.cma.gov.cn/	RI-2021	mm/d
	Rainfall duration (20 July 2021)	http://ha.cma.gov.cn/	T	min
Topographic data	DEM 30m	https://www.usgs.gov/	DEM	-
Third National Land Survey data	Land use	-	-	-
	Land cover	-	-	-

Enter the relevant data using Arcgis 10.8 to establish a typical rainfall scenario ensemble, record the historical maximum rainfall of the storm at the site as $Pmax/d$, and calculate the required carrying rainfall for the storage cluster Zr

$$Q = qyF \tag{1}$$

$$Z = QT \tag{2}$$

$$Zr = 1.2Z \tag{3}$$

Where Q is the design flow rate of the stormwater system, q is the local storm intensity, y is the local runoff coefficient, and F is the local catchment area; Z is the volume of the storage group, and T is the rainfall duration of the storm.

In Arcgis 10. 8, enter the historical rainfall and water level data of the site, and record the starting time of the field rainfall as T1, the average water level of the regional river network at the time of T1 as W1, the time when the water level of the river network reaches the peak of the field rainfall as T2, and the corresponding peak of the water level at the time of T2 as W2, and the rainfall process from T1 to T2 is defined as the rainfall and water rise period of a field, and in the 24h before the time of T1, the average rainfall intensity should be less than 1mm/d; the maximum rainfall $P \geq 250$mm/d in a single day during the T1-T2 period.

3.2. framework of the Blue-Green solutions

The process has been formalized as the Blue-Green Solutions and is implemented through the following five steps: (1) Delineate important mountain and river corridors as ecological protection zones and protect their ecological protection function. The specific way is to accurately identify the extent of the floodway within the corridor, and put forward control requirements -- the road across the ecological corridor should be in the form of a bridge or other does not block the corridor, and leave sufficient safety protection distance on both sides of the floodway and other measures; (2) Include existing gullies into ecological protection. The specific way is to identify the existing gullies that have flood function, delineate the protection line and propose the control requirements - the ecological space within the gullies should be protected from obstruction, filling and construction. The gully within the growth boundary of the town could be landscaped with public recreational demands while ensuring flood safety; (3) Delineate safety groups and calculate water catchment. The safety group is delimited by considering the catchment zoning, the river and the urban growth boundary. Then, the detention space requirements for excess storm water in each safety group under extreme storm conditions are calculated; (4) Implement specific Blue-Green Solutions according to different site conditions; (5) Attractive development areas are created based on blue-green spaces. The specific way is to landscape the above blue-green spaces and develop them into country parks, riverside green spaces, rain gardens and so on. In normal times, these blue-green systems are superimposed with functions such as pedestrian system, interaction space, agriculture and forestry survival, while in extreme weather conditions, they become important distributed flood storage areas and disaster prevention systems.

3.3. Hydrological Model Selection

There are a variety of ways to assess the effectiveness of the implementation of the Blue-Green Solutions, the most direct and accurate method is using models. A plethora of models have been devised to forecast the consequences of flooding and the efficacy of water systems. Examples of such models include MIKE, Infoworks ICM, and SWAT (Luo & Zhang, 2022; Mignot & Dewals, 2022; Wang, Li, Yu, & Zhang, 2021; Wu et al., 2017). However, it should be noted that the majority of these models are commercially available and are unable to simulate the hydrodynamics of 1D drainage networks and 2D surface flows simultaneously. Consequently, there is a necessity for the development of a comprehensive, accurate, simple, and visual open-source urban flood model for computation (Tan et al., 2024). SWMM is an open-source computational model based on rainfall runoff dynamics developed by the U.S. Environmental Protection Agency (EPA) and is widely used to simulate the quantity and quality of urban runoff (Shahed Behrouz, Sample, & Nayeb Yazdi, 2023). The model is based on physical processes, such as surface runoff, infiltration, surface ponding and flow paths, and can therefore simulate storm runoff volumes (Luan et al., 2017). In comparison to other models, SWMM exhibits superior simulation efficacy and has been extensively employed by scholars engaged in the assessment and forecasting of storm-flood surface runoff processes (Gironás, Roesner, Rossman, & Davis, 2010; Luan et al., 2017; Tan et al., 2024).

In this study, the selected software was SWMM version 5.1, which was employed to describe the dynamic process of rainfall runoff. The construction of SWMM in the study area was based on the urban planning map and the stormwater network layout map. The required basic data, including topographic data, drainage network data, elevation data, and land use type, were analyzed and processed using AutoCAD 2021 and ArcGIS 10.8 software.

4. Results

The topography-based Blue-Green Solutions is applied in Zhengzhou City. The team selected three sites, representing three different topographic and natural conditions, each covering approximately 10 square kilometers in a watershed with high potential flood risk in the center of Zhengzhou City, as demonstration areas to showcase the improved design approach of the Blue-Green Solutions. The final validation was carried out by SWMM to calculate the increased water storage space under the Blue-Green Solutions.

4.1 Trench Ring + Dry Pond mode

This approach has been specifically designed for settlements situated on terraces or sloping plains upstream from the main urban center (Fig.3). The topographical characteristics of these areas typically include steep slopes with gradients greater than 8 degrees and the presence of naturally occurring lowlands, which can be scattered or concentrated. The primary objectives of this mode are twofold: firstly, to ensure the flood safety of the settlement itself and secondly, to prevent the exacerbation of the flood control and drainage burdens on the main city during periods of excessive rainfall. The strategic implementation entails the excavation of trenches around the perimeter of the town's development boundary, thereby creating a trench ring for each group of settlements. The trenches serve to intercept and manage upstream catchment waters in an effective manner. Concurrently, the delineation of boundaries for flood storage areas, termed dry ponds, is based on the existing natural lowlands. Subsequently, these boundaries are incorporated into the land use plan, with a stipulation that prohibits any urban construction within these designated areas. This ensures the preservation of these critical flood mitigation features.

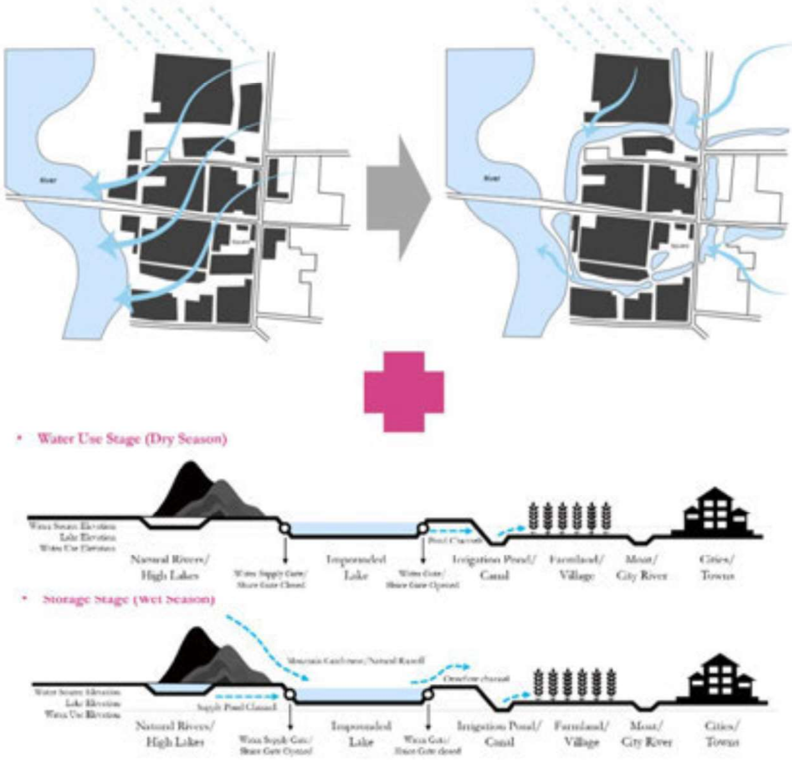

Fig. 3. Trench Ring + Dry Pond mode.

4.2 Connected Ponds + Sponging Infrastructure mode

This mode is particularly suited to main cities located within the plains, which are characterized by a more gentle topography with slopes ranging from approximately 3‰ to 8‰ and a sparse river network (Fig.4). The objective is to address the challenge of urban flooding due to heavy rainfall by providing storage or diversion for such floodwaters. The strategic approach involves the construction of a continuous system of dry ponds, which are interconnected and strategically positioned along natural lowlands and catchment pathways. In areas of the old city where open spaces are scarce, the creation of large, low-lying wet green spaces or natural lands is recommended. Such green spaces are then enhanced through the integration of grey infrastructure and urban renewal initiatives, such as the renovation of rain gardens in parks and courtyard spaces, and the implementation of eco-roofs and vertical greening on existing buildings. These measures not only contribute to flood resilience but also promote biodiversity and enhance the aesthetic appeal of the urban environment.

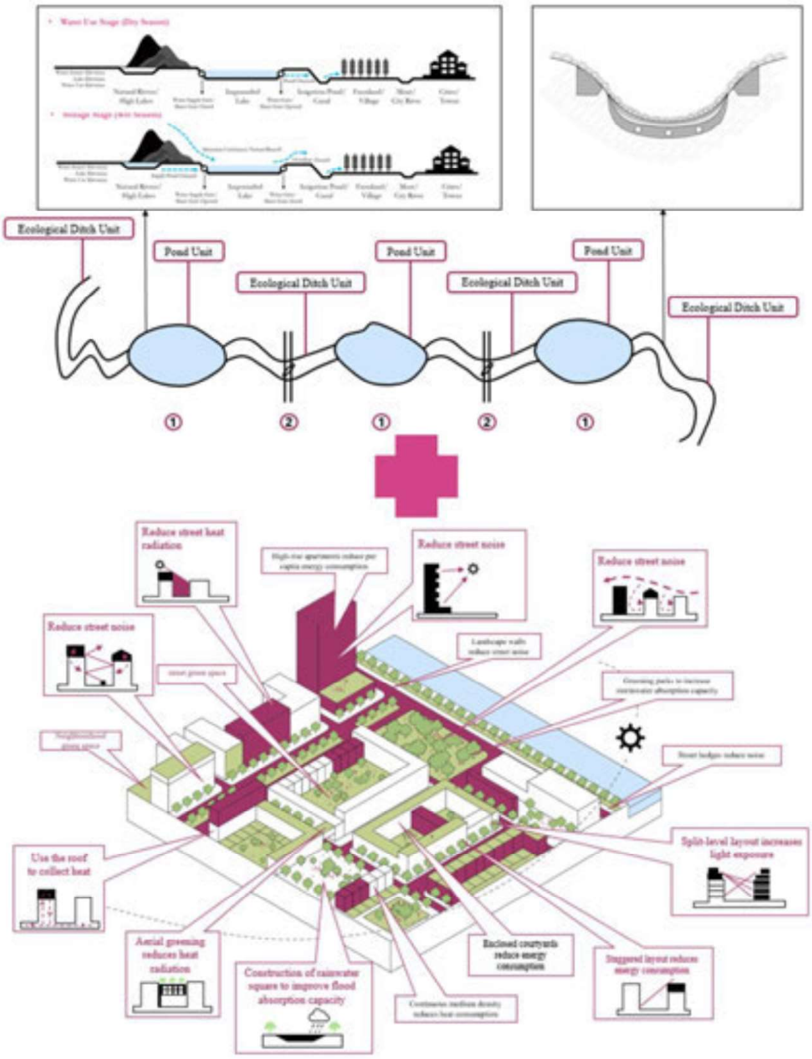

Fig. 4. Connected Ponds + Sponging Infrastructure mode.

4.3 Blue-Green Network + Elevated Groups Mode

This mode is designed for settlements in the low-lying plains downstream of the main city, where the topography is generally flat with a gradient of less than 1‰ and an abundance of rivers and ponds. The settlements' objectives are multifaceted (Fig.5). They include the storage or diversion of urban flooding resulting from heavy rainfall and the facilitation of the rapid drainage of rainwater through the utilization of blue-green spaces. The strategic response entails the preservation of the site's existing hydrological features and the creation of a landscape comprising ponds, farmland, and streams, thereby forming residential clusters that are surrounded and buffered by blue-green spaces. In order to mitigate the risk of flooding in each cluster, it is proposed that the earth excavated from these areas be strategically used to elevate the road networks and the sites themselves. This elevation provides a crucial buffer, ideally exceeding 3 meters above the surrounding areas, offering protection against potential floodwaters and ensuring the continued habitability and safety of the settlements.

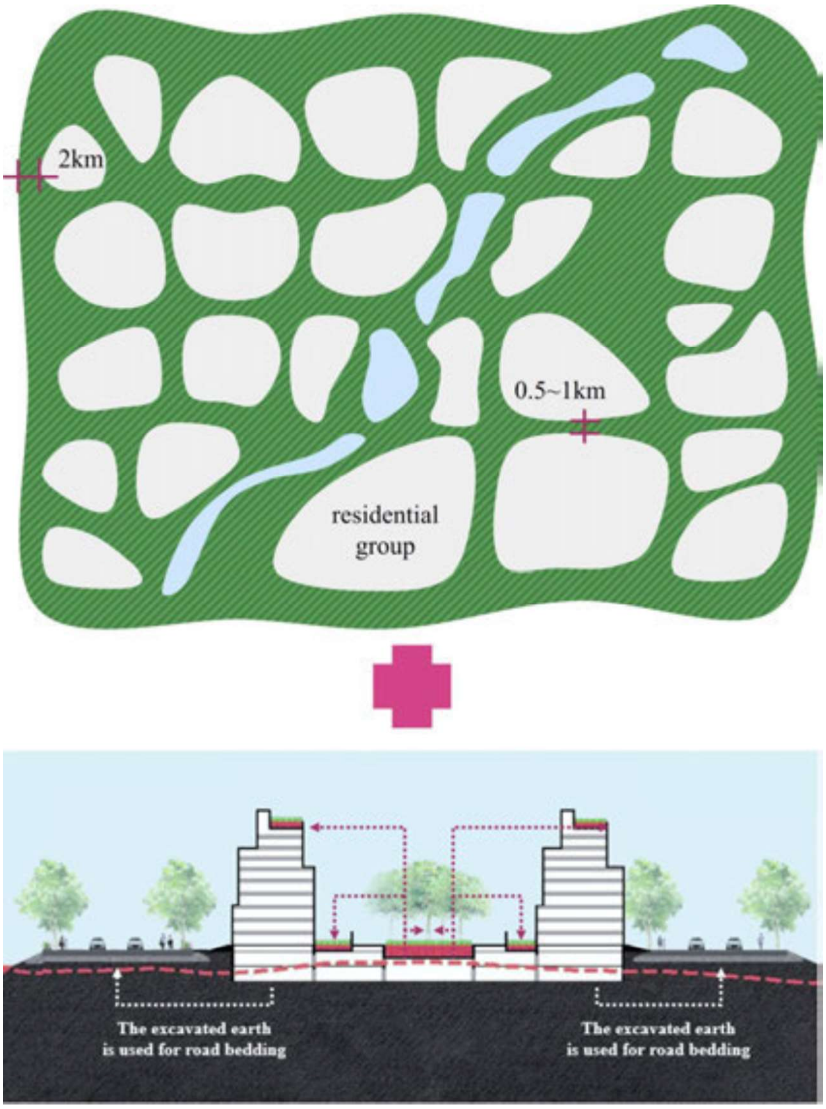

Fig. 5. Blue-Green Network + Elevated Groups Mode.

4.4 SWMM calculates the increased water storage space

In this study, the rainfall data of 20 July 2021 in Zhengzhou City was used to simulate the water storage capacity of the blue-green system under extreme rainfall conditions. A total of three sites were selected as the simulation area (Fig.6), of which Site 1 used the Trench Ring + Dry Pond mode, Site 2 used the Connected Ponds + Sponging Infrastructure mode, and Site 3 used the Blue-Green Network + Elevated Groups mode.

Under the conditions of 1-in-1,000-year rainfall in Zhengzhou City, Site 1 used the Trench

Ring + Dry Pond mode to increase the water storage space by 3918.6 cubic meters compared to the previous one (Fig.7), Site 2 used the Connected Ponds + Sponging Infrastructure mode to increase the water storage space by 2,450.6 cubic meters compared to the previous one (Fig. 8), and Site 3 used the Blue-Green Network + Elevated Groups mode to increase the water storage space by 3,932.9 cubic meters compared to the previous one (Fig. 9). In total, up to 40,000 cubic meters of water storage can be added in Zhengzhou using the three modes above, reflecting the effectiveness of the Blue-Green solutions.

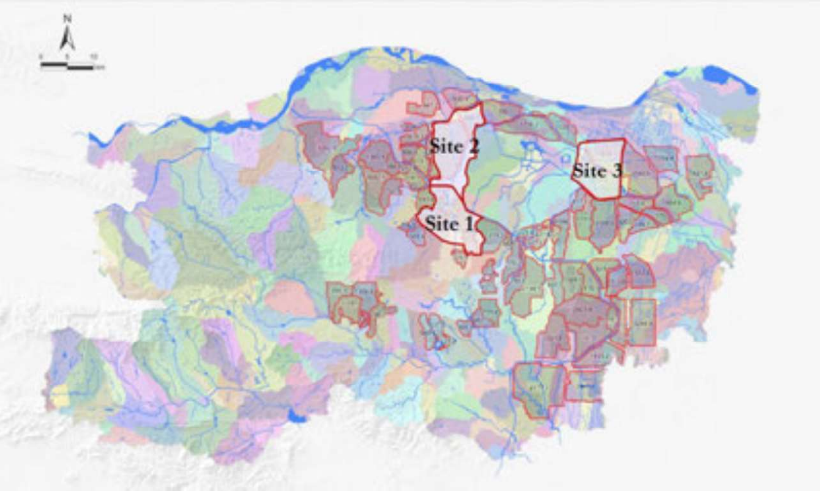

Fig. 6. Blue-Green Network + Elevated Groups Mode.

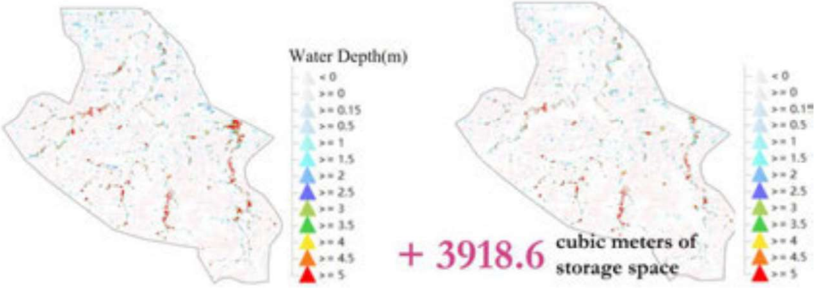

Fig. 7. Blue-Green Network + Elevated Groups Mode.

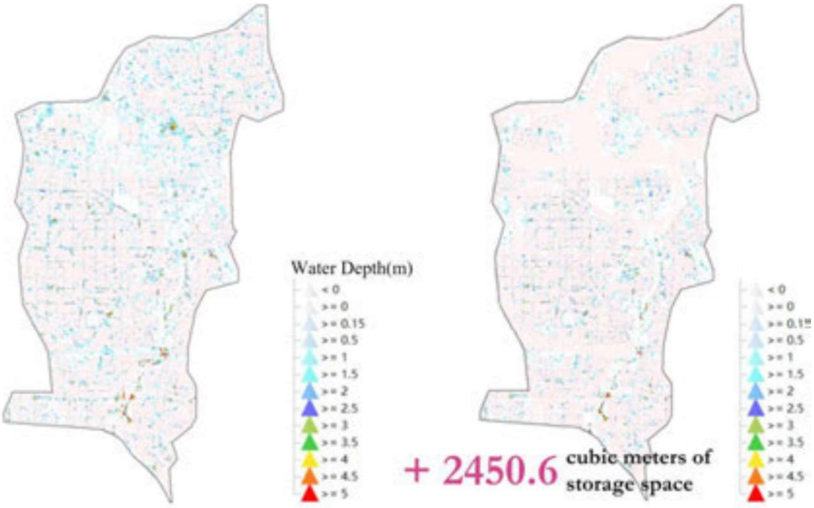

Fig. 8. Blue-Green Network + Elevated Groups Mode.

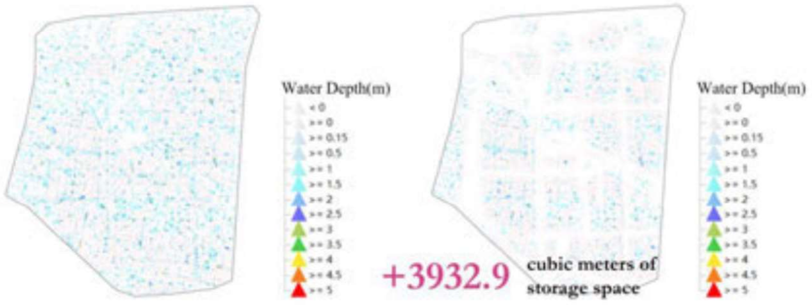

Fig. 9. Blue-Green Network + Elevated Groups Mode.

5. Discussion and conclusion

The results of the study underscore the critical role of topography in controlling urban waterlogging, especially in the context of high-density urban areas such as Zhengzhou City. The application of Blue-Green Solutions tailored to the city's diverse topographic conditions has shown significant potential to improve flood resilience and reduce economic losses associated with extreme rainfall events (Lu, Sun, & Steffen, 2023). At the same time, the study provides some spatial recommendations for policy makers and urban planners to improve resilience.

The Trench Ring + Dry Pond mode, designed for hilly or sloping areas, effectively intercepts and manages upstream catchment waters, thereby safeguarding settlements and alleviating the drainage burden on the main city. This approach aligns with the principles of

Sustainable Drainage Systems (SuDS), which emphasize the importance of source control and the use of natural features to manage water runoff (Nguyen et al., 2020). In contrast, the Connected Ponds + Sponging Infrastructure mode addresses the challenges of urban flooding in plain areas with gentle slopes. The creation of interconnected dry ponds and the integration of grey infrastructure with urban green spaces not only contribute to flood resilience but also promote biodiversity and urban aesthetics (Lu et al., 2023). This multifunctional approach reflects the concept of Sponge City Construction, which seeks to mimic natural water absorption and retention through urban design (M. Wang et al., 2023). The Blue-Green Network + Elevated Groups Mode, tailored for low-lying plains, preserves existing hydrological features and creates a landscape that buffers residential clusters against floodwaters. This strategy resonates with the Water Sensitive Urban Design (WSUD) principles, which advocate for the integration of water management into urban planning to enhance the city's adaptability to climate variability (Hammond et al., 2013).

The use of SWMM for validating the effectiveness of the Blue-Green solutions is a testament to the model's robustness and its widespread application in urban hydrology. SWMM's ability to simulate the dynamic process of rainfall runoff makes it a valuable tool for assessing the hydrological performance of urban water management strategies (Luan et al., 2017). The study's results, which indicate an increase of up to 40,000 cubic meters of water storage through the implementation of Blue-Green solutions, highlight the economic and environmental benefits of these approaches. The savings realized are more than three times that of traditional solutions, suggesting a strong case for the adoption of nature-based solutions in urban waterlogging management. However, the study also acknowledges the challenges of implementing these solutions in high-density urban areas, where land resource constraints can limit the space available for waterlogging management (H. Zhang, Zhang, Fang, & Yang, 2022). This underscores the need for innovative and space-efficient solutions, as well as the importance of policy support and community engagement in realizing the full potential of Blue-Green infrastructure (Xiao et al., 2023).

In conclusion, the study provides a comprehensive framework for improving flood resilience in urban areas through the application of Blue-Green solutions. The findings offer valuable insights for urban planners and policymakers, emphasizing the importance of considering local topographic conditions and the integration of nature-based solutions into urban design. By doing so, cities can become more resilient to the impacts of climate change and extreme weather events, ensuring the safety and sustainability of urban environments.

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