19th WORLD CONFERENCE OF THE ASSOCIATED RESEARCH CENTRES FOR THE URBAN UNDERGROUND SPACE
Belgrade, Serbia, November 4-7, 2025.

ACUUS BELGRADE 2025

Paper No: 3.1.147
DOI No: 10.46793/ACUUS2025.3.1.147

CLIMATIC CHANGE INDUCED VULNERABILITY EVALUATION OF URBAN UNDERGROUND SPACES

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Abstract: Urban underground spaces (UUS) are increasingly vulnerable to climatic change-induced disasters, e.g., flooding, subsidence, and extreme heat, necessitating advanced strategies for risk mitigation. This study integrates risk-informed and deterministic models into vulnerability evaluation frameworks to enhance risk assessment and early warning systems for UUS. Multi-source data, e.g., geological, hydrological, and urban infrastructure datasets are integrated into both risk-informed and deterministic models to quantify dynamic risks and spatial-temporal vulnerabilities. In the risk-informed model, a perception-based survey is conducted to evaluate stakeholders' awareness of underground risks to reveal discrepancies between perceived and actual threats. The inundation disaster in Zhengzhou in July 2021 is used a site case to conduct the analysis. Results demonstrate that risk-informed vulnerability evaluation with participatory perception data significantly improves risk prediction accuracy and public preparedness. The proposed framework offers scalable solutions for cities globally and advocates for smarter integration of technology, infrastructure, and community engagement in climate adaptation strategies.

Keywords: Climatic change, urban underground space, risk assessment, risk-formed model, vulnerability evaluation.

1. INTRODUCTION

With the intensification of climate change, extreme precipitation events have become more frequent, significantly increasing the risk of urban flooding (IPCC, 2023). Climate change poses a severe challenge to urban hydrological systems. Excessive urbanisation has led to a reduction in natural vegetation and an increase in impervious surfaces. Flood management has become more intricate due to climate change and heavy rainfall, which have also intensified the risk of urban flooding and waterlogging. This highlights the urgency of comprehensively assessing flood risks and formulating proactive flood prevention strategies. Many cities, particularly inland ones, struggle with insufficient drainage systems that cannot cope with these extreme weather events (Liu et al., 2024). Urban flooding and water accumulation are increasingly frequent, particularly in inland cities, due to the fragile drainage systems that struggle to handle heavy rainfall. For example, floods in China during 2021 affected 34.81 million people, resulted in 146 deaths or missing individuals, caused 72,000 houses to collapse, and led to direct economic losses of 123 billion yuan (Chan, 2023). Among the many affected areas, underground space is particularly vulnerable and has become a key risk area in urban flooding (He et al., 2024). Over the years, the cumulative area of underground construction has significantly increased. This growth reflects the rapid expansion of urban underground spaces (UUS), particularly in subway systems, which in turn leads to a notable increase in the number of facilities exposed to flood risks (Yan et al., 2021). Once drainage capacity is restricted, extensive flooding can occur within a very short period of time, causing traffic paralysis, damage to facilities, and even casualties. Such incidents have occurred many times, which caused serious economic losses and posed a major threat to urban operations and public safety. Therefore, strengthening the identification and assessment of flood risks in underground spaces is a key step in improving the overall resilience of cities and optimizing emergency response mechanisms. This fact also highlights the urgency and necessity of conducting urban flood risk assessments and formulating targeted flood control strategies.

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Underground spaces, such as subway systems, underground commercial areas, and parking lots, face substantial risks during such events (Lyu et al., 2020; Yan et al., 2021). This paper presents an integrated approach to assess urban flooding risks, resilience, and evacuation strategies, with a particular focus on underground spaces. The study uses the 2021 Zhengzhou "7.20 Storm" as a case study, providing an in-depth analysis of the vulnerability of underground spaces to flooding.

2. MATERIAL AND METHODS

2.1. Zhengzhou Disaster

The "7.20 Storm" in Zhengzhou, which occurred in July 2021, resulted in catastrophic flooding across the city. Zhengzhou received 624 mm of rainfall, nearly matching its annual average, with 201.9 mm of rainfall recorded in just one hour, breaking national records. According to the national investigation report (DIT-SC, 2022), approximately 14.79 million people were affected in this severe event, with 380 reported deaths. Among them, Zhengzhou accounted for 95.5% of the total deaths and missing people. The direct economic loss reached 120.06 billion yuan. Zhengzhou alone accounted for 40.9 billion yuan, or 34.1% of the total. The disaster severely impacted underground spaces, particularly the subway system. All stations on Line 5 of the Zhengzhou subway were flooded, and transport services were disrupted for several days. The impact on underground infrastructure underscored the vulnerability of such spaces to extreme weather.

Figure 1 shows the geological and hydrological distribution of the administrative area of Zhengzhou. The city centre is the most developed zone, with seven subway lines and a dense road network by 2022. The entire topography of Zhengzhou is characterised by a high elevation in the southwest and a low elevation in the northeast. This case study highlights the urgency of strengthening flood resilience measures in urban underground spaces. The official report from the national disaster investigation group criticized the event, stating, "The overall cause is a natural disaster, but there are also significant man-made factors involved". The findings suggest a need for better flood risk assessment tools, enhanced flood management strategies, and the optimization of evacuation planning for these spaces.

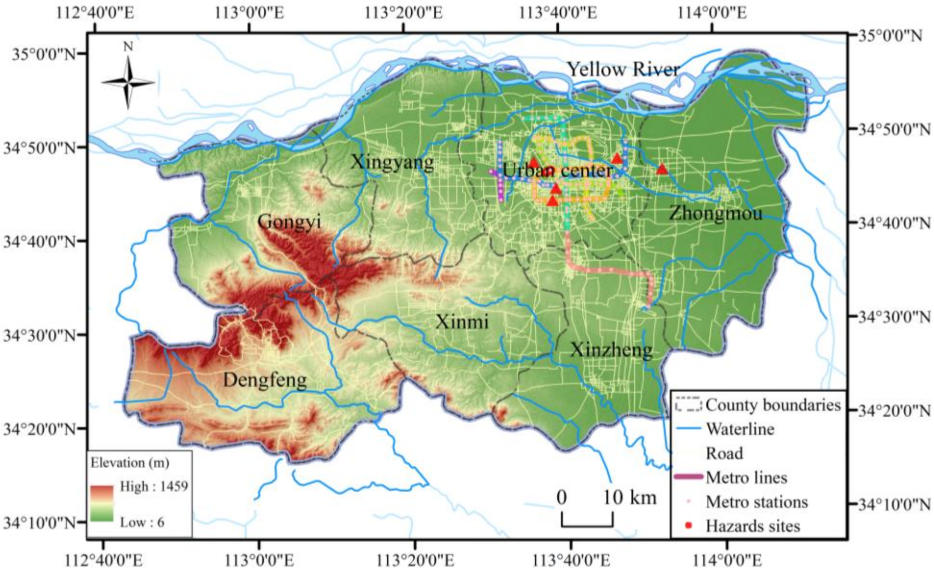

Figure 1. *Distribution of geomorphology, hydrology, and administrative region of Zhengzhou*

2.2. Methods

This study adopts a qualitative-to-quantitative and global-to-local analytical approach to comprehensively assess urban flooding and waterlogging hazards and resilience measures. The schematic of the research procedure in this study is illustrated in Figure 2.

First, disaster-related factors are extracted and weighted using Multi-Criteria Decision Making (MCDM) methods. Based on the weighted factors, the risk levels across different areas are assessed and classified. By combining historical rainfall data with hydrological simulations (HEC-HMS), sub-basins in the high-risk area can be delineated and their surface runoff calculated.

Then, Geographic Information Systems (GIS) are used to extract high-risk zones from the city-wide flood risk distribution map. Urban resilience is assessed using methods as CRITIC, VIKOR, focusing on the recovery capacity and reliability of each sub-basin, especially those with dense underground infrastructure. This part of the analysis progresses from the overall flood risk to the resilience of local sub-basins, gradually identifying key problem areas.

To further refine the modelling process, HEC-RAS is employed to simulate the inundation process and predict spatial distribution of water accumulation under different rainfall scenarios. A consistency check is conducted by comparing simulation outputs with observed water accumulation points, ensuring model validity and reliability.

Finally, GIS and Python are used to export modelling flood distribution. Based on these, evacuation routes are optimized by integrating road topology and flood data, focusing on high-risk and low-resilience underground spaces. This approach systematically combines qualitative analysis and quantitative modelling, advancing from overall risk to localized response planning, provides scientific support for enhancing flood resilience in high-risk urban areas.

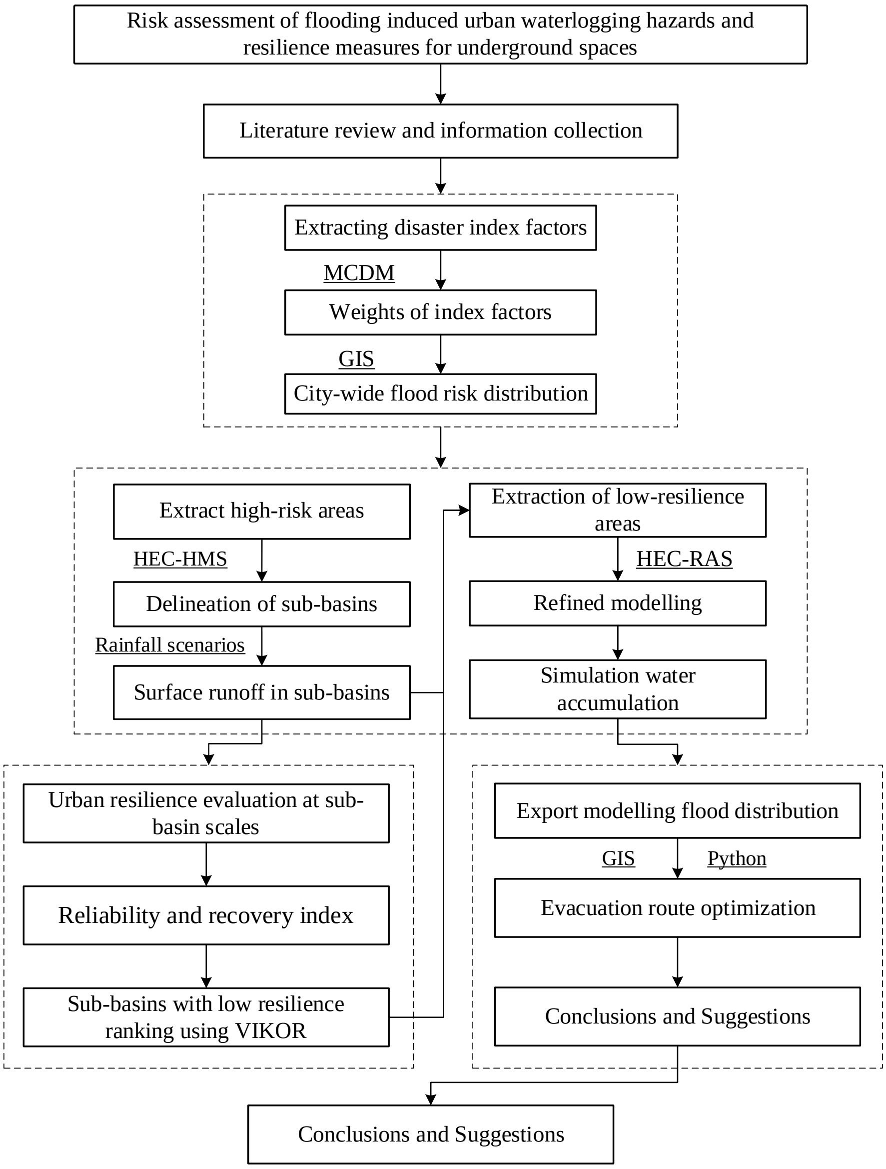

Figure 2. *Outline of research methodology used in the study*

3. RESULTS

The results of the flood risk mapping, resilience assessment, and scenario simulations emphasize the critical need for targeted interventions in high-risk areas, particularly those with underground infrastructure such as subway systems. The vulnerability of these spaces, especially in the urban center and near subway stations, highlights the need for integrated flood management systems and strategic evacuation planning.

3.1 Urban centre resilience

Risk mapping was conducted using the G-DEMATEL-AHP method, integrating grey theory with Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Analytical Hierarchy Process (AHP) to evaluate the urban flood risk (Zheng et al., 2022). The method considered several factors, such as rainfall distribution ("7.20 Storm"), land use type, and the location of underground infrastructure. The integration of these factors allows for a comprehensive evaluation of the flood risk across urban regions, taking both environmental and infrastructural variables into account.

Figure 3 presents the risk distribution results, which includes a city-wide flood risk map and the subway system risk distribution. As shown in Figure 3(a), the results of the risk mapping process identified several high-risk zones (red areas), particularly in the urban centre and near subway stations. In these areas, the flood risk is significantly amplified due to inadequate drainage systems and dense infrastructure. These findings underline the critical need for improved flood management strategies, especially in regions with high concentrations of underground spaces like subway systems, which are particularly vulnerable during extreme weather events.

Figure 3(b) provides a more detailed view of the subway system's flood risk distribution, with flood risk values represented by a gradient of colors. Light orange indicates lower flood risk (<0.45), while dark red shows higher risk (>0.65). Subway stations and lines are marked with distinct symbols, and waterlogging stations are highlighted with green circles.

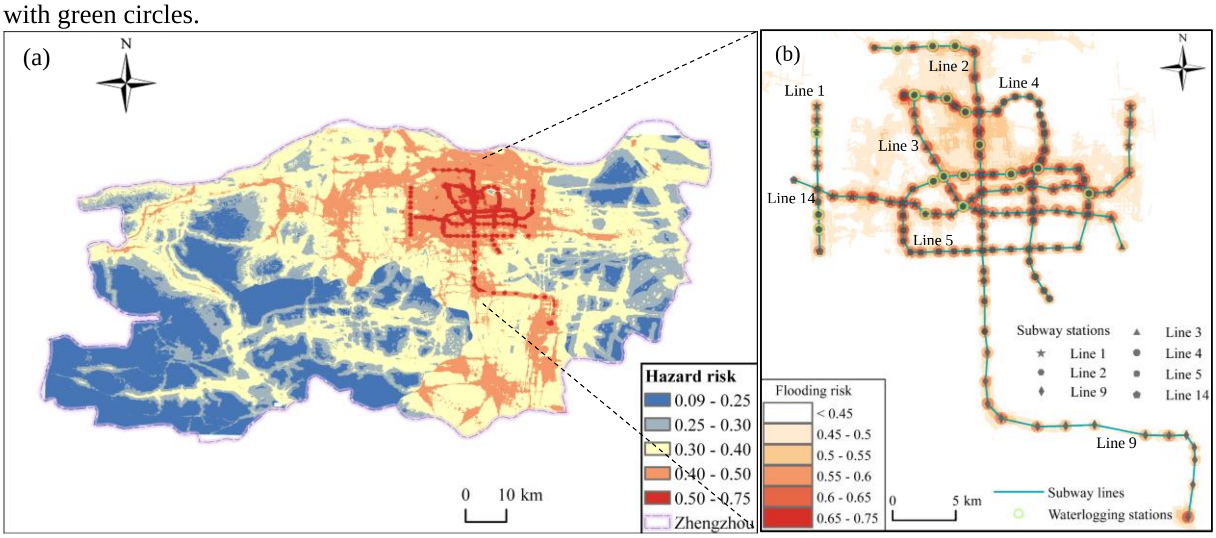

Figure 3. *Risk distribution results: (a) city-wide flood risk map and (b) subway system risk distribution.*

Beyond validating the model's accuracy, the results also highlight structural and functional factors contributing to flood vulnerability in underground systems. All lines experienced some degree of damage, but stations that were most severely affected—such as Haitansi Station (Line 5) and Henan Sports Centre Station (Line 3) —also serve as major transfer hubs. Notably, Line 5 is a circular line with numerous intersecting stations, making it a critical component of the subway network. Its structural layout and centrality lead to high passenger flow and system interconnectivity, which in turn increase its vulnerability to flooding. These stations often have more complex layouts, deeper or wider underground volumes, and higher passenger throughput. Such characteristics not only increase exposure to floodwater but also complicate emergency drainage and evacuation operations. This suggests that flood risk in underground spaces is influenced not only by geographic location but also by functional importance and structural design complexity.

3.2 Urban center resilience

To evaluate the resilience of urban spaces to flooding, this study developed a sub-basin-scale resilience assessment framework guided by the Sendai Framework for Disaster Risk Reduction. The framework integrates physical, socio-economic, and infrastructural factors using methods such as CRITIC, GRA, and VIKOR. This multi-criteria decision analysis (MCDM) approach provides a comprehensive resilience index for different sub-basins.

Figure 4 shows the spatial distribution of resilience across the study area, with (a) presenting the overall resilience map by sub-basin and (b) highlighting the resilience index values for each sub-basin. The map in (a) illustrates a gradient of resilience levels, where darker blue indicates higher resilience and lighter shades represent lower resilience. Notably, sub-basins 5, 6, 19, and 20, located in the urban centre, exhibit the lowest resilience (Qi > 0.7). These areas are characterized by dense underground infrastructure, low shelter accessibility, and complex post-disaster response environments, making them particularly vulnerable to flooding. In contrast, sub-basins in the southeastern region—such as 4, 8, 14, 16, and 24—also show lower resilience (Qi > 0.5), largely due to their downstream location and lower elevation, which make them more susceptible to cumulative runoff. Furthermore, sub-basins 31 and 32, located at the river outlets, are exposed to compound flood risks, including stagnation in low-lying areas, insufficient drainage capacity, and delayed recovery due to limited infrastructure and evacuation access.

The resilience assessment revealed significant spatial disparities in the resilience of different sub-basins. For example, the urban centre, with its dense underground infrastructure and poor shelter accessibility, exhibited the lowest resilience index. This indicates that areas with high underground space density are particularly vulnerable to flooding and should be prioritized for resilience improvements (He et al., 2024). These findings underscore the need for targeted interventions in flood-prone areas, particularly in the urban core, where the integration of flood management systems, infrastructure upgrades, and enhanced shelter access will be crucial for improving overall resilience (Cutter et al., 2010).

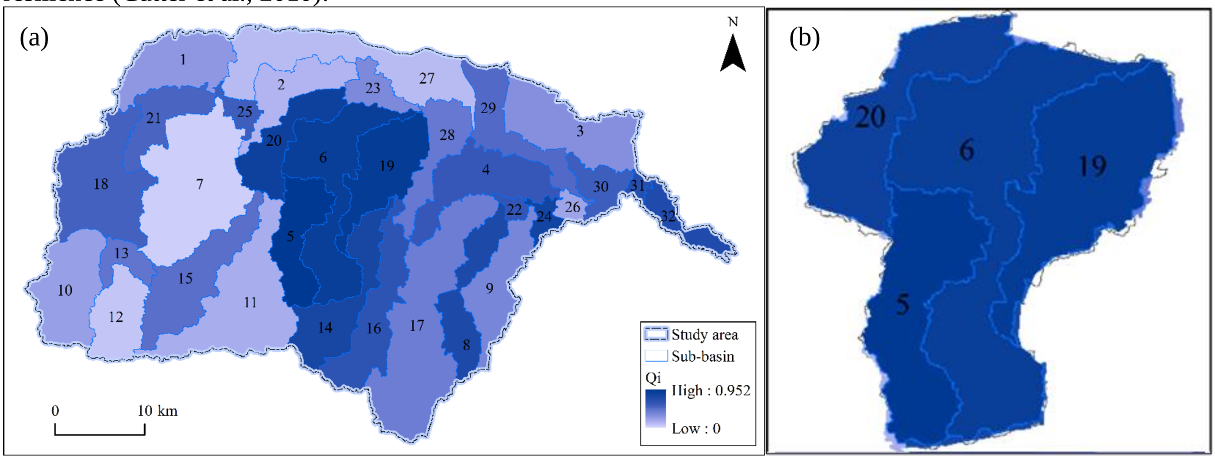

Figure 4. *Spatial distribution of urban resilience: (a) urban resilience index for sub-basins in high-risk area, (b) identified low-resilience and high-risk area.*

3.3 Waterlogging: Scenario simulation

Flood risk simulations were performed using HEC-HMS and HEC-RAS models, focusing on six rainfall scenarios with different return periods (3, 5, 10, 30, 50, and 100 years). HEC-HMS was used to simulate the rainfall-runoff processes, estimating the volume and timing of surface runoff for each scenario. The runoff data generated by HEC-HMS was then used as input for HEC-RAS, which modeled the propagation of floodwaters across the urban landscape. These simulations were conducted specifically within sub-basins previously identified as high flood risk and low resilience, based on earlier risk and resilience assessments. These scenarios simulate the potential flood depths and inundation areas under various rainfall conditions, offering insights into the spatial-temporal evolution of flooding. The simulations were validated with data from the "7.20 Storm," showing consistent results with actual flood events.

Figure 5 shows the flood inundation simulation and model validation results for the "7.20 Storm" scenario using HEC-RAS model. Figure 5(a) displays the maximum flood depth distribution map, with varying colour scales representing flood depths ranging from less than 0.25 m to more than 2 m. The map highlights critical urban infrastructures such as subways, primary roads, and water systems. Several validation points (1–11) are marked on the map to compare simulated and observed flood depths.

Figure 5(b) compares the flood depths recorded at the validation points with the simulated results. The solid squares represent recorded data, while the dashed circles represent the simulated results. It is evident that the simulated results closely align with the observed data for most validation points, particularly in areas with higher flood depths, such as validation points 4 and 5, indicating the model's good fit for extreme rainfall scenarios. However, some discrepancies are observed at certain validation points (e.g., points 6, 8, and 10), where the simulation slightly deviates from the recorded data. This may be due to localized geographic or infrastructure factors influencing the flood behaviour.

The results indicated that low-lying areas, primary roads, and underground spaces are particularly vulnerable during extreme rainfall events. The flood depth increased significantly under longer return period scenarios, emphasizing the need for adaptive flood management strategies and the optimization of urban drainage systems.

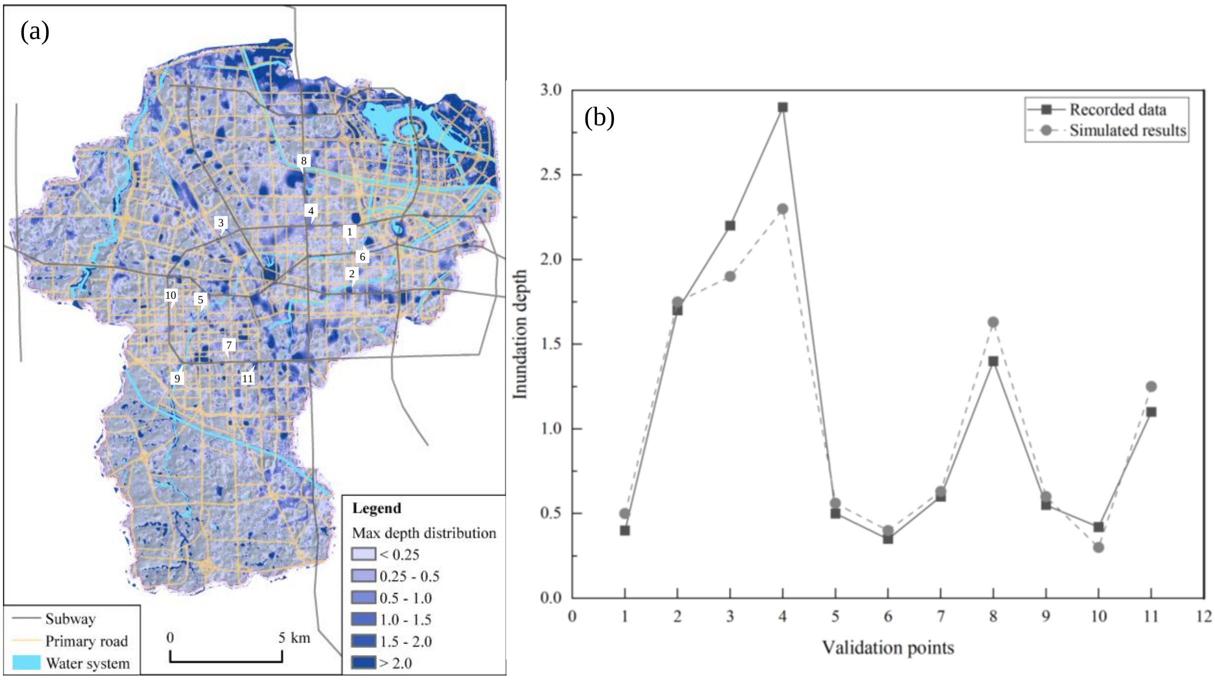

Figure 5. *Flood inundation simulation and model validation results: (a) Maximum flood depth distribution under extreme rainfall scenario; (b) Validation of simulated depth against observed data.*

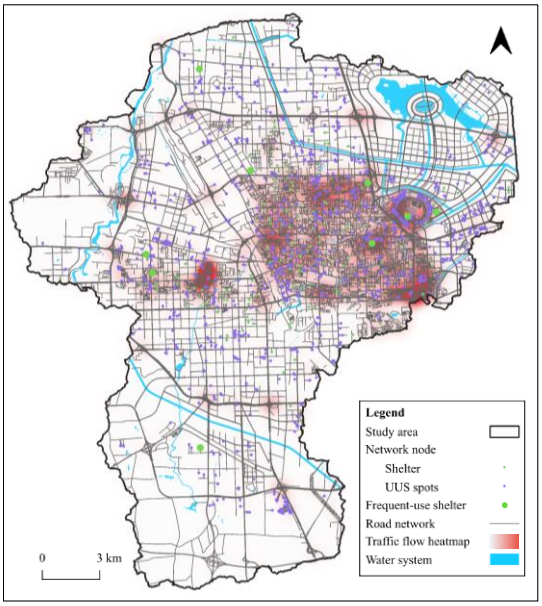

Figure 6. *"7.20 Storm" traffic and shelter flow analysis*

3.4 Evacuation planning

Evacuation planning plays a critical role in enhancing urban resilience during floods. In this study, an evacuation route optimization framework was developed using GIS, road network topology, and flood risk models. The framework aims to optimize evacuation routes from underground spaces to designated emergency shelters, considering flood risk, shelter accessibility, and potential congestion during evacuation. Route calculation was based on the Dijkstra algorithm, which identifies the shortest and safest paths on the weighted road network under flood constraints. Flood inundation depth used in the optimization process was derived from previous HEC-RAS simulation results, ensuring that evacuation routes account for spatial variations in flood severity.

Figure 6 presents a heat map of traffic flow, with red areas indicating heavy traffic and the intensity reflecting congestion levels. The road network is shown as grey lines, and water systems (rivers, lakes) are displayed. Shelters are marked as green points, including both official and planned (Plan) shelters, while UUS spots are represented by purple points. For clarity, road network nodes are omitted in the map. Frequent-use shelters are determined by identifying shelter locations with evacuation flows greater than 25, marked as large green points. All eight frequent-use shelters are from the proposed planned shelters, highlighting their strategic importance. One of these shelters, located in the southern area, addresses the shortage of shelters in that region, further emphasizing the value of the proposed shelters in evacuation planning.

Simulation results revealed that the number of existing shelters is inadequate to support large-scale evacuation needs, especially in high-risk areas (Shu et al., 2025). To address this, the study proposes the inclusion of non-traditional shelters, such as school playgrounds and public squares, to enhance shelter accessibility. These locations offer good accessibility and sufficient open space, making them effective supplements to official shelters.

4. DISCUSSION

To further enhance urban flood resilience, future efforts could focus on the development of a mobile application that bridges the gap between flood risk evaluation and public awareness. Such an app could integrate real-time AI analytics to deliver localized early warnings, adaptive evacuation routes, and dynamic flood risk communication. By leveraging sensor networks deployed in underground spaces, the system may monitor critical environmental indicators—such as water levels and structural stability—thus enabling timely responses to extreme weather events.

Given the simulation results indicating that low-lying areas, major roads, and underground infrastructure are especially vulnerable, the envisioned system should support dynamic evacuation planning. In particular, it could utilize real-time flood depth data (e.g., derived from HEC-RAS outputs) to continuously update and optimize evacuation routes, aiming to reduce congestion and improve safety during emergencies.

Additionally, resilience assessments have underscored the importance of shelter accessibility. In future iterations, the app could incorporate updated information on official and proposed shelters, especially in high-risk zones with limited coverage. By including non-traditional shelters—such as school playgrounds and public squares—the platform may help enhance the spatial equity of emergency resources.

Ultimately, this app-based system is envisioned as an adaptive, real-time decision-support tool. It could not only improve situational awareness among residents but also assist emergency planners in coordinating effective responses. By linking spatiotemporal flood modeling with public communication strategies, this approach holds promise for strengthening urban resilience in the face of intensifying climate risks.

5. CONCLUSION

This paper presents a comprehensive approach to assessing urban flood risks, focusing on the vulnerability of underground spaces such as subway systems. By combining flood risk mapping, resilience assessments, and scenario simulations, the study identifies high-risk areas and emphasizes the need for targeted flood management strategies. The main findings of this study are as follows:

(1) This study proposed the G-DEMATEL-AHP methodology to improve the efficiency of flood risk assessment and designed a corresponding questionnaire format to enhance the accuracy and reliability of data collection.

(2) A sub-basin-level urban resilience assessment framework was developed based on the Sendai Framework, combining CRITIC, GRA, and VIKOR methods to evaluate both reliability and recovery, with particular attention to the role of underground spaces for localized resilience planning.

(3) It integrated HEC-HMS and HEC-RAS models to simulate surface runoff and flood inundation, and introduced an equivalent rainfall calculation method to better represent the impact of extreme rainfall and urban drainage systems.

(4) The study demonstrated the necessity of supplementing official shelters with additional planned shelters to overcome issues such as limited capacity and poor accessibility, thereby improving overall shelter availability and evacuation effectiveness during flood emergencies.

6. ACKNOWLEDGMENTS

The research work was funded by Guangdong Provincial Basic and Applied Basic Research Fund Committee (2022A1515240073).

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