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The Resilience Assessment Study Based on Urban Flooding Model：A Case Study of Suqian City

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ABSTRACT

In recent years, urban water security issues have become increasingly prominent due to multiple factors such as climate change, accelerated urbanization, and intensified human activities. Flooding disasters have become a global issue, and the concept of resilience has provided new insights for urban flood control research. To quantitatively assess the resilience of cities in responding to flooding disasters, this study is based on the theories of resilient cities and disaster chain. It selects indicators from three dimensions—urban space, lifeline infrastructure, and rapid recovery capacity—to establish an evaluation system. By combining a one-dimensional and two-dimensional coupled urban flooding model, a method for quantifying urban flood resilience levels is proposed. This method is used to investigate the spatial distribution of urban resilience and explore the driving factors of flood resilience. The study focuses on the southwest area of Suqian City, which is frequently affected by flooding disasters. Using the proposed method, the resilience level of Suqian City in 2022 is evaluated. The results show that: (1) The level of urban waterlogging risk is positively correlated with the resilience level—higher waterlogging risk corresponds to lower resilience; (2) Indicators such as green coverage rate, distance to river networks, distance to waterlogging-prone areas, and drainage network density have a significant impact on resilience levels; (3) The distribution of resilience levels in the study area is not completely random but exhibits spatial clustering, with 38.7% of the area showing significant clustering. The proposed method for quantifying resilience levels has important significance for urban flood control and disaster reduction.

KEY WORDS: urban flooding; resilience assessment; flood simulation; assessment framework; Quantitative evaluation indicators

1 INTRODUCTION

Against the backdrop of climate change, the frequency, duration, and spatial impact of extreme disaster events are continuously increasing. Among these, flood disasters, as one of the most prevalent natural hazards globally, inflict the most severe damage and losses. A report issued by the United Nations Office for Disaster Risk Reduction (UNDRR) indicates a trend of increased occurrence and frequency of global flood disasters. Compared to the previous 20-year period, the number of flood events from 2000 to 2019 increased by approximately 2.3 times. Globally, 3,254 flood-related disaster events were recorded, accounting for 44% of all disaster events, resulting in 104,614 fatalities and economic losses totaling USD 651 billion, and affecting nearly 1.65 billion people[1]. CHENG et al.[2] found that under the influence of climate change, the global water cycle has intensified by 2.6% to 4.4% since 1960, posing challenges to urban water security. Some studies estimate that nearly 23% of the global population is currently directly exposed to the threat of a 1-in-100-year flood[3].

Currently, the flood risk management paradigm reliant solely on urban flood control and drainage engineering systems is insufficient to address the challenges posed by the changing environment. While flood risk may be unavoidable, it can be substantially mitigated through the adoption of resilience-based flood management concepts[4]. The concept of "resilience" moves beyond a purely defensive approach, viewing the enhancement of urban capacity as a dynamic process. This provides a new perspective for urban development. Building resilient cities is a key strategy for addressing urban flood issues and achieving sustainable urban development, making related research urgently needed.

Internationally, the conceptual approach to flood management has undergone several shifts, evolving through three distinct phases: the initial flood defense stage, followed by the flood risk management stage, and currently progressing towards the flood resilience management stage. Numerous scholars have conducted extensive research on urban flood resilience. For instance, Cutter et al.[5] developed the Baseline Resilience Indicators for Communities (BRIC) model, which assesses resilience across five dimensions—economic, social, ecological, institutional, and infrastructural—to measure changes in resilience over time. Joerin et al.[6] constructed the Climate Disaster Resilience Index (CDRI) based on economic, institutional, natural, physical, and social aspects, with results reflecting the capacity of people and institutions in Chennai, India, to cope with potential climate-related disasters. Bruneau et al.[7] introduced a quantitative framework for disaster resilience, using system performance curves to depict urban resilience levels and defining resilience as the system's ability to reduce disaster probability, absorb shocks, and recover rapidly.

Building upon domestic and international research on urban flood resilience, this paper selects Suqian City—a plain river-network city—as the study area. Based on an established urban flood model, an urban flood resilience assessment framework is constructed to conduct research on urban flood resilience.

2 MATERIALS AND METHODS

2.1 Study Area

This study selects Suqian City, located in Jiangsu Province, China, as the research subject. Situated in northern Jiangsu, Suqian features convenient transportation with an extensive network of land and water transportation routes. Characterized by relatively flat terrain, it is a typical plain river-network city.

Precipitation in Suqian is spatially uneven, generally increasing from north to south. The multi-year average annual precipitation is 915 mm, with approximately 70% of the annual total concentrated during the flood season from June to September. This precipitation pattern makes the area highly prone to floods and droughts. The topography of the SW District is generally higher in the north and lower in the south, as well as higher in the west and lower in the east. The overview of the SW District is shown in Fig. 1. The land use pattern is presented in Fig. 2.

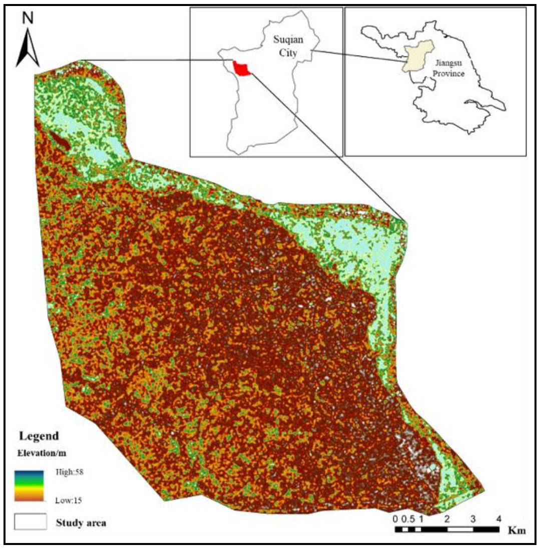

Fig. 1: Study Area

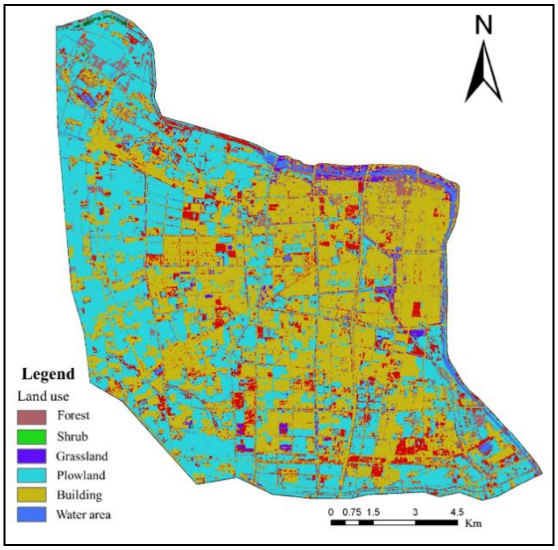

Fig. 2: Land Use Map of the Study Area

2.2 Research Framework

Based on literature review, analysis of typical urban flood disaster cases, historical disaster records, and urban drainage system data, and in conjunction with the city's spatial layout, topography, and infrastructure development, this study classifies urban flood risk zones of different levels for storms of various recurrence intervals. This model identifies high-risk locations with significant water depth and flow velocity, thereby clarifying the baseline conditions of urban flood disasters.

The framework assesses urban flood risk points based on the hazard level of disaster-inducing factors, the risk of hazard-formative environments, and the vulnerability of hazard-affected bodies. It defines key evaluation objectives for urban flood resilience. Considering dimensions such as urban space, society, economy, and infrastructure, and accounting for characteristics of different city types, the framework identifies key urban protection targets.

The framework establishes tailored resilience enhancement strategies for different cities, focusing on multiple phases: adaptation, resistance, and recovery. In the adaptation phase, measures include deploying green sponge facilities to improve urban surface runoff control, and implementing retrofitting measures in high-risk buildings, and integrates technologies such as various infrastructure sensors and big data to enhance urban situational awareness. This enables refined forecasting and early warning, thereby strengthening the city's ability to withstand disasters. In the recovery phase, rapid response capability is paramount. Furthermore, establishing a disaster insurance system can effectively disperse losses and plays a crucial role in post-disaster urban recovery, enabling the city to return swiftly, either fully or partially, to its pre-disaster state.

Resilience enhancement measures aligned with waterlogging prevention and control goals are integrated into the urban landscape. Combined with refined modeling and simulation methods, the layout of these resilience measures is optimized through simulation analysis. Through exercises and drills, the city's disaster response capability and flood resilience level are continuously improved.

The research framework is illustrated in Figure 3.

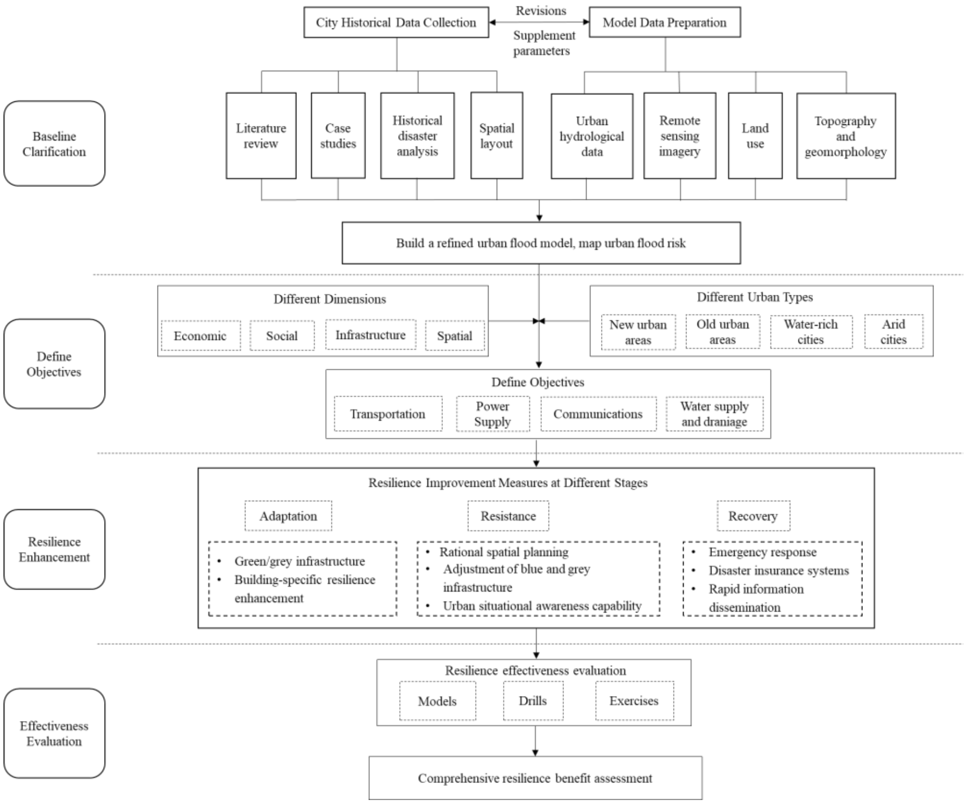

Fig. 3: Research Framework

3 RESEARCH METHODS

3.1 IFMS Model

This study utilizes the Integrated Flood Modeling System for Urban areas (IFMS/Urban) software platform. This platform integrates modules for urban drainage networks, one-dimensional river networks, and two-dimensional overland flow, enabling coupled 1D-2D modeling. The software is broadly applicable to various scenarios, including river flood control assessment, urban stormwater and flood risk analysis, drainage network evaluation, and the design of stormwater storage facilities. Its practicality and reliability have been effectively validated through application in multiple practical engineering projects[8]. The modeling domain for the southwestern district of Suqian City is shown in Fig. 4.

Fig. 4: 1D-2D Coupled Model

3.2 Calculation of Indicator Weights

3.2.1 Methods for Calculating Indicator Weights

To enhance the scientific rigor and reliability of the indicator weight assignment and to mitigate the limitations inherent in using a single assignment method, this study adopts a combined subjective-objective approach to calculate indicator weights. The subjective method employs the Analytic Hierarchy Process (AHP), while the objective method utilizes the entropy weight method. The final comprehensive weight for each indicator is derived by combining the weights obtained from both methods.

3.2.2 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method that facilitates quantitative analysis of qualitative problems. Its characteristic lies in classifying and synthesizing the various factors of a complex problem, typically structuring them into a hierarchy comprising the goal layer, criterion layer, and indicator layer. The operational procedure involves constructing a judgment matrix to compare the relative importance of indicators within the same hierarchical level. The relative priorities of these indicators are then calculated. Finally, these priorities are used to compute the weights for each indicator at every level of the hierarchy. Based on the main influencing factors of urban flood resilience and their interrelationships, a hierarchical structure model was constructed, consisting of the goal layer, the criterion layer, and the indicator layer.

3.3 Urban Flood Resilience Level

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) evaluation method is employed to classify the resilience levels of urban areas. TOPSIS is a widely used comprehensive evaluation method that fully utilizes the information from raw data, and its results can accurately reflect the differences among various evaluation alternatives[9].

Urban flood resilience can be represented by this relative closeness S_i, with a value range of 0 to 1. A value closer to 1 indicates a higher level of urban flood resilience, while a value closer to 0 indicates a lower level.

4 CASE STUDY

4.1 Selection of Evaluation Indicators

As a complex social-ecological system, cities have prompted some scholars to propose resilience assessment frameworks encompassing four dimensions: social, economic, ecological, and infrastructural[10~12]. Other researchers have categorized the influencing factors of urban systems into three dimensions—Pressure, State, and Response—for resilience level evaluation[13]. Additionally, frameworks have been established based on the three dimensions of resilience building: resistance capacity, recovery capacity, and adaptive capacity[14]. While resilience is a dynamic process, most existing frameworks often treat it as a static concept for easier quantification[15]. Drawing upon the concept of urban flood resilience achieved through "transformation," and considering the disaster chain propagation of urban flood hazards, this study references domestic and international scholarly frameworks. It views resilience as a dynamically evolving process, establishing an urban flood resilience assessment framework based on three dimensions: pre-disaster urban spatial layout, protection of lifelines during disasters, and post-disaster rapid recovery, as illustrated in Figure 5.

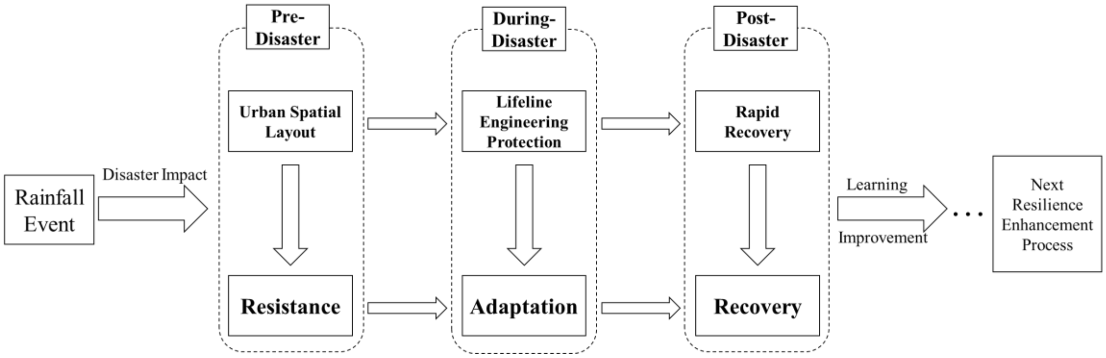

Fig. 5: Dimensions of Urban Flood Resilience

These three dimensions collectively constitute the full-process framework of urban flood resilience. Emphasizing comprehensive measures across the pre-disaster planning, in-disaster protection, and post-disaster recovery stages helps cities better cope with natural disasters such as floods. This paper selects indicators from the three dimensions of urban space, lifeline systems, and rapid recovery to establish an evaluation system. The assessment indicators are shown in Table 1.

Table 1 Urban Flood Resilience Evaluation Indicator System

Dimension	Indicator	Description	Representation Data
Urban Space (A)	Land Use (A_1)	The proportion of the total area of blue space and green space to the	Green coverage rate (A_{11})

		total area of the city; **positive indicator**	Water body coverage rate (A_{12})
	Topography & Landscape (A_2)	Terrain slope and ground elevation are important factors affecting urban waterlogging; **positive indicator**	Terrain slope (A_{21}) Ground elevation (A_{22})
	Urban River Network (A_3)	The ratio of natural rivers to artificial ditches, accounting for the total length of the river network in the area; **positive indicator**	Distance to river channel (A_{31})
	Urban Waterlogging (A_4)	Ground water accumulation during flood disasters; areas with a water depth > 0.15m are defined as waterlogging points; **negative indicator**	Distance to waterlogging point (A_{41}) Ground water depth (A_{42})
Lifeline Engineering (B)	Medical Resources (B_1)	Ability to provide medical assistance during flood disasters (including hospitals, medical institutions); **negative indicator**	Distance to medical institutions (B_{11})
	Transportation Network (B_2)	The proportion of road network length to the area of the district; **positive indicator**	Road network density (B_{21}) Distance to transportation stations (B_{22})
	Pipeline Facilities (B_3)	The proportion of drainage pipeline length to the area of the district; **positive indicator**	Drainage pipeline network density (B_{31})
	Communication Facilities (B_4)	Information transmission during disasters; **negative indicator**	Distance to communication maintenance stations (B_{41})
	Water Supply Facilities (B_5)	Water supply guarantee for residents during disasters; **positive indicator**	Water supply pipeline network density (B_{51})
	Power Facilities (B_6)	Power supply guarantee during disasters; **negative indicator**	Distance to power maintenance stations (B_{61})
	Population Density (B_7)	Population density; **negative indicator**	Population density (B_{71})
Rapid Recovery (C)	Regional Economic Situation (C_1)	Night lighting is positively correlated with social economy; used to characterize economic conditions; **positive indicator**	Night lighting (C_{11})
	Emergency Drainage &	Represented by the total hourly drainage capacity of emergency	Distance to drainage pump stations (C_{21})

	Rescue Capacity (C_2)	drainage and rescue equipment; **positive indicator**	Distance to sluice gates (C_{22})
	Emergency Rescue (C_3)	Preparedness for emergency management, command and rescue during disasters; the more timely the rescue, the more the indicator is reduced; **negative indicator**	Distance to emergency rescue stations (C_{31})
	Shelter (C_4)	Including civil engineering, schools, gymnasiums, hotels, squares, parks, etc.; **negative indicator**	Distance to shelter (C_{41})

4.2 Resilience Assessment Framework

Based on an analysis of the concept of urban flood resilience, the process by which a city copes with flood disasters can be divided into three stages: pre-disaster, in-disaster, and post-disaster. Initially, a city demonstrates its capacity to resist disasters before they occur. Once the disaster intensity exceeds the system threshold, the city enters an unpredictable state during the disaster, testing its adaptive capacity. Finally, the city undergoes a recovery process after the disaster. The level of urban resilience is reflected in the system's resistance, adaptation, and recovery capabilities. Ideally, a city will also undergo a process of learning and enhancement, leading to a continuous improvement in its resilience level.

To assess flood resilience, this study selects 20 indicators from three dimensions: pre-disaster urban spatial layout, in-disaster protection of lifeline systems, and post-disaster rapid recovery, thereby constructing an urban flood resilience evaluation indicator system. An improved entropy weight method combining subjective and objective approaches is used to describe the causal relationships among indicators and quantify their contribution rates to the resilience level. Furthermore, reasonableness analysis and correlation analysis are employed to evaluate the research results. Finally, based on simulation results from the urban stormwater model and combined with the evaluation indicator system, the city's resilience level and its spatial distribution characteristics are quantitatively analyzed.

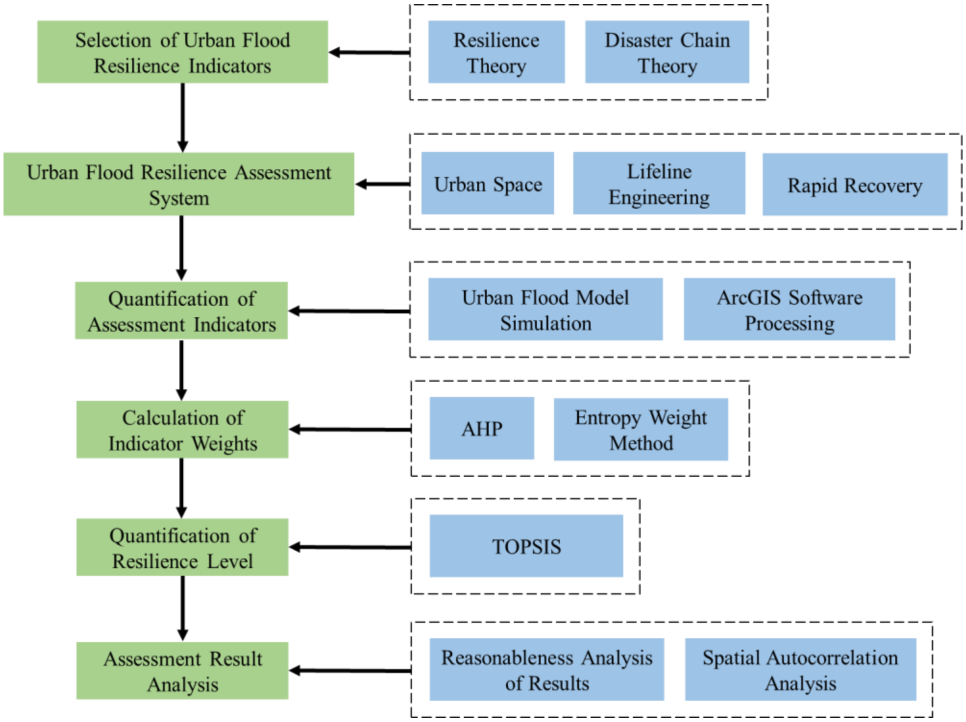

Fig. 6: Technical Workflow of the Urban Flood Resilience Assessment Framework

Based on scenario simulations using the IFMS/Urban model, the water depth and inundation duration within the study area under different scenarios were determined. The validation of urban waterlogging results was primarily conducted through the following methods: comparing waterlogging points and water depths, and assessing whether the simulated maximum water depth aligned with actual conditions. This study employed two approaches for model validation: comparing observed waterlogging-prone points and maximum inundation depths. Rainfall events from May 29, 2023, and July 13, 2023, were selected for validation. The maximum hourly rainfall intensities for these two events were 33 mm and 27.5 mm, respectively, both causing urban waterlogging and inundation. Using the rainfall data and corresponding urban river stage-discharge relationships from these two events as model inputs, the simulated inundation distribution and results were largely consistent with the actual situation, verifying the reliability of the waterlogging model simulation. The model-simulated distribution of waterlogging-prone points was used for quantitative resilience assessment, supporting urban flood resilience evaluation research, as shown in Figure 7.

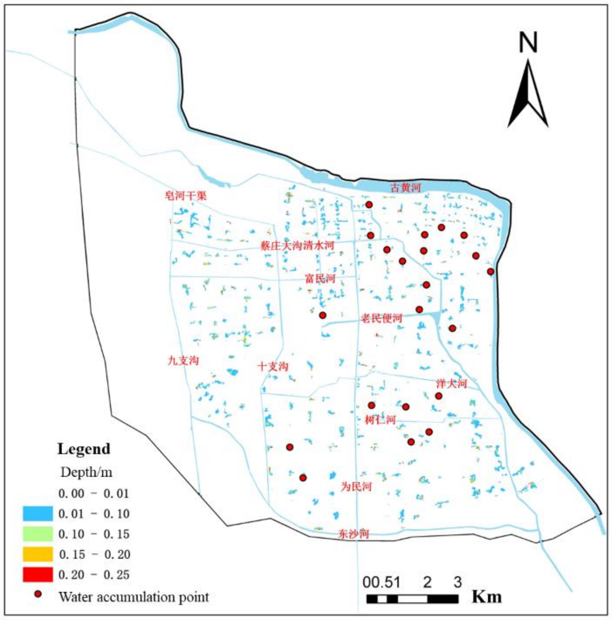

Fig. 7: Simulation Results of Waterlogging Points

5 RESULTS AND DISCUSSION

5.1 Urban Flood Resilience

This study utilized the indicator values from each grid cell and the indicator weights calculated using the improved entropy weight method. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was then employed to calculate the resilience level of the southwestern district of Suqian City, resulting in a resilience score between 0 and 1 for each grid cell. The natural breaks classification method (Jenks) was applied to categorize the urban flood resilience levels in the southwestern district of Suqian into five grades: high resilience, relatively high resilience, medium resilience, relatively low resilience, and low resilience.

By synthesizing the spatial distribution of resilience levels across the three dimensions—urban space, lifeline systems, and rapid recovery—a comprehensive resilience level distribution map for the southwestern district of Suqian City was generated, as shown in Figure 8. The resilience levels were classified into the aforementioned five grades using the natural breaks method. Among the sub-districts, the Jiuzhigou sub-district, the Ximinbian River sub-district 1, and the ancient Yellow River sub-district 1 scored relatively high in the urban space and lifeline system dimensions but lower in the rapid recovery dimension. Overall, their comprehensive resilience levels were the highest. In contrast, the ancient Yellow River sub-district 2, the Weimin River sub-district, and the old Minbian River sub-district scored lower in the urban space and lifeline system dimensions, resulting in the lowest overall comprehensive resilience levels.

Overall, the central urban area, compared to the peripheral suburban and village areas, exhibits advantages primarily in relatively well-developed infrastructure and higher economic levels. However, excessive urban development and irrational urban planning can increase flood risk, exposing the city to higher hazards and lower resilience. Furthermore, as central urban areas concentrate a large number of infrastructure and lifeline systems (e.g., power, water supply, transportation), the impact of flooding on these critical facilities may lead to widespread consequences, thereby reducing the overall urban resilience. Suburban and village areas, despite facing challenges such as lagging infrastructure construction and lower economic levels (which can hinder post-disaster rescue and recovery), generally face lower flood risks. Consequently, when confronting extreme disaster events, the impacts are often less severe, contributing to their relatively higher resilience levels.

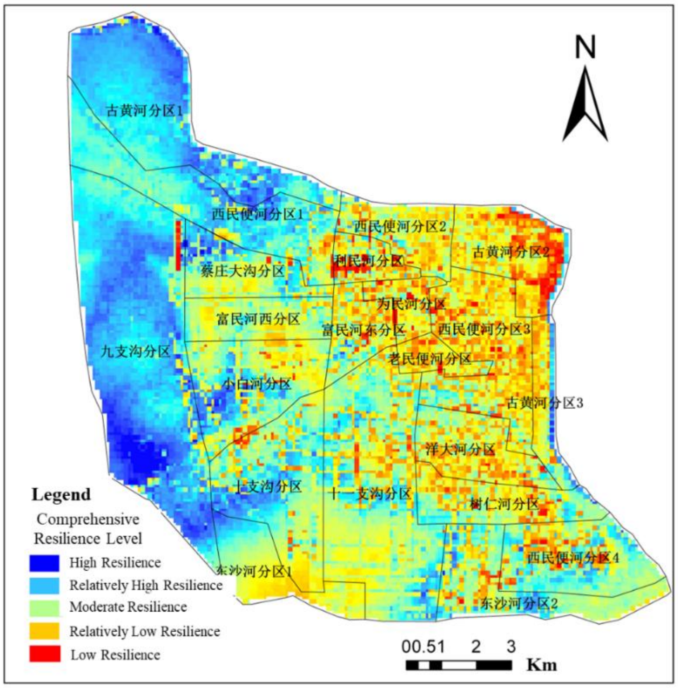

Fig. 8: Comprehensive Resilience Level Distribution

5.2 Reasonableness Analysis of Results

Based on the resilience assessment results obtained from the improved entropy weight-TOPSIS method, the reasonableness of these results was analyzed. Radar charts were constructed using the average values of indicators for different resilience grades, as shown in Figure 9. Indicators such as green coverage rate, distance to the river network, distance to waterlogging-prone points, sluice-gate regulation capacity, and drainage network density have a significant impact on the resilience assessment results.

As indicated in Figure 9, areas with high resilience levels are generally located farther from the river network and waterlogging-prone points, exhibit higher green coverage rates, denser water supply and drainage networks, lower population densities, and stronger sluice-gate regulation capacities. When flood disasters occur, these areas, being farther from hazard sources (river network, waterlogging-prone points), face lower risks of waterlogging and inundation. Factors such as low population density, high green coverage, and strong sluice-gate regulation capacity contribute to their higher resilience levels. Conversely, areas with low resilience levels are often located near waterlogging-prone points, characterized by lower densities of water supply and drainage networks, poorer sluice-gate regulation and pumping station drainage capacities, and greater distances from hospitals and emergency shelters. Furthermore, the spatial distribution of these low-resilience areas largely aligns with the high-risk waterlogging points identified in the "Systematic Implementation Plan for Urban Waterlogging Control in Suqian Central City." Therefore, the resilience level assessment results for the southwestern district of Suqian City presented in this study can be considered fundamentally reasonable.

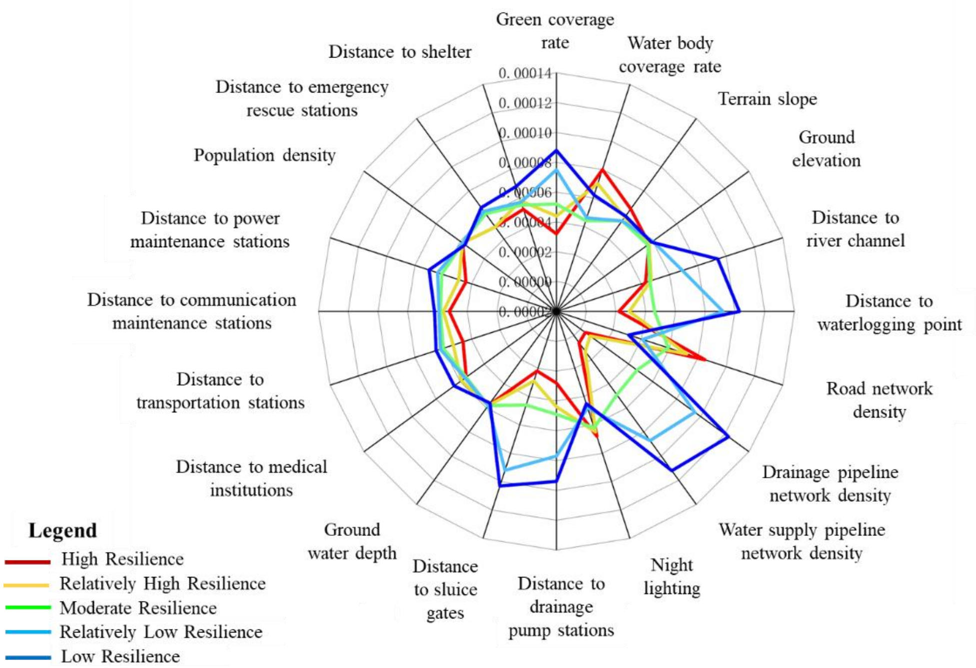

Fig. 9: Average Indicator Values for Different Resilience Grades

5.3 Spatial Autocorrelation Analysis

Spatial autocorrelation refers to the correlation of the same variable across different spatial distributions. It is a method used to measure the degree of clustering of attributes across spatial units and can reveal patterns and trends in the spatial distribution of a given attribute. This study employed the spatial autocorrelation index (Moran's I) to conduct a correlation analysis of the resilience results. The obtained Moran's I score was 0.708, with a p-value less than 0.05, passing the significance test. This indicates a global spatial clustering pattern in the distribution of resilience levels across the southwestern district. Furthermore, using the LISA (Local Indicators of Spatial Association) cluster analysis method in ArcGIS, a local clustering analysis of the resilience levels in the southwestern district was performed, as shown in Figure 10.

The results indicate that areas with non-significant clustering account for 61.23% of the region, while areas with significant clustering account for 38.77%. This suggests that the distribution of resilience levels within the study area is not completely random; rather, there is spatial clustering of similar values. Specifically, the proportions of High-Low and Low-High cluster areas are 0.31% and 0.25%, respectively. High-High cluster areas account for 19.93%, indicating that areas with high resilience levels are concentrated, primarily located in the western part of the study area. Low-Low cluster areas account for 18.29%, showing that areas with low resilience levels are also concentrated, mainly distributed in the central urban area on the eastern side of the study area.

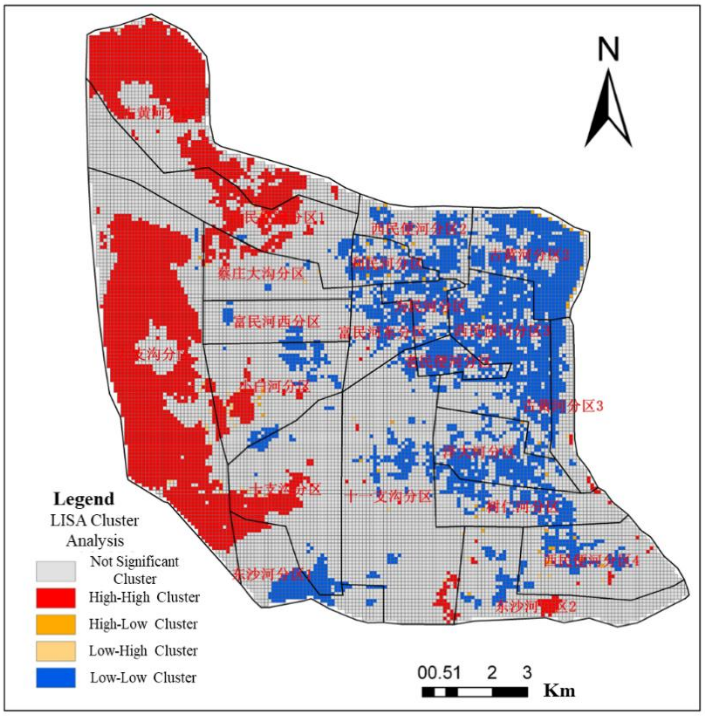

Fig. 10: LISA Cluster Analysis

6 CONCLUSIONS

This study focuses on the issue of urban flood disasters. Integrating the current resilience concept in flood management and the theory of urban flood disaster chains, and based on a systematic review of the fundamental concepts and influencing factors of urban flood resilience, an urban flood resilience assessment framework was proposed using the IFMS/Urban urban flood simulation model. Taking the southwestern district of Suqian City as a case study, factors affecting the urban resilience level were analyzed. Addressing the practical needs of urban disaster prevention and mitigation, the overall strategy and technical system for enhancing urban flood resilience were proposed. Based on the resilience assessment results for the southwestern district of Suqian City, specific resilience improvement strategies were suggested, and their potential effects were analyzed.

The research findings indicate that indicators such as green coverage rate, distance to the river network, distance to waterlogging-prone points, sluice-gate regulation capacity, and drainage network density significantly influence the resilience assessment results. The resilience assessment results largely align with the locations of high-risk urban waterlogging points published by Suqian City, demonstrating the fundamental reasonableness of the assessment. The results also reveal that the flood resilience index for most areas exhibits a clear local spatial clustering effect. Within the study area, there are High-High clusters and Low-Low clusters. High-resilience cluster areas account for 19.93%, while low-resilience cluster areas account for 18.29%.

As an interdisciplinary and comprehensive subject, research on urban flood resilience will, with deepening theories and advancing technologies, increasingly emphasize the integration and synergy in urban resilience building in the future. This will promote the translation of theory into practice, providing sustainable solutions for cities worldwide to cope with flood disasters.

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