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URBAN FLOOD RESILIENCE ASSESSMENT OF BEIJING-TIANJIN-HEBEI REGION BASED ON MULTI-SOURCE DATA

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ABSTRACT

Existing urban flood resilience assessments face challenges such as inconsistent indicator systems, limited research methodologies, and inadequate spatial analysis, making it difficult to accommodate the "multi-center, high heterogeneity" regional characteristics of the Beijing-Tianjin-Hebei urban agglomeration. This study examines 13 cities in the Beijing-Tianjin-Hebei region by integrating multi-source remote sensing data with socio-economic statistics. A flood resilience evaluation framework was constructed across four dimensions: infrastructure, environment, economy, and society. The analytic hierarchy process was employed to determine indicator weights, while the TOPSIS method was utilized to quantitatively assess resilience levels across cities. Spatial visualization of resilience rankings was achieved through advanced spatial analysis techniques. Findings reveal significant spatial disparities in urban flood resilience within the region, exhibiting a hierarchical distribution pattern characterized by "high resilience in Beijing-Tianjin dual cores, relatively high levels in the Beijing metropolitan ring, and lower resilience in central-southern Hebei." Economic resilience and social resilience emerged as key determinants of regional flood vulnerability. High-resilience cities are concentrated in Beijing and Tianjin, whereas low-resilience cities are predominantly located in Xingtai and Hengshui. These findings provide scientific foundations and decision-making references for coordinated flood disaster prevention, resilient city development, and cross-regional collaborative mitigation strategies in the Beijing-Tianjin-Hebei area.

KEYWORDS: Beijing-Tianjin-Hebei region; flood resilience; Analytic Hierarchy Process (AHP); TopSIS method; multi-source data fusion

1. INTRODUCTION

Flooding disasters rank among the most widespread and frequent natural disasters in China. In 2023 alone, severe flooding caused by extreme rainfall in the Beijing-Tianjin-Hebei region resulted in direct economic losses totaling 165.79 billion yuan[1]. The non-ecological urban development and changes in underlying surfaces have further exacerbated the potential threats of flooding, making resilient disaster prevention measures an essential component in flood response strategies[2].

Resilience was initially defined as the ability of systems to return to their original state after external stressors. Holing pioneered the application of resilience concepts in ecology, while the Local Government Sustainable Development Institute (ICLEI) introduced the term "urban resilience" into disaster prevention research in 2002[4]. Against the backdrop of climate change, academic attention to urban flood resilience has grown significantly, with resilience emerging as an innovative research perspective for enhancing urban flood response capabilities[5]. In developing evaluation frameworks and quantitative studies, scholars have adopted diverse approaches based on resilience system components and characteristics. Liu Gang et al.[7]established an urban flood resilience assessment system using the Performance-Simulation Research (PSR) framework, analyzing resilience mechanisms through process dynamics. Li Dezhi et al.[8] quantified urban flood resilience through the "4R" characteristics: Robustness, Resourcefulness, Rapidity, and Redundancy. He Shanfeng et al.[9]developed a multi-dimensional evaluation index system encompassing social, economic, infrastructure, and environmental dimensions. Building on resilience assessment methodologies, empirical studies have been conducted to evaluate flood disaster resilience across regions including Greater Vancouver, Jiangsu Province, and Nanjing City [10-12]. These studies emphasize tracking temporal variation patterns of resilience and identifying regional disparities in resilience levels.

Based on this foundation, this study examines 13 cities in the Beijing-Tianjin-Hebei region by integrating multi-source remote sensing data with socio-economic statistics to develop an urban flood resilience evaluation index system across four dimensions: infrastructure, environment, economy, and society. The analytic hierarchy process was employed to determine indicator weights, while the TOPSIS method was utilized for comprehensive quantitative assessment of flood resilience levels. Spatial visualization techniques were applied to present resilience rankings, revealing spatial differentiation patterns and distribution characteristics of urban flood resilience in the region. The findings provide scientific evidence and decision-making references for flood risk prevention, resilient city development, and cross-regional joint prevention systems in the Beijing-Tianjin-Hebei area, thereby enhancing regional comprehensive flood response capabilities.

2. OVERVIEW OF THE STUDY AREA

The Beijing-Tianjin-Hebei urban agglomeration comprises two municipalities directly under the central government—Beijing and Tianjin—as well as 11 prefecture-level cities in Hebei Province, including Shijiazhuang, Tangshan, and Qinhuangdao. The region features complex hydrological conditions with multiple rivers such as the Luan River, Yongding River, Daqing River, and Ziya River, exhibiting substantial average annual runoff. It also hosts Baiyangdian Lake, the largest inland freshwater lake in North China. Frequent heavy rainfall caused by intense convective weather during summer has led to recurrent cross-administrative and inter-basin flooding incidents, resulting in high disaster risks. Figure 1 illustrates the study area overview.

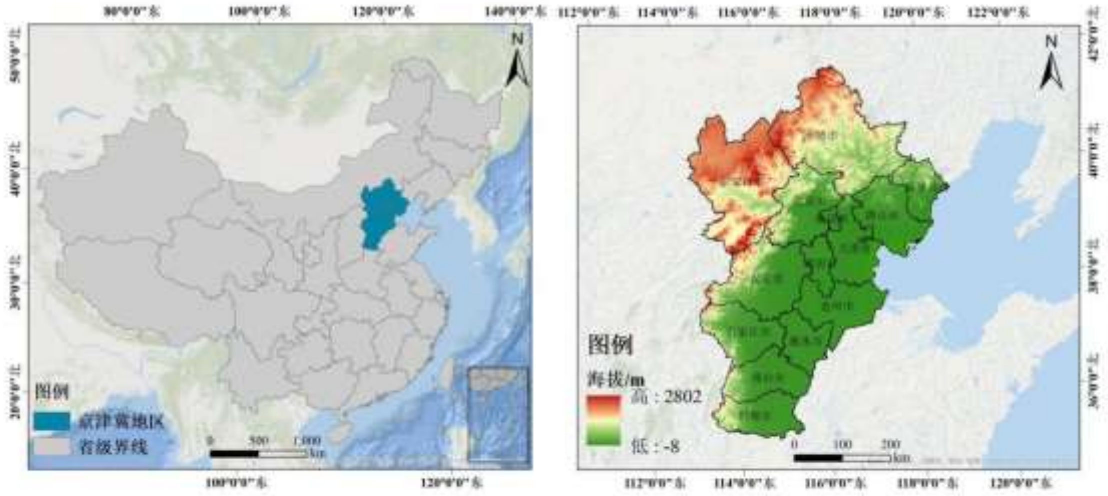

Figure 1 Overview of the study area

3、DATA SOURCES, RESEARCH METHODS, AND INDICATOR CONSTRUCTION

3.1 Research Methods and Indicator Construction

3.1.1 Data normalization processing

Each indicator may have different units and dimensions. To eliminate the influence of unit and dimension differences, standardized processing is uniformly applied to the data collected in the study [13].

For positive indicators, the standardized processing formula adopted in the study is as follows:

$$Z_i = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

For negative indicators, the standardized processing formula adopted in the study is as follows:

$$Z_i = \frac{X_{max} - X_i}{X_{max} - X_{min}}$$

The data $X_i X_{max} X_{min} Z_i$values include the maximum data value, the minimum data value, and the standardized data.

3.1.2 Indicator Construction

First, based on existing domestic and international indicator systems [7-11,14-15], and taking into account the natural environment and socio-economic development status of the Beijing-Tianjin-Hebei region, while balancing data quality and availability, and in conjunction with China's current standard

"Guidelines for Safe and Resilient City Evaluation," we selected 21 frequently used urban flood disaster resilience indicators with urban flood disaster resilience as the research focus. Then, considering issues such as redundancy, ambiguity, and overlapping connotations in the initially selected indicators, we applied the "Flood Disaster-Carrying Carrier-Emergency Management" public safety triangular theory proposed by Fan Weicheng et al. [16], and invited 8 experts from related fields such as urban resilience, water disaster management, and urban planning to screen the initial indicators, resulting in 12 evaluation indicators. Finally, the 12 selected evaluation indicators were assigned to four dimensions—infrastructure, environment, economy, and society—to complete the indicator selection process.

3.1.3 Indicator Weight Calculation

Fifteen cross-disciplinary experts were invited to participate in the weight determination process, covering areas such as disaster risk management, urban hydraulic engineering, geospatial analysis, urban planning, and emergency management. Among them, there were 6 professors/researchers, 7 associate professors/senior engineers, and 2 PhD holders, with an average professional experience of over 12 years. All participants possess expertise in Beijing-Tianjin-Hebei regional studies, ensuring both professional rigor and regional relevance in the evaluation.

A 1-9 scale method was employed to construct a judgment matrix, where experts conducted pairwise comparisons of relative importance among indicators at the same level. Fifteen valid questionnaires were collected, and opinions were consolidated $\lambda_{\max} = 5.123, \mathrm{CI} = 0.031, \mathrm{CR} = 0.028 < 0.1$through arithmetic averaging to form the criterion-level judgment matrix. The root mean square method was used to calculate weights for each criterion level and its subordinate indicators. The resulting criterion-level judgment matrix passed consistency testing. The final criterion-level weights and indicator-level weights are presented in Table 1, providing a basis for subsequent quantitative assessment of flood resilience.

3.1.4 Flood Resilience Assessment

This study employs the TOPSIS method for assessing flood resilience. TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution), also known as the "Ideal Solution Approximation Ranking Method," is an evaluation approach that ranks multiple assessment objects based on their relative proximity to an ideal solution to determine relative superiority. The specific calculation method is as follows [17]:

First, computations must be performed based on standardized data. Let the dimensionless decision $\mathrm{ZZ} = (z_{ij})_{m \times n}$matrix composed of standardized data be denoted as.

Next, determine the optimal and worst $z_j^{+} z_j^{-}$solutions for each indicator:

$$\begin{cases} z_j^{+} = \max\{z_{1j}, z_{2j}, \cdots, z_{mj}\} \\ z_j^{-} = \max\{z_{1j}, z_{2j}, \cdots, z_{mj}\} \end{cases}$$

Subsequently, the weighted Euclidean distances between each evaluation $D_i^{+}D_i^{-}$object and both the optimal solution and the worst solution are calculated.

$$\begin{cases} D_i^{+} = \sqrt{\sum_{j=1}^{n}\left[w_j\left(z_{ij}^{-} - z_j^{+}\right)\right]^{2}} \\ D_i^{-} = \sqrt{\sum_{j=1}^{n}\left[w_j\left(z_{ij} - z_j^{-}\right)\right]^{2}} \end{cases}$$

The combination $w_j$weight for indicator j is included.

Finally, determine the proximityC_i:

$$C_i = \frac{D_i^{-}}{D_i^{+} +\cdot D_i^{-}}$$

C_iThe closer the value is to 1, the closer the object is to the optimal solution, indicating relative superiority. Objects are ultimately sorted by their proximity values in descending order.

3.2 Data Sources

The data in this study cover two categories: remote sensing spatial data and statistical data, with a unified time dimension of 2021. Among them, raster data such as vegetation coverage, altitude, distance from water bodies, and building density are sourced from the Geospatial Data Cloud and the Resource and Environmental Science Data Center of the Chinese Academy of Sciences; vector data such as drainage density and road density are obtained from the National Geographic Information Resource Catalog Service System and urban master plan data; socioeconomic indicators including per capita GDP, fiscal revenue, healthcare, education, and medical insurance are derived from the "China Urban Statistical Yearbook" and statistical yearbooks and bulletins of cities in the Beijing-Tianjin-Hebei region; flood control investment proportion data are sourced from municipal fiscal budget and final account reports and water conservancy development bulletins. All data underwent unified projection, resampling, and matching preprocessing to provide data support for resilience assessment.

4. RESULTS AND ANALYSIS

4.1 Calculation Results of Indicator Weighting

This study selects 12 indicators based on scientific validity, accessibility, and comprehensiveness, incorporating relevant domestic and international research findings to evaluate urban flood resilience in the Beijing-Tianjin-Hebei region. The weights were calculated using the Analytic Hierarchy Process (AHP), as detailed in Table 1.

Table 1 Urban Flood Disaster Resilience Evaluation Index System

Target layer	principle layer	Criterion level weight	index level	Indicator level weight	Indicator Properties	data type
Urban Flood Disaster Resilience	infrastructure	0.220	drainage density	0.455	forward direction	vector data
			roading density	0.273	forward direction	vector data
			building density	0.188	negative direction	raster data
	environment	0.150	vegetation coverage rate	0.120	negative direction	raster data
			above sea level	0.138	negative direction	raster data
			Distance from water body	0.334	negative direction	raster data
	economy	0.350	Proportion of flood control expenditure in public expenditure	0.400	forward direction	statistical data
			per capita GDP	0.350	forward direction	statistical data
			government receipts	0.250	forward direction	statistical data

society	0.280	Number of hospital beds per 10,000 population	0.333	forward direction	statistical data
		Proportion of higher education talents	0.134	forward direction	statistical data
		Basic medical insurance coverage rate	0.334	forward direction	statistical data

This study employs the TOPSIS method for evaluating flood resilience. A critical step in the computational process involves calculating the weighted Euclidean distances between each evaluation object and both the optimal and worst solutions. The weighted Euclidean distances are then utilized to determine proximity scores, ultimately yielding the final assessment ranking.

At the criterion level, economic resilience carries the highest weight (0.350), followed by social resilience (0.280), infrastructure resilience (0.220), and environmental resilience (0.150). This indicates that urban flood resilience in the Beijing-Tianjin-Hebei region is significantly influenced by economic support capacity and social emergency response capabilities. Economic development and fiscal investment serve as key determinants of regional flood prevention, disaster mitigation, and post-disaster recovery capabilities.

Specifically, within the infrastructure resilience framework, drainage density (0.455) carries the highest weight, while building density (0.188) has the lowest weight. In the environmental resilience dimension, distance from water bodies (0.334) dominates the weighting scale, with vegetation coverage (0.120) ranking lowest. For economic resilience, flood control expenditure as a percentage of public spending (0.400) holds the greatest significance, whereas fiscal revenue (0.250) carries the least weight. Regarding social resilience, basic medical insurance coverage (0.334) exhibits the highest weighting, while the proportion of higher education graduates (0.134) ranks lowest.

At the indicator level, the top three indicators by weight proportion were the ratio of flood control investment to public expenditure (0.140), basic medical insurance coverage rate (0.094), and the number of hospital beds per 10,000 population (0.093). The bottom three indicators by proportion were vegetation coverage rate (0.018), the proportion of higher education graduates (0.038), and building density (0.041).

This indicates that to enhance the overall flood resilience score of cities in the Beijing-Tianjin-Hebei region, special attention must be paid to the impact of flood risks on urban areas. Key measures include increasing flood control funding, upgrading urban drainage systems, and strengthening infrastructure's flood resistance capabilities. It is essential to continuously consolidate economic foundations, improve local fiscal security, and enhance post-disaster recovery and emergency response capacities. Additionally, efforts should focus on improving healthcare systems, optimizing medical resource allocation, expanding social security networks, and boosting government response efficiency to mitigate the adverse effects of floods on social welfare and economic operations.

4.2 Urban Flood Resilience Ranking and Spatial Distribution in the Beijing-Tianjin-Hebei Region

To reveal the internal disparities in flood resilience among cities within the Beijing-Tianjin-Hebei region, the TOPSIS method was employed to evaluate four criterion levelsC_i—infrastructure resilience, environmental resilience, economic resilience, and social resilience—as well as comprehensive flood resilience. The cities were ranked by proximity from highest to lowest, yielding the TOPSIS rankings of flood resilience for 13 cities in the region, as shown in Tables 2 and 3.

4.2.1 TOPSIS Ranking and Analysis of the Criterion Layer

In the infrastructure resilience ranking, Beijing, Tianjin, and Tangshan ranked in the top three, while Xingtai, Hengshui, and Zhangjiakou ranked relatively lower. This indicates that core cities such as Beijing and Tianjin have more comprehensive flood prevention and drainage infrastructure, including drainage systems and road networks, whereas some cities in central and southern Hebei as well as northern Hebei lag behind in infrastructure development, resulting in weaker flood resistance capabilities.

In the environmental resilience ranking, Chengde, Zhangjiakou, and Qinhuangdao ranked at the top. Beijing and Tianjin exhibited moderate environmental resilience due to high urban hardening ratios and dense building density. Xingtai and Hengshui, characterized by low-lying terrain and limited ecological storage capacity, ranked lower in environmental resilience.

In the economic resilience ranking, Beijing, Tianjin, and Shijiazhuang ranked in the top three, while Hengshui, Xingtai, and Zhangjiakou ranked lower. The level of economic development and fiscal capacity directly determine flood prevention investment and post-disaster reconstruction capabilities. The uneven economic development across the Beijing-Tianjin-Hebei region has led to significant gradient differences in economic resilience.

In the social resilience ranking, Beijing, Tianjin, and Tangshan ranked higher due to their comprehensive medical resources and social security systems. In contrast, cities such as Xingtai, Hengshui, and Handan were constrained by economic development, resulting in limited medical beds, talent reserves, and social insurance coverage, leading to relatively weaker social resilience.

Table 2 TOPSIS Ranking of Flood Resilience Criteria Layers in the Beijing-Tianjin-Hebei Region

city	**Infrastructure Resilience Ranking**	**environmental resilience ranking**	**Economic Resilience Ranking**	**Social Resilience Ranking**
Beijing	1	8	1	1
Tianjin	2	9	2	2
Tangshan	3	7	4	3
Shijiazhuang	4	6	3	4
Langfang	5	5	5	5
Qinhuangdao	6	1	7	6
Cangzhou	7	4	6	7
Chengteh	13	2	9	9
Zhangjiakou	12	3	11	10
Handan	9	11	8	11
Baoding	8	10	10	8
Xingtai	11	12	12	12
Hengshui	10	13	13	13

4.2.2 Comprehensive Flood Resilience TOPSIS Ranking and Spatial Patterns

The comprehensive flood resilience TOPSIS rankings for cities in the Beijing-Tianjin-Hebei region were synthesized by weighting results from four criterion layers. The spatial pattern demonstrates a dual-core leadership by Beijing and Tianjin, with higher resilience levels in the Beijing metropolitan area and lower levels in central and southern Hebei. High-resilience cities are concentrated in Beijing-Tianjin and adjacent regions, while low-resilience cities are clustered in Xingtai, Hengshui, Handan, and other areas.

Table 3 Comprehensive TOPSIS Ranking of Flood Resilience in Beijing-Tianjin-Hebei Urban Areas

ranking	city	toughness grade
1	Beijing	high tenacity
2	Tianjin	high tenacity
3	Tangshan	Higher toughness
4	Shijiazhuang	Higher toughness
5	Langfang	Higher toughness
6	Qinhuangdao	moderate toughness
7	Cangzhou	moderate toughness
8	Chengteh	moderate toughness
9	Zhangjiakou	moderate toughness
10	Handan	lower toughness
11	Baoding	lower toughness
12	Xingtai	Low toughness
13	Hengshui	Low toughness

To further analyze the urban flood resilience levels in the Beijing-Tianjin-Hebei region, the TOPSIS scores for flood resilience were categorized into five levels using the natural breakpoint method: low resilience, relatively low resilience, moderate resilience, relatively high resilience, and high resilience. The classification results were visualized as shown in Figure 2.

Figure 2 Spatial distribution of urban flood resilience levels in the Beijing-Tianjin-Hebei region

Overall, most cities in the Beijing-Tianjin-Hebei region exhibit low flood resilience levels. Among 13 prefecture-level cities, only 5 demonstrate high or excellent flood resilience ratings, while 2 show low resilience. Significant disparities exist across urban resilience levels, forming a concentric distribution pattern with Beijing and Tianjin at the core, gradually declining toward peripheral areas. High-resilience cities cluster around the Beijing-Tianjin dual-core area, leveraging robust economic foundations, comprehensive infrastructure, and social security systems to excel in flood prevention. Cities with moderate resilience—including Tangshan, Shijiazhuang, and Langfang—benefit from strategic locations near Beijing and strong economic-engineering support. Medium-resilience cities predominantly consist of ecological hubs in northern Hebei and coastal areas, maintaining favorable environmental conditions but facing economic constraints. Low-resilience cities concentrated in central-southern Hebei (e.g., Xingtai and Hengshui) commonly suffer from inadequate flood control investments, underdeveloped drainage systems, and limited emergency response capabilities, representing critical vulnerabilities in regional flood management.

5. CONCLUSION

This study examines 13 cities in the Beijing-Tianjin-Hebei region, integrating multi-source data to establish a flood resilience evaluation index system. Using a comprehensive assessment approach combining Analytic Hierarchy Process (AHP), TOPSIS method, and spatial analysis techniques, the results reveal a distinct spatial differentiation pattern: "Beijing and Tianjin lead with dual core effects, higher resilience in the Beijing metropolitan area, and relatively lower resilience in central and southern Hebei." Economic resilience and social resilience emerge as key drivers, with high-resilience cities concentrated in Beijing and Tianjin, while low-resilience cities are predominantly located in Xingtai and Hengshui, highlighting significant regional development disparities.

In the future, it is essential to strengthen funding for flood prevention and drainage infrastructure construction, enhance economic support and emergency response capabilities, promote joint prevention, control, and collaborative governance of flood disasters in the Beijing-Tianjin-Hebei region, and comprehensively improve the overall flood resilience level of the area.

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