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

ACUUS BELGRADE 2025

Paper No: 3.8.96
DOI: 10.46793/ACUUS2025.3.8.96

FLOOD RISK ASSESSMENT AND RESILIENCE STRATEGIES FOR URBAN METROS UNDER EXTREME RAINFALL

Shuguang Liu[1], Weiqiang Zheng[2], Guihui Zhong[3], Zhengzheng Zhou[4]

Abstract: Shanghai, located at the Yangtze River estuary, is one of China's fastest-growing cities in underground transportation and also highly vulnerable to flood disasters. With extreme weather events becoming more frequent, the city's metro system faces increasing flood risks. This study selects eight indicators—including rainfall intensity, terrain slope, and passenger volume—and uses the entropy weight method to assign indicator weights. A flood risk assessment framework is developed and applied to 282 metro stations in Shanghai's central urban area. The spatial distributions of hazard, exposure, vulnerability, and defense indices are analyzed, and stations are classified into different risk zones. Based on the assessment, targeted disaster mitigation strategies are proposed to enhance flood resilience. Results indicate that flood risk generally decreases from northeast to southwest, and the spatial pattern of overall risk aligns closely with hazard levels. Stations in the northeastern region show high hazard and require improved responses to extreme rainfall. Central stations, characterized by high exposure and weak mitigation capacity, need enhanced surface and drainage infrastructure. Southwestern and southeastern stations show high vulnerability, highlighting the need for better emergency preparedness. The findings contribute to resilience-oriented urban planning and provide technical support for sustainable development in flood-prone metropolitan areas.

Keywords: Flood risk assessment; Indicator system; Metro stations; Shanghai; Resilience-based mitigation

1. INTRODUCTION

Flood disasters are among the most severe natural hazards affecting human society. Floods and their cascading impacts have become major obstacles to sustainable urban development and the advancement of urban resilience. According to the *Blue book on urban underground space development in China 2024*, 19 out of 93 underground space disasters and accidents in China in 2023 were caused by water-related events—accounting for nearly one-fifth of all cases [1]. Urban underground spaces are particularly vulnerable due to poor drainage, limited rescue accessibility, and frequent secondary disasters [2]. On July 20, 2021, a severe flood struck Henan Province, China, resulting in extreme urban inundation in Zhengzhou. Water flooded into metro trains in Tunnel Line 5, leading to 14 fatalities. On May 21, 2020, heavy rainfall in Guangzhou caused floodwaters to backflow into metro tunnels, shutting down the entire Metro Line 13. These frequent extreme events pose growing threats to the increasingly developed underground transportation systems in cities and hinder the sustainable development of modern urban environments.

Common flood risk assessment approaches include historical loss analysis, scenario simulation, and indicator-based methods. Historical analysis relies on past disaster records to assess risk levels across different entities. For instance, Rodda (2005) reviewed data from 30 major floods in the Czech Republic to map inundation and water depth [3]. Scenario simulation builds hydrological-hydrodynamic models for specific cases to simulate flood

[1] Professor, Liu, Shuguang, Ph.D. Geography, College of Civil Engineering, Tongji University, Siping Road No.1239, Shanghai, China, liusgliu@tongji.edu.cn.
[2] Ph.D. Student, Zheng, Weiqiang, B.Sc. Harbor, Waterway and Coastal Engineering, College of Civil Engineering, Tongji University, Siping Road No.1239, Shanghai, China, zhengweiqiang@tongji.edu.cn.
[3] Professor, Zhong, Guihui, Ph.D. Civil Engineering, College of Civil Engineering, Tongji University, Siping Road No.1239, Shanghai, China, 04098@tongji.edu.cn.
[4] Associate Professor, Zhou, Zhengzheng, Ph.D. Hydraulic Engineering, College of Civil Engineering, Tongji University, Siping Road No.1239, Shanghai, China, 19058@tongji.edu.cn.

progression and assess risks, widely applied in East Asia—for example, Liu et al. (2022) on building flood zoning [4], Shin et al. (2021) on underground escape routes [5], and Lyu et al. (2019) on submersion in metro systems [6]. Indicator-based methods evaluate risks by selecting multiple factors that represent the characteristics of hazards and the environment. These include studies by Lyu et al. (2018), Wang et al. (2021), and Yuan et al. (2024) on metro flood risk and submersion time [7-9]. Such methods typically incorporate hazard, exposure, vulnerability, and defense indicators.

Each method, however, has limitations. Historical analysis depends heavily on detailed event records, often unavailable for underground spaces. Scenario simulations face challenges in accurately defining boundary conditions and modeling real underground structures, especially for large-scale applications [6]. Indicator-based approaches, while widely used, often suffer from subjectivity in indicator selection and weighting, and are highly region-specific [7]. Additionally, they usually provide only relative, rather than absolute, risk levels [10].

Shanghai, located at the confluence of the Yangtze River and the East China Sea, is the last major city through which the Yangtze flows. Each flood season, the city faces compound threats from storm surges, extreme rainfall, astronomical tides, and upstream discharges. In October 2013, Typhoon Fitow caused severe flooding in central Shanghai, inundating 97 roads and over 900 residential communities, affecting more than 100,000 people and causing economic losses of CNY 890 million. In July 2021, Typhoon In-Fa triggered widespread street and residential flooding. Therefore, Shanghai's underground spaces face severe challenges in flood disaster prevention and control.

Given the limited attention paid to flood risk assessment and resilience planning for urban underground transport systems, and considering that metro stations in central urban area of Shanghai (within the outer-ring road) are mostly underground and located in zones of high population density and economic activity, this study focuses on evaluating the flood risk and resilience of these metro systems. The study targets underground facilities within metro stations, including entrances and subsurface spaces, and proposes resilience-based flood mitigation strategies to support the sustainable development of underground transport infrastructure in Shanghai. The remainder of this paper is organized as follows: Section 2 introduces the methodology; Section 3 describes the study area and data sources; Section 4 presents the risk assessment results; Section 5 offers concluding remarks.

2. METHODOLOGY

2.1. Pearson type III distribution and its *L*-moment estimators

This study computes rainfall-related indicators based on rainfall frequency analysis. The Pearson Type III (P-III) distribution is used to fit the annual maximum series of rainfall. The P-III distribution is recommended in China's national flood control standards as a suitable distribution for modeling annual maxima. The probability density function (PDF) and cumulative distribution function (CDF) of the P-III distribution are [11]:

$$f_X(x) = \frac{(x-\xi)^{\alpha-1} e^{-(x-\xi)/\beta}}{\beta^{\alpha}\Gamma(\alpha)},\ F_X(x) = \mathrm{G}\left(\alpha, \frac{x-\xi}{\beta}\right)\Big/\Gamma(\alpha)\,, \tag{1}$$

where ξ, β, and α are referred to as the location, scale, and shape parameters, respectively. $\Gamma(x)$ and $\mathrm{G}(s, x)$ denote the gamma function and the lower incomplete gamma function, respectively, which are defined as:

$$\Gamma(x) = \int_0^{\infty} p^{x-1} e^{-t}\ \mathrm{d}p,\ \mathrm{G}(s,x) = \int_0^{x} p^{s-1} e^{-t}\ \mathrm{d}p\,. \tag{2}$$

The value of the scale parameter β is typically related to the physical characteristics of the studied object. In rainfall frequency analysis, β is usually taken to be positive ($\beta > 0$).

We adopt the *L*-moment method to obtain point estimates of the distribution parameters. Hosking and Wallis (1997) recommended using *L*-moments as linear combinations of the expectations of order statistics [11]. The *L*-moment method estimates the parameters by solving a system of equations that equates the population *L*-moments to their corresponding sample *L*-moments.

Assume that $X_1 < X_2 < \ldots < X_n$ is an ordered sample of size n drawn from the P-III distribution defined in Equation (1). The population *L*-moments (or *L*-moment ratios) are defined as follows:

$$\lambda_1 = \xi + \alpha\beta,\ \lambda_2 = \pi^{-0.5}\beta\,\Gamma(\alpha+0.5)\big/\Gamma(\alpha),\ \tau_3 = 6I_{1/3}(\alpha, 2\alpha) - 3\,, \tag{3}$$

where $I_x(s, t)$ is the incomplete beta function and defined as:

$$I_x(s,t) = \frac{\Gamma(s+t)}{\Gamma(s)\Gamma(t)} \int_0^{x} p^{s-1}(1-p)^{t-1}\ \mathrm{d}p\,. \tag{4}$$

The sample *L*-moments (or *L*-moment ratios) are defined as:

$$\begin{cases} \lambda_1 = b_1,\ \lambda_2 = 2b_2 - b_1,\ \tau_3 = \left(6b_3 - 6b_2 + b_1\right) / \left(2b_2 - b_1\right) \\ b_t = \dfrac{1}{n} \sum_{i=t}^{n} \dfrac{(i-1)(i-2)...(i-t+1)}{(n-1)(n-2)...(n-t+1)} X_n,\ t = 1,2,3 \end{cases} . \tag{5}$$

2.2. Entropy weight method

The entropy weight method is a technique used to determine indicator weights based on the concept of information entropy [12]. The greater the variation in the observed values of an indicator, the more significant it is considered in the evaluation process. Conversely, when the values of a specific indicator show little variation among evaluation objects, its contribution to the assessment is limited. As a mathematical method that assigns weights based on the degree of data dispersion, the entropy weight method ensures that the weighting process remains objective, effective, and scientifically grounded.

An evaluation matrix is constructed based on the selected M flood-related indicators and N corresponding evaluation objects. Since different indicators represent various dimensions and scales, their values are not directly comparable. Therefore, normalization must be performed before applying the entropy weight method. Let the weight matrix be:

$$Q = \begin{pmatrix} q_{11} & \cdots & q_{1N} \\ \vdots & \ddots & \vdots \\ q_{M1} & \cdots & q_{MN} \end{pmatrix}, \tag{6}$$

where q_{ij} ($1 \le i \le M$, $1 \le j \le N$) is the (normalized) value of the i-th indicator for the j-th evaluation object. Then the proportion of q_{ij} is defined as:

$$w_{ij} = q_{ij} \Big/ \sum_{s=1}^{N} q_{is} . \tag{7}$$

The entropy value of the i-th indicator is defined as:

$$H_i = -\left(\sum_{s=1}^{N} w_{is} \ln w_{is} \right) \Big/ \ln N . \tag{8}$$

Thus, the entropy weight of the i-th indicator is:

$$W_i = \left(1 - H_i\right) \Big/ \sum_{s=1}^{M} \left(1 - H_s\right) . \tag{9}$$

3. STUDY AREA AND DATA

3.1. Study area

Shanghai City, located at the lower reaches of the Yangtze River, spans an area of 6,340.5 km^2 near the East China Sea (Figure 1). It falls within a subtropical monsoon zone, experiencing an average annual precipitation of 1,097 mm. The flood season, lasting from May to September, is marked by frequent cyclonic storms, which are the main contributors to extreme rainfall events. In 2024, Shanghai's Gross Domestic Product (GDP) reached CNY 5.39 trillion, accounting for nearly 39.97‰ of the national GDP, while occupying less than 0.66‰ of the country's total land area. The city's high degree of urbanization and population density make it particularly vulnerable to extreme rainfall events.

Considering that metro stations in the central urban area of Shanghai are primarily underground, while suburban stations are mostly above ground, this study focuses on metro stations located within the central urban area (i.e., within the outer-ring road), as shown in Figure 1. In terms of administrative divisions, the study area mainly includes the entire of Yangpu, Hongkou, Jing'an, and Huangpu Districts, the majority of Changning, Xuhui, Putuo, and Pudong (New Area) Districts, as well as parts of Minhang, Jiading, and Baoshan Districts.

3.2. Data

Metro stations. The study focuses on 282 metro stations located within Shanghai's central urban area that had been completed by the end of 2019, as shown in Figure 1. The spatial distribution of these stations is as follows: 94 in Pudong New Area (for convenience, referred to as "Pudong District" in the following text), 34 in Xuhui

District, 29 in Yangpu District, 27 in Putuo District, 20 in Baoshan District, 19 in Jing'an District, 18 in Huangpu District, 14 in Changning District, 13 in Hongkou District, 11 in Minhang District, and 3 in Jiading District.

Rainfall data. Daily rainfall observations from 1961 to 2019 were collected from 15 rain gauges distributed across Shanghai (locations shown in Figure 1). The data were downloaded from the China Meteorological Data Center (http://data.cma.cn/).

Topographic data. The 2018 Digital Elevation Model (DEM) of Shanghai was used to characterize the city's terrain, as shown in Figure 1.

Hydrological data. The spatial distribution of water bodies in Shanghai as of 2019 was incorporated into the analysis (see Figure 1).

Passenger flow data. The average daily passenger volume for each metro station was represented by the Dec ember 2018 ridership data. These data were sourced from online public (https://mlzhongguo.com/article/detail-21 08.html).

Physical attributes of metro stations. Information on the structural features of each metro station was obtained through a combination of field surveys and satellite imagery from Baidu Maps (https://map.baidu.com/).

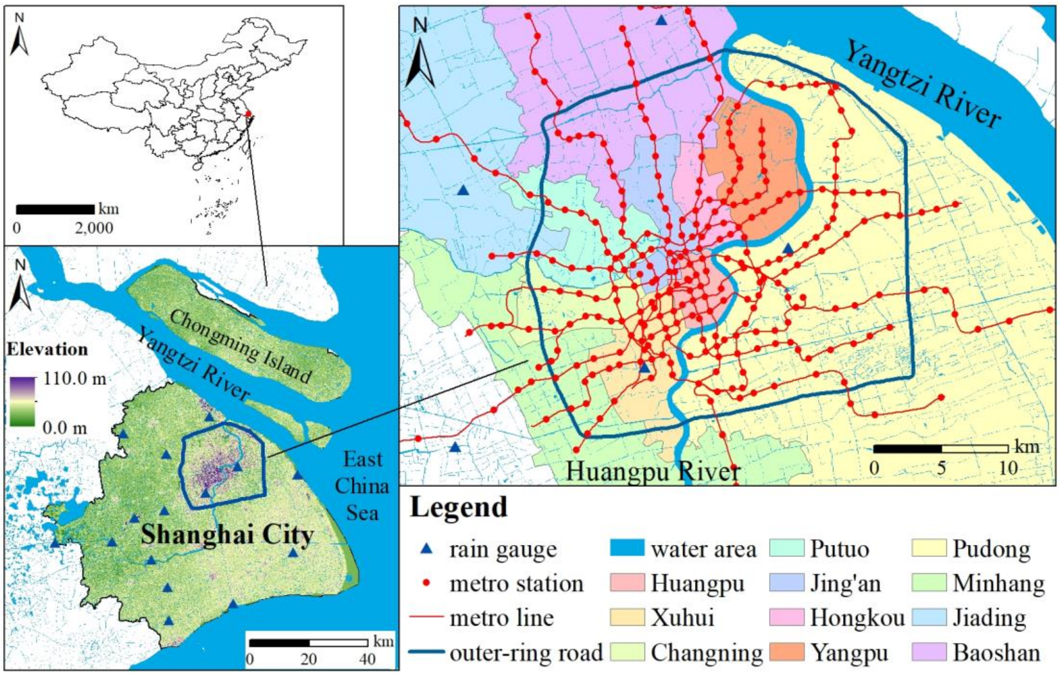

Figure 1. *Study area and location of metro stations*

4. RESULTS

4.1. Indicators and their entropy weights

Based on the practice of urban flood management in China, flood risk is generally influenced by four major dimensions: hazard (H), exposure (E), vulnerability (V), and defense (D). This study selects appropriate indicators from each of these dimensions, considering data availability and the actual conditions of Shanghai.

Hazard. Rainfall is the most direct flood-inducing factor in Shanghai. The greater the rainfall intensity and the more frequent the extreme precipitation events, the higher the flood risk. Therefore, rainfall intensity and rainfall frequency are selected as hazard indicators. Considering that the flood protection standard for central Shanghai has reached a return period of 50 years, we use the 100-year design rainfall depth (i.e., exceedance probability of 0.01) to represent extreme rainfall intensity. According to the standards issued by the China Meteorological Administration, a 24-hour rainfall of 100.0 mm is classified as "heavy rainstorm". Hence, we use the exceedance probability of 100.0 mm daily rainfall to represent extreme rainfall frequency.

Exposure. Urban terrain characteristics are key environmental factors contributing to flood exposure for underground spaces in Shanghai. Metro stations located in lower and flatter terrain are considered more exposed. Therefore, the relative elevation and terrain slope are selected as indicators of exposure.

Vulnerability. The metro stations (including concourse and platform levels) serve as the main elements at risk in this study. Their vulnerability depends on both physical and social attributes. Physical vulnerability includes flood-blocking and water intake conditions, while social vulnerability is represented by the station's passenger volume. Specifically, flood-blocking capacity is measured by hump height (i.e., the stair height at entrances); water intake potential is represented by the number of station entrances; and social importance is represented by average daily passenger volume.

Defense. There are currently no explicit design standards for flood protection and drainage capacity in Chinese metro stations. Drainage systems are typically designed only for daily operations. Therefore, the key determinant of a station's flood defense capability is its drainage condition, proxied by the distance to the nearest water body. A longer drainage distance implies weaker drainage capacity and thus lower adaptive capacity.

The spatial distribution of all indicators is shown in Figure 2, where the higher (normalized) values mean the more dangerous situations in flood. The entropy weight method was used to determine the weight of each indicator, with results presented in Table 1. Among hazard indicators, rainfall frequency holds greater weight than rainfall intensity, suggesting that sustained heavy rainfall events pose higher risks to metro stations in Shanghai. For exposure, slope carries significantly higher weight than elevation, indicating that stations located in flatter areas are more prone to flood risks. Among vulnerability indicators, passenger volume has the highest weight, reflecting the increased economic and social vulnerability of highly trafficked stations. In terms of adaptive capacity, drainage distance also holds considerable weight, underscoring its role in mitigating flood impacts. Overall, slope, passenger volume, and drainage distance are the most influential factors in flood risk for Shanghai's metro system.

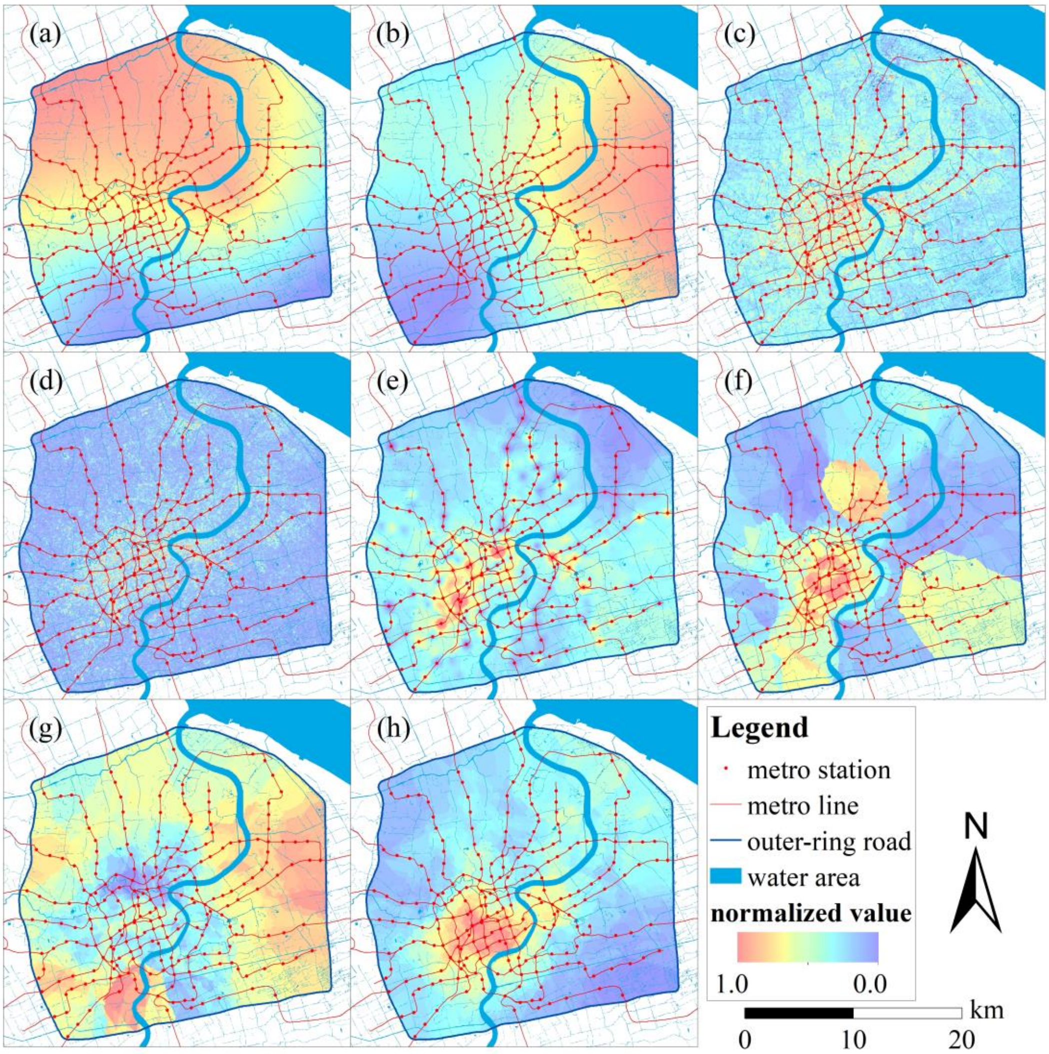

Figure 2. *Spatial distribution of the indicators, where the higher values mean the more dangerous situations. (a) rainfall intensity. (b) rainfall frequency. (c) relative elevation. (d) terrain slope. (e) stair height. (f) number of entrances. (g) passenger volume. (h) drainage distance*

Table 1. *Selected Indicators and their weights*

Dimension	Indicator	Weight	Data Source
H	rainfall intensity	0.102200	rainfall frequency analysis
	rainfall frequency	0.127900	
E	relative elevation	0.007898	DEM of Shanghai
	terrain slope	0.236700	
V	stair height	0.055520	field surveys and satellite imagery
	number of entrances	0.011620	
	passenger volume	0.325500	online public
D	drainage distance	0.132800	land-use type of Shanghai

4.2. Flood risk assessment for metro stations

The values of rainfall intensity and rainfall frequency were combined using entropy weights to assess the hazard level, as shown in Figure 3(a). The spatial distribution of hazard levels demonstrates a decreasing trend from northeast to southwest within the study area. Metro stations with higher hazard levels are mainly located in Pudong, Yangpu, and Hongkou Districts. The spatial distribution of exposure, representing the disaster-prone environment, is shown in Figure 3(b). Overall, the exposure of metro stations in Shanghai is relatively low due to the city's generally flat terrain. The central urban area exhibits similar topographic features across different locations, resulting in comparable exposure values among metro stations. Areas with flatter terrain are scattered and mainly concentrated in Huangpu, Xuhui, and Changning Districts. The spatial distribution of vulnerability is illustrated in Figure 3(c). Metro stations with higher vulnerability are primarily located in the southwestern and southeastern corners of the study area, including Huangpu, Xuhui, Pudong, and Hongkou Districts. These stations are situated in bustling commercial areas with high passenger density. Moreover, many of them were constructed earlier, and typically have lower stair heights at entrances, indicating weaker inundation-blocking capability. The spatial distribution of defense is shown in Figure 3(d). Overall, metro stations with weaker adaptive capacity are concentrated in central urban areas such as Huangpu, Xuhui, and Changning Districts. These areas are highly urbanized with low water system coverage, resulting in longer drainage distances for metro stations and therefore weaker disaster mitigation capacity.

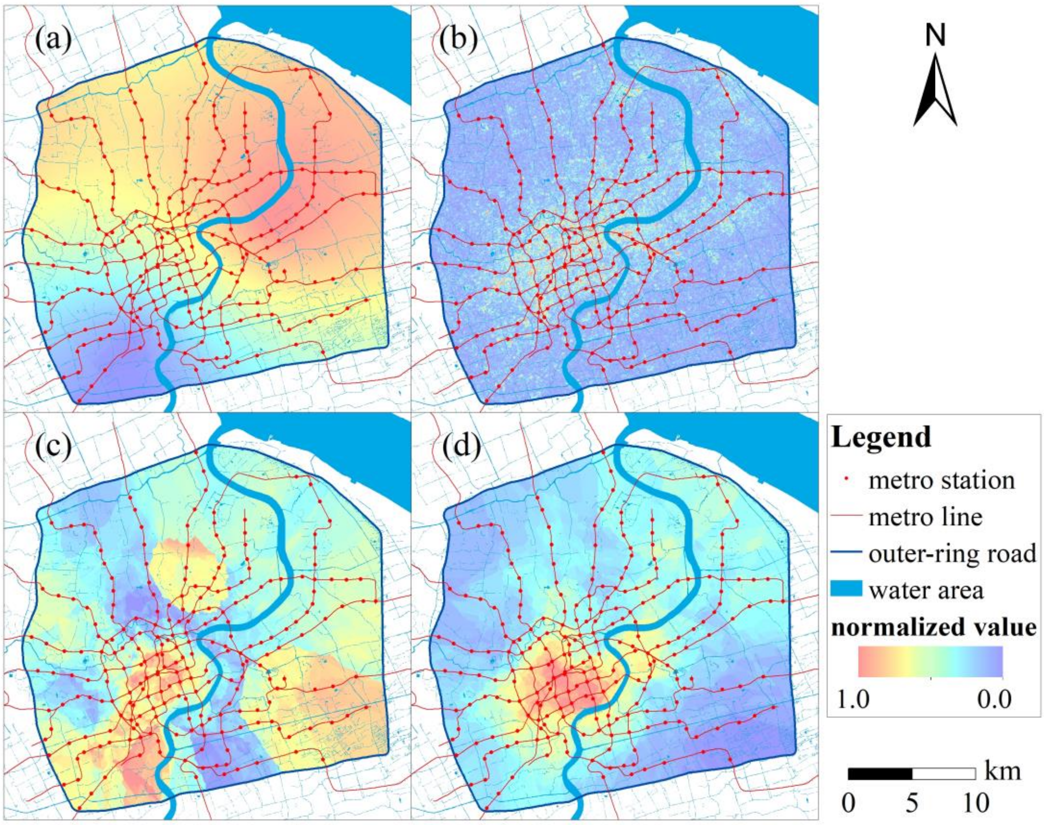

Figure 3. *Spatial distribution of the dimensions. (a) hazard. (b) exposure. (c) vulnerability. (d) defense.*

Considering that the defense dimension primarily function after flood events occur, its contribution to the overall flood risk is moderately reduced. According to the *Shanghai Flood and Drought Disaster Risk Assessment and Zoning Project*, the weights for hazard, exposure, vulnerability, and defense are set at 0.3, 0.3, 0.3, and 0.1, respectively. Based on the evaluation results of these four dimensions, flood risk zoning for metro stations within the study area was conducted. The comprehensive flood risk values were first calculated and then classified into four risk levels—low, medium, high, and very high—using the natural breaks method. The results are shown in Figure 4.

Overall, the flood risk zoning of metro stations within the outer-ring road closely resembles the spatial distribution of hazard level. Metro stations identified as very high risk are mainly located in the northeastern and central parts of the study area. In the northeast, both the intensity and frequency of heavy rainfall are high, making the region more prone to extreme rainfall events and thus presenting a high hazard. In the central area, relatively flat and low-lying terrain leads to rapid accumulation of surface water under extreme rainfall, resulting in high exposure levels. High-risk metro stations are primarily distributed in the northwest and southeast. In the northwest, high rainfall intensity leads to increased hazard levels; in the southeast, although the hazard level is relatively low, the stations experience high passenger volume, contributing to greater vulnerability level. Medium-risk metro stations are mainly located in the southwestern-central region, including Xuhui and Changning Districts. Despite higher vulnerability level and weaker defense level, these areas are less affected by intense or frequent rainfall events, resulting in relatively lower overall flood risk. Low-risk metro stations are located in the southwestern part of the study area, primarily in Minhang District. Although the vulnerability level in this region is relatively high, the other indicators suggest lower flood risk, contributing to the overall lower comprehensive risk. The number of metro stations at different risk levels in each district is shown in Table 2.

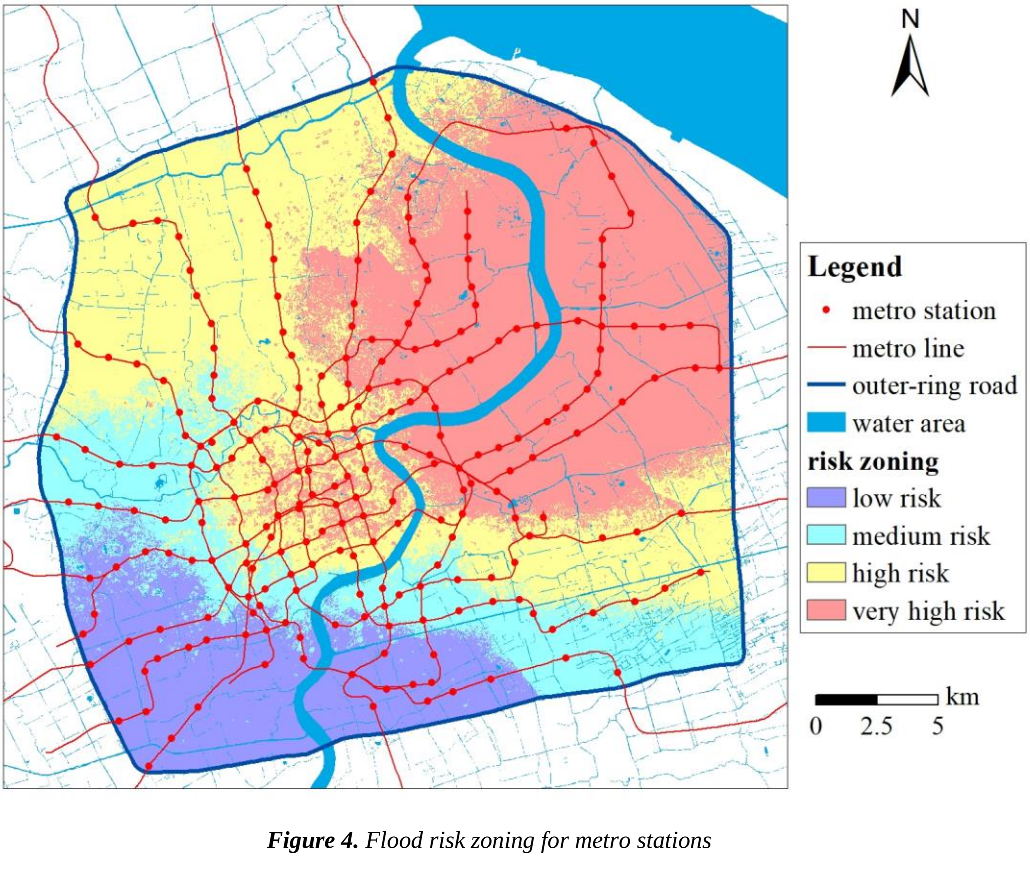

Figure 4. *Flood risk zoning for metro stations*

Table 2. *Number of metro stations at different risk levels in each district*

District	Low risk	Medium risk	High risk	Very high risk
Pudong	11	18	13	52
Xuhui	17	7	6	4
Yangpu	0	0	4	29
Putuo	0	14	12	1
Baoshan	0	1	18	1

Jing'an	0	1	14	4
Huangpu	0	0	10	8
Changning	4	9	1	0
Hongkou	0	0	7	6
Minhang	7	4	0	0
Jiading	0	1	2	0
Total	39	55	87	101

4.3. Flood disaster mitigation strategies

Metro stations with high hazard levels are primarily located in the northeastern part of the study area, where flood control should focus on coping with extreme rainfall events. With the ongoing process of urbanization, the temporal patterns of regional heavy rainfall have become increasingly complex. Overall, rainfall extremes and totals are increasing, while the number of rainy days is decreasing, indicating a growing concentration of precipitation. In areas with high rainfall intensity (northern regions), greater emphasis should be placed on non-structural measures to improve sensitivity to storm forecasts and early warnings, thereby reducing the threat posed by high-intensity rainfall to metro stations. In contrast, for areas with high rainfall frequency (eastern regions), structural measures should be prioritized. These include enhancing flood protection standards at metro stations, such as raising entrance humps and increasing drainage capacity, to effectively manage frequent and intense extreme rainfall.

Metro stations with high exposure level are mainly located in the central area, where the primary concern is the adverse terrain conditions. Due to Shanghai's overall low elevation, altering relative elevation is difficult. Therefore, reducing the flatness of surrounding areas and mitigating the risk of localized inundation becomes critical. Structural measures such as increasing the gradient near metro station entrances can help redirect water away and reduce the risk of water accumulation.

Metro stations with high vulnerability level are mainly distributed in the southwestern and southeastern regions. The focus here is to establish effective on-site flood protection mechanisms. Given a fixed number of entrances, increasing hump heights at station entrances can help reduce the impact of urban flooding. In addition, expanding the station concourse area can facilitate water dispersion, thereby lowering the risk of severe flooding loss. As these metro stations typically have high passenger volumes, non-structural measures are also crucial. These stations should actively conduct emergency flood drills, plan evacuation routes in advance, arrange emergency rescue deployments, and develop scientifically sound contingency plans to ensure timely and effective response and evacuation in the event of a flood.

Metro stations with weak defense level are mainly located in the central area, primarily due to high urban development density and low surface water coverage. For these stations, targeted structural measures can be implemented within the station premises, such as installing dedicated dewatering pump stations or establishing storage and drainage facilities to enhance flood resilience.

4.4. Discussion

In this study, the entropy weight method was employed to determine the weights of the selected indicators, thereby avoiding the influence of subjective judgments regarding their relative importance. However, it is important to emphasize that the results obtained reflect only a form of *relative risk*, and may still differ from the actual *absolute risk*. In other engineering fields, risk is often defined in probabilistic terms. However, applying such definitions to flood risk assessment remains particularly challenging.

Although rainfall frequency analysis enables probabilistic estimation of rainfall intensity, many uncertainties still exist in the process of translating rainfall into urban flooding. First, the spatial distribution of rainfall is highly complex. While techniques such as stochastic storm transposition are developing rapidly [13], their application in urban flood management remains limited due to the spatial scale of urban areas [14]. Second, for underground spaces, it is particularly difficult to accurately predict the depth of water accumulation at station entrances during heavy rainfall events. Although hydrological and hydrodynamic models have seen significant advancements, the assumptions made within these models can result in discrepancies between simulation outputs and actual conditions, thus limiting their direct applicability to flood mitigation practices [15].

Given the difficulty in precisely identifying hazard levels and the high cost of altering exposure or vulnerability level, China's flood mitigation practices have increasingly focused on improving defense level [16]. For example, even when water accumulation exceeds the height of entrance humps, authorities may artificially increase water-blocking measures or close stations based on advance warnings, effectively preventing water ingress. Although such emergency measures are difficult to quantify in flood risk assessments, they play a crucial role in disaster prevention and control.

Moreover, flood resilience in underground spaces often relies heavily on the overall urban flood management system. Within this context, our findings gain greater significance. This study identifies the specific vulnerabilities of different regions to flood disasters, providing valuable insights for targeted resource allocation and enhancing the overall flood resilience of the metro system.

5. CONCLUSION

This study focuses on metro stations located within the outer-ring road of Shanghai and develops a flood risk assessment framework for the Shanghai metro system using an indicator-based approach. The main conclusions are as follows:

(1) Eight indicators were selected from four dimensions: hazard, exposure, vulnerability, and defense. The entropy weight method was used to determine the weights of each indicator. In terms of hazard, rainfall frequency has a slightly greater influence on metro flood risk than rainfall intensity. For exposure, terrain slope plays a more significant role than relative elevation. Regarding vulnerability, passenger volume has a major impact on flood risk. Among the eight indicators, their relative influence on metro flood risk in descending order is: passenger volume, terrain slope, drainage distance, rainfall frequency, rainfall intensity, stair height, number of entrances, and relative elevation.

(2) Based on the established indicator system, flood risk and its spatial distribution were assessed for metro stations within the outer-ring road. The spatial patterns of hazard, exposure, vulnerability, and defense were analyzed, and metro stations were classified into four flood risk categories: very high, high, medium, and low, based on the integrated risk values. Hazard levels tend to decrease from the northeast to the southwest of the study area. Exposure is generally low, but scattered areas with higher exposure exist in flat city-center zones. Vulnerability is higher in the southwestern and southeastern corners, primarily due to high passenger volumes. Defense is generally strong, but metro stations in Huangpu, Xuhui, and Changning Districts face greater flood drainage pressure. The very high- and high-risk metro stations are mainly located in the central and northeastern parts of the study area, while low-risk stations are mostly found in the southwestern region.

(3) Based on the results of flood risk assessment and zoning, targeted flood mitigation and drainage measures are proposed to enhance the resilience of Shanghai's metro system. For very high- and high-risk areas, priority should be given to strengthening entrance protection facilities, upgrading pumping capacity, and developing emergency passenger evacuation plans. For medium-risk areas, optimizing drainage systems, improving the layout of discharge channels, and ensuring regular maintenance are recommended. For low-risk areas, maintaining the current level of protection while reinforcing routine inspection and early warning systems would be appropriate. The implementation of such differentiated strategies can effectively improve the overall flood prevention and resilience of the metro system.

6. ACKNOWLEDGMENTS

This study was supported by the National Natural Science Foundation of China (Grant Nos. 42271031 and 42371030). The authors sincerely appreciate the assistance from Runyao Lin (College of Environmental Science and Engineering, Tongji University), Congju Liu (College of Civil Engineering, Tongji University), and Zhi Li (College of Civil Engineering, Tongji University), for their contributions to data collection from Baidu Maps. The authors sincerely appreciate the valuable feedback provided by the reviewers, whose insightful comments have significantly contributed to enhancing the quality of this paper.

7. REFERENCES

[1] Strategic Consulting Center of Chinese Academy of Engineering, Chinese Society for Rock Mechanics and Engineering (Sub-society for Underground Space), & China Association of City Planning (Sub-association for Underground Space Planning). (2024). Blue book on urban underground space development in China 2024 (in Chinese). Proceedings of the 7th International Academic Conference on Underground Space, Shenzhen, China. https://www.planning.org.cn/uploads/ueditor/php/upload/file/20241205/1733379580688450.pdf

[2] Bi, W., Schooling, J., & Macaskill, K. (2024). Assessing flood resilience of urban rail transit systems: Complex network modelling and stress testing in a case study of London. Transportation Research Part D: Transport and Environment, 134, 104263. https://doi.org/10.1016/j.trd.2024.104263

[3] Rodda, H. J. E. (2006). The development and application of a flood risk model for the Czech Republic. Natural Hazards, 36(1–2), 207–220. https://doi.org/10.1007/s11069-004-4549-4

[4] Liu, S., Zheng, W., Zhou, Z., Zhong, G., Zhen, Y., & Shi, Z. (2022). Flood risk assessment of buildings based on vulnerability curve: A case study in Anji County. Water, 14(21), 3572. https://doi.org/10.3390/w14213572

[5] Shin, E., Kim, H., Rhee, D. S., Eom, T., & Song, C. G. (2021). Spatiotemporal flood risk assessment of underground space considering flood intensity and escape route. Natural Hazards, 109(2), 1539–1555. https://doi.org/10.1007/s11069-021-04888-2

[6] Lyu, H., Shen, S., Yang, J., & Yin, Z. (2019). Inundation analysis of metro systems with the storm water management model incorporated into a geographical information system: A case study in Shanghai. Hydrology and Earth System Sciences, 23(10), 4293–4307. https://doi.org/10.5194/hess-23-4293-2019

[7] Lyu, H., Sun, W., Shen, S., & Arulrajah, A. (2018). Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach. Science of the Total Environment, 626, 1012–1025. https://doi.org/10.1016/j.scitotenv.2018.01.138

[8] Wang, G., Liu, Y., Hu, Z., Zhang, G., Liu, J., Lyu, Y., Gu, Y., Huang, X., Zhang, Q., & Liu, L. (2021). Flood risk assessment of subway systems in metropolitan areas under land subsidence scenario: A case study of Beijing. Remote Sensing, 13(4), 637. https://doi.org/10.3390/rs13040637

[9] Yuan, X., Wu, M., Tian, F., Wang, X., & Wang, R. (2024). Identification of influencing factors and risk assessment of underground space flooding in the mountain city. International Journal of Disaster Risk Reduction, 113, 104807. https://doi.org/10.1016/j.ijdrr.2024.104807

[10] Zhen, Y., Liu, S., Zhong, G., Zhou, Z., Liang, J., Zheng, W., & Fang, Q. (2022). Risk assessment of flash flood to buildings using an indicator-based methodology: A case study of mountainous rural settlements in southwest China. Frontiers in Environmental Science, 10, 931029. https://doi.org/10.3389/fenvs.2022.931029

[11] Hosking, J. R. M., & Wallis, J. R. (1997). Regional frequency analysis: An approach based on L-moments. Cambridge University Press. https://doi.org/10.1017/CBO9780511529443

[12] Liu, H., Li, Z., & He, Q. (2023). Suitability assessment of multilayer urban underground space based on entropy and CRITIC combined weighting method: A case study in Xiong'an New Area, China. Applied Sciences, 13(18), 10231. https://doi.org/10.3390/app131810231

[13] Smith, J. A., Baeck, M. L., Villarini, G., Welty, C., Miller, A. J., & Krajewski, W. F. (2015). Analyses of a long-term, high-resolution radar rainfall data set for the Baltimore metropolitan region. Water Resources Research, 48, W04504. https://doi.org/10.1029/2011WR010641

[14] Zhuang, Q., Liu, S., & Zhou, Z. (2020). Spatial heterogeneity analysis of short-duration extreme rainfall events in megacities in China. Water, 12(12), 3364. https://doi.org/10.3390/w12123364

[15] He, R., Tiong, R. L. K., Yuan, Y., & Zhang, L. (2024). Enhancing resilience of urban underground space under floods: Current status and future directions. Tunnelling and Underground Space Technology, 147, 105674. https://doi.org/10.1016/j.tust.2024.105674

[16] He, R., Zhang, L., & Tiong, R. L. K. (2025). Responding of metro stations to upcoming floods: To close or to protect? Reliability Engineering & System Safety, 256, 110683. https://doi.org/10.1016/j.ress.2024.110683