Evaluation of urban flood resilience and analysis of obstacle factors in northeast Sichuan based on PSR modeling

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Abstract: In this study, a comprehensive evaluation system of flood resilience is constructed based on the PSR framework with five cities in the northeastern region of Sichuan Province as samples. By quantitatively assessing the development dynamics of urban flood resilience during the decade 2014-2023, and applying the barrier degree model to identify key constraints. It is found that: the overall level of urban flood resilience in the study area shows a steady improvement trend, but the spatial differentiation characteristics are significant, and there are obvious gaps in the level of resilience development among different cities; river density, topographic slope and over-density of population are the main constraints to the regional resilience enhancement of the obstacle factors. Based on this, it is recommended to adopt differentiated management strategies, strengthen the layout of flood control infrastructure in areas with significant topographic relief, optimize the spatial distribution pattern of population to reduce disaster exposure, and systematically promote the ecological restoration of urban water systems and comprehensive management projects, so as to enhance the resilience level of regional floods with a multi-dimensional synergistic path.

1. Introduction

Under the combined effect of continuous intensification of climate change, rapid urban expansion and continuous population agglomeration, the frequency and hazardous degree of flooding are rising year by year, which has caused multidimensional impacts on regional economic development, ecological balance and people's health[1-3]. Heavy rainfall weather process occurred in northeastern Sichuan in August 2021, which led to the occurrence of flooding of several rivers at over-warning and over-guaranteed water levels, and severe flooding occurred in some places. flooding, resulting in human damage and property loss. Although some efforts have been made to prevent flooding in northeastern Sichuan, it still faces many challenges.

In recent years, scholars at home and abroad have achieved rich results in flood resilience research, Hossain[4] and others analyzed the impact factors of urban flooding through GIS risk assessment model, revealing the potential risk of urban flooding.Zhu[5] and others constructed a framework for urban flood resilience assessment by using the VIKOR and grey correlation analysis method.Li[6] and others constructed evaluation index system from four dimensions, namely infrastructure, economic system, social system and ecosystem, to evaluate the level of coping capacity of cities in different time periods of risk occurrence. , social system and ecosystem dimensions to construct an evaluation index system to evaluate the level of the city's coping capacity during different time periods of risk occurrence. Wu Huaqing[7] and others constructed an evaluation index system for urban disaster resilience by considering the changes in the resilience of the city in the four phases of resistance, early warning, reaction, response, and recovery from the urban disaster response phase. Zhou Zhenhong[8] et al. based on PSR-TOPSIS evaluation model to study the characteristics of urban flood resilience development in Hefei from 2015 to 2019. Gao Yuqin[9] et al. constructed an urban flood resilience evaluation model from four dimensions: basic resistance, disaster prevention and warning, emergency response and adaptation and recovery. Ren Jie [10] et al. constructed a flood resilience evaluation model for cities in the Yellow River Basin based on the PSR theoretical framework, and analyzed the spatial and temporal evolution characteristics of flood resilience in 25 central cities in the Yellow River Basin from 2012 to 2020.

The deep integration of the Pressure-State-Response (PSR) conceptual model with spatial information technology enables precise characterization and visual representation of the spatiotemporal heterogeneity and underlying mechanisms governing multifaceted pressures, dynamic states, and tiered responses in complex human-environment systems.Therefore,this paper comprehensively considers the climatic conditions and topographic and geomorphic features of northeastern Sichuan, and evaluates the resilience of torrential rainfall and flooding in northeastern Sichuan from 2014 to 2023 based on the "Pressure-State-Response" model in terms of the three dimensions of pressure, state and response,

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and analyzes the main obstacle factors affecting the level of resilience based on the analysis of the spatial and temporal evolution of flood resilience. On the basis of the spatial and temporal evolution analysis of flood resilience, the main obstacle factors affecting the resilience level are analyzed by using the obstacle degree model; with a view to providing theoretical references for improving the risk response capacity and resilience governance level of torrential rainfall and flooding in the northeastern region of Sichuan Province.

2. Overview of the study area and data sources

2.1. Overview of the study area

The northeastern region of Sichuan Province mainly includes five cities of Dazhou, Bazhong, Nanchong, Guangyuan and Guang'an, which are located in the intersection of the Sichuan Basin and the Qinba Mountainous Region, bordered by Shaanxi and Gansu in the north and Chongqing in the east, and are the Sichuan-Shaanxi transportation hub and geographic transition zone. The region's topography is mainly hilly and mountainous, both karst and Danxia landforms; complex geological conditions, landslides, mudslides and other disasters are frequent; water system, the region's rivers are densely distributed in the form of dendrites, belonging to the Jialing River, the Qiujiang River, the two major waterways; climate, the region is a subtropical monsoon climate, subtropical high pressure in the summer by the influence of heavy rainfall is frequent, the rate of rainy nights, easy to cause urban flooding. This region, with its typical geographic transition characteristics, complex water system network, extreme weather events and compound disaster risks, has become an important sample for the study of disaster prevention and mitigation and regional sustainable development, with both academic value and practical significance.

2.2. Data sources

This paper takes five cities in northeastern Sichuan Province as the study area, and considers the completeness and accessibility of the data, and chooses 2014 to 2023 as the study scope; the data are obtained from China County Cities Statistical Yearbook (County and Municipal Volume), local statistical yearbooks, and National Economic and Social Development Statistical Bulletins of districts and counties, etc.; the missing data are filled in by linear interpolation, average growth rate filling method, and other methods for Scientific supplementation.

3. Evaluation system construction

3.1. Construction of the indicator system

Currently, the research direction of urban flood risk analysis and evaluation mainly includes flood risk evaluation based on indicator system[11,12], flood risk analysis based on mathematical model[13,14], and flood risk evaluation based on GIS and remote sensing data sources[15,16]. The Pressure-State-Response (PSR) model was initially used to study environmental problems[17], and the urban flooding system involves many natural and social factors, such as climatic characteristics, natural ecological environment, economic level, and construction of flood control facilities[18]. Based on the theory of PSR, the resilience level of urban flood disaster is the result of the integrated action of pressure layer, state layer and response layer[19], the urban system is stimulated by flood disaster pressure, which leads to changes in the system state, and the system adopts corresponding response measures to recover rapidly from the impact of the disaster, and at the same time, it continues to develop and evolve, and improves its ability to cope with the flood disaster in the future[20].The cause and effect of PSR model can be well reflected by its causal oriented features can well reflect the dynamic nature of the resilience action mechanism[21].

This study constructs a flood resilience evaluation system based on the PSR framework, and screens the evaluation indexes through relevant literature analysis and frequency statistics, and finally determines the urban flood resilience evaluation index system in northeast Sichuan containing 17 evaluation indexes from the three dimensions of pressure, state and response, as shown in Table 1.

3.2. Determination of evaluation indicator weights

3.2.1 Data processing

In this study, the entropy method was used to assign weights to the indicators, and the polar deviation method was applied to standardize the indicators, as shown in equations (1) and (2).

Positive indicators:

$$X_{ij}^{'} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

Negative indicators:

$$X_{ij}^{'} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}} \tag{2}$$

Among them, $X_{ij}^{'}$ is the standardized value, X_{ij} is the original value of the j indicator in the year i , $X_{\max}$ and $X_{\min}$ are the maximum and minimum values of the indicator respectively.

3.2.2 Indicator assignment based on entropy value method

The steps for calculating the weights by the entropy method are as follows, and the specific formulas are shown in Eqs. (3) to (6).Specific calculations are shown in Table 1.

$$P_{ij}=\frac{Y_{ij}}{\sum_{i=1}^{m}Y_{ij}} \quad (3)$$

(1) Calculate the weight of the ith city's indicator value under the j indicator.

(2) Calculate the entropy value of the jth indicator in year t e_j

$$e_j=-k\sum P_{ij}\ln P_{ij} \qquad (k=\frac{1}{\ln m}) \quad (4)$$

(3) Calculate the coefficient of variation for indicator j g_j

$$g_j=1-e_j \quad (5)$$

(4) Obtain the weight of indicator j in year t ω_j

$$\omega_j=\frac{g_j}{\sum g_j} \quad (6)$$

Table 1 Indicator system of urban flood resilience in northeast Sichuan and indicator weights

Target Level	Dimension	Indicator Layer	Serial Number	Unit	Causality	Weights
Urban flood resilience	Pressure	Annual rainfall	X1	mm	-	0.0150
		Number of days of heavy rainfall per year	X2	day	-	0.0281
		Degree of topographic relief	X3	m	-	0.0728
		Average elevation	X4	m	-	0.0957
		Average slope	X5	degree	-	0.1401
	State	population density	X6	persons/km^2	-	0.0966
		Urbanization rate	X7	%	+	0.0355
		Forest cover	X8	%	+	0.0499
		Greening coverage in built-up areas	X9	%	+	0.0203
		River density	X10	km/km^2	+	0.1530
	Response	GDP per capita	X11	yuan	+	0.0398
		Per capita disposable income of urban residents	X12	yuan	+	0.0531
		Tertiary sector as % of GDP	X13	%	+	0.0332
		General budget revenues from local finances	X14	billions	+	0.0702
		Number of beds in medical institutions per 10,000 persons	X15	Sheets per 10,000 persons	+	0.0406
		Density of water supply pipes in built-up areas	X16	km/km^2	+	0.0134
		Density of drainage pipes in built-up areas	X17	km/km^2	+	0.0428

3.3. Urban flood resilience index

On the basis of the weights of the indicators in 2.2.2, the weighted comprehensive evaluation method is used to calculate the urban flood resilience index with the following formula:

Guideline layer resilience index:

$$R_x=\sum_{j=1}^{5}\omega_j X_{ij}^{'}(i=1,2...,n) \quad (7)$$

$$R_y=\sum_{j=6}^{10}\omega_j X_{ij}^{'}(i=1,2...,n) \quad (8)$$

$$R_z=\sum_{j=11}^{17}\omega_j X_{ij}^{'}(i=1,2...,n) \quad (9)$$

R_x , R_y and R_z represent the urban flood disaster resilience indices for the three dimensions of pressure, state, and response respectively.

Composite urban flood resilience index R:

$$R=R_x+R_y+R_z \quad (10)$$

3.4. Barrier degree model

The barrier degree model is used to analyze the main barrier factors of urban flood resilience in northeastern Sichuan, and targeted countermeasures to enhance urban flood resilience in northeastern Sichuan are proposed based on the main barrier factors. The formula for calculating the barrier degree is as follows:

$$O_{ij}=\frac{\omega_j\times(1-X_{ij}^{'})}{\sum_{j=1}^{n}\omega_j\times(1-X_{ij}^{'})} \quad (11)$$

Where O_{ij} is the barrier degree of the ith indicator in year j, ω_j is the weight of the indicator, and $X_{ij}^{'}$ is the value of the indicator after standardization.

4. Analysis of results

4.1. Analysis of the temporal evolution of urban flood risk

Based on the index weights calculated in Section 2.2, Equation (7) to Equation (10) were applied to calculate the resilience indices for each dimension of urban flooding as well as the composite resilience index for the northeastern region of Sichuan from 2014 to 2023.

4.1.1 Comprehensive resilience index analysis

The results of the calculation of the comprehensive urban flood resilience index in northeastern Sichuan from 2014 to 2023 are shown in Fig.1. From the calculation results, it can be seen that the overall urban flood resilience in northeastern Sichuan shows an obvious upward trend from 2014 to 2023. The flood disaster resilience of Guangyuan City is raised from 0.2438 in 2014 to 0.4184 in 2023, with an overall increase of 71.62%, the flood disaster resilience of Dazhou City is raised from 0.2782 in 2014 to 0.4766 in 2023, with an overall increase of 71.32%, and the overall increase in Bazhong City is also up to 66.46%; the flood disaster resilience of Guang'an City and Nanchong City in the study period also has a different trend. Guangzhou City and Nanchong City also have different degrees of growth in flood resilience, although the rate of increase is not as high as the other three cities, but its flood resilience index value has been at a higher level compared to the other three cities.

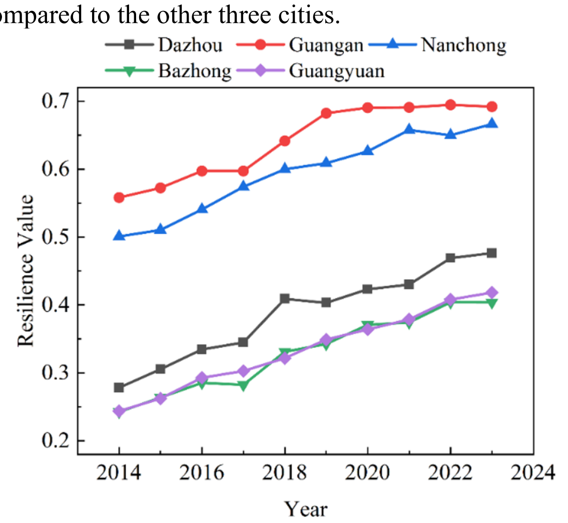


Fig. 1 Temporal evolution analysis of urban flood resilience in northeastern Sichuan, 2014-2023

4.1.2 Analysis of guideline layer resilience indices

In order to better analyze the evolution characteristics of flood resilience in five cities in northeast Sichuan during the study period, the resilience evolution was specifically analyzed from the three dimensions of pressure, state and response. According to the results of the guideline layer resilience index calculation using Origin software to visualize the time evolution results of the guideline layer resilience index, as shown in Fig.2.

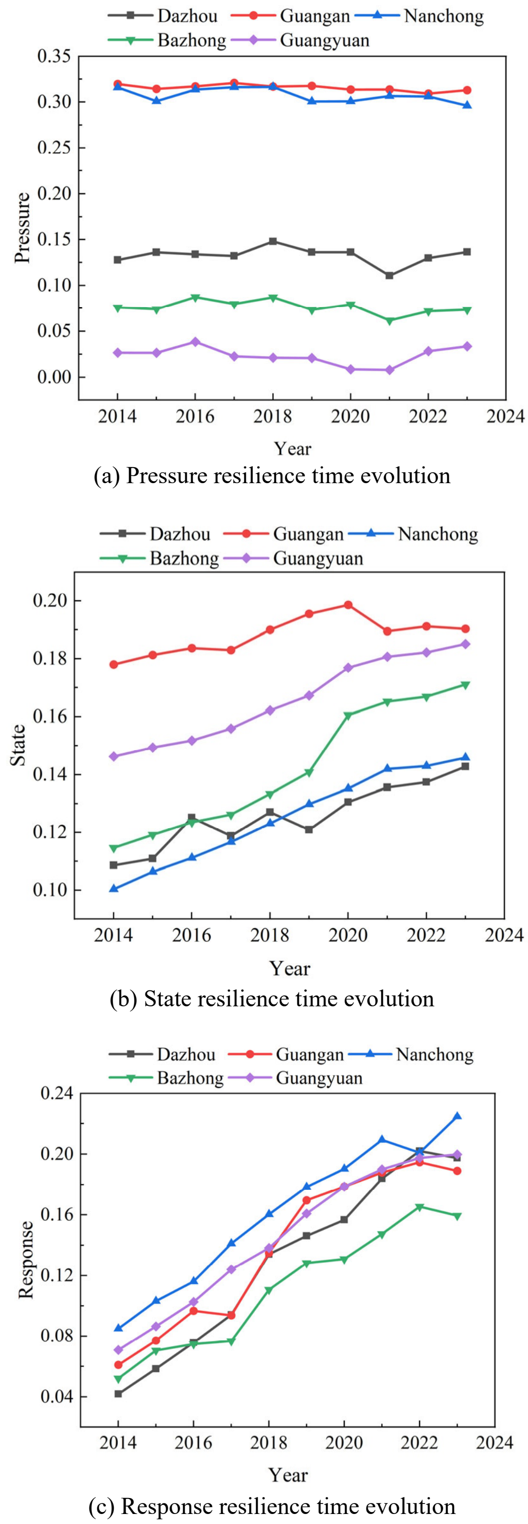
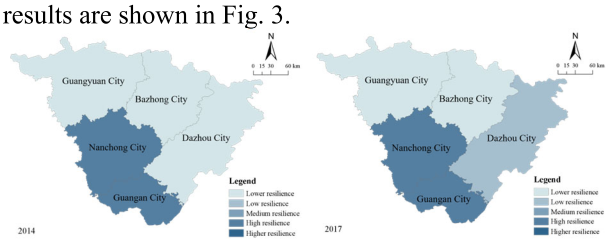


Fig. 2 Trends in time evolution of resilience levels for pressure, state and response dimensions

From Fig.2(a), it can be seen that the pressure resilience of the five cities in northeastern Sichuan fluctuates slightly during the study period, but the overall stability; the pressure resilience evaluation indexes are mainly composed of urban meteorological conditions and topographical conditions, and the topography of Guangyuan and Nanchong is more gentle, with fewer torrential rainfalls, and thus the flood pressure resilience level is at a higher level than that of the other three cities. From Fig.2(b), it can be seen that the five cities in northeastern Sichuan showed a steady increase in resilience between 2014 and 2023; the resilience evaluation indexes cover the demographic and urban ecological aspects, and in recent years, the demographic pressure of Bazhong City showed a decreasing trend from year to year, while at the same time, the urban ecological environment has been significantly improved, and the resilience level of its state has been most prominently increased. Fig.2(c) shows that the response resilience levels of the five cities show a significant increase. Response resilience evaluation indicators focus on two key aspects, namely, the level of urban economy and the degree of social infrastructure construction. Among the five cities, Nanchong has a relatively larger economic scale and more complete urban water supply and drainage facilities. Based on these advantages, Nanchong's response resilience level is at a higher level compared to the other cities. During the study period, Dazhou was repeatedly hit by severe floods, which brought huge economic losses to the area. However, Dazhou city has attached great importance to the urban social security system as well as the construction of infrastructure while actively promoting economic development. Through a series of powerful initiatives, Dazhou city has significantly improved its response level to flooding. Specifically, the value of its response resilience-related indicators has steadily climbed from 2014 to 2023, with an increase of 370.97%.

4.2. Analysis of the spatial evolution of urban flood resilience

ArcGis was used to visualize and express the spatial evolution trend of flood resilience of five cities in northeastern Sichuan in 2014, 2017, 2020 and 2023; the natural breakpoint method was used to classify the disaster resilience level of the five cities into five grades, namely low resilience, lower resilience, medium resilience, higher resilience, and high resilience; the results are shown in Fig. 3.



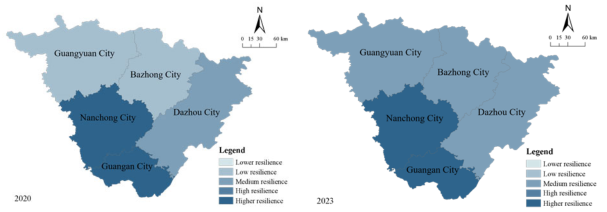


Fig. 3 Spatial evolution trend of urban flood resilience in northeastern Sichuan

As can be seen from Figure 3, urban flood resilience in northeast Sichuan gradually changes from low resilience dominance to higher resilience dominance.In 2014, low resilience cities in northeast Sichuan accounted for 60% of floods, and the proportion of low resilience cities decreased to 40% by 2017.In 2020, cities with medium resilience or higher began to dominate, accounting for 60%, and by 2023, all the cities reached the medium resilience level. Among them, Nanchong and Guang'an are always at a high level of flood resilience, with a significant gap with other cities. This is mainly because the two cities have larger economies and well-developed infrastructure such as water supply and drainage, which is conducive to flood prevention and drainage; stronger social assistance capacity, which allows for quick response to reduce losses; it may also be related to the local geographic and topographic conditions, which provide advantages in flood prevention; and, at the same time, the local government performs much better in the development of flood prevention and resilience policies and the implementation of planning. Taken together, there are large differences in the development of flood resilience in northeastern Sichuan, although the level of resilience compared to a decade ago have significantly improved, but the differences between the regional development is obvious, and spatially has been in the north of the distribution of low and high in the south of the distribution characteristics.

4.3. Analysis of barrier factors

According to Equation (11), the barrier level of flood resilience evaluation indicators of five cities in northeastern Sichuan can be obtained during the study period, and the barrier levels of the pressure, state and response dimensions are shown in Fig.4. As can be seen in Fig.4, the state dimension is the main obstacle factor restricting the development of flood resilience in northeastern Sichuan from 2014 to 2023. With the rapid economic development of the cities and the continuous improvement of infrastructure, the degree of influence of the response dimension on flood resilience gradually decreases. In recent years, the degree of constraints on flood resilience from urban climatic conditions as well as geographic and topographic conditions has begun to rise due to the influence of extreme weather around the globe.

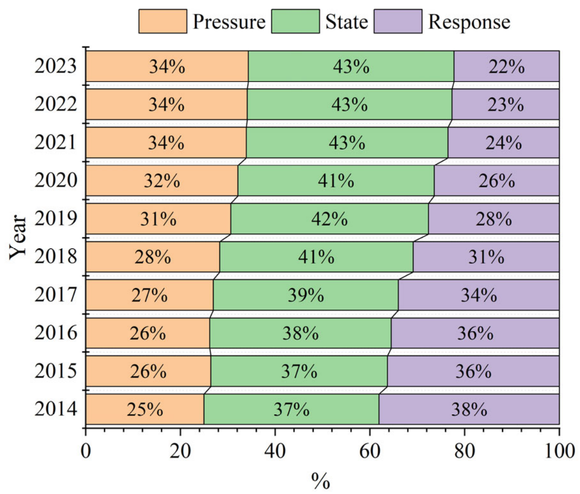


Fig. 4 Proportion of barrier levels for the three dimensions of pressure, state and response

In order to better study the factors affecting the development of flood resilience in northeastern Sichuan, the obstacle degree of each indicator from 2014 to 2023 was calculated and counted to obtain the main obstacle factors that ranked in the top 5 of the obstacle degree of the flood resilience evaluation indicators in the study time period, and the statistical results are shown in Table 2.

Table 2 Main barriers to flood resilience in northeastern Sichuan, 2014-2023

Year Ranking	1	2	3	4	5
2014	X10	X5	X6	X14	X12
2015	X10	X5	X6	X14	X12
2016	X10	X5	X6	X14	X12
2017	X10	X5	X6	X14	X4
2018	X10	X5	X6	X14	X4
2019	X10	X6	X5	X14	X4
2020	X10	X5	X6	X14	X4
2021	X10	X5	X6	X14	X4
2022	X10	X5	X6	X14	X4
2023	X10	X5	X6	X14	X4

As can be seen from Table 2, the top five obstacle factors of the flood resilience evaluation indicators in northeastern Sichuan from 2014 to 2023 mainly include: river density (X10), average slope (X5), population density (X6), general budget revenue of the local finance (X14), per capita disposable income (X12), and average elevation (X4). Among them, the obstacle degree of river density has been in the first rank during the study period, indicating that river density has a significant impact on the development of flood resilience in northeastern Sichuan, and that moderate river density can help to improve the regional drainage capacity and thus reduce the risk of urban flooding. In addition, steep urban slopes and high-elevation areas have fast rainwater runoff flow rates and short convergence times, which are prone to exacerbate flood risks and induce geologic hazards, while areas with gentle slopes have smoother drainage, which is conducive to enhancing flood resilience. High population density in floods in areas facing greater pressure on evacuation and resettlement, easy to aggravate the disaster damage, reduce the resilience, while the population distribution of reasonable areas easier to organize emergency response, enhance the resilience. Insufficient local budget revenue will restrict the construction of flood prevention facilities and emergency resources, reducing the resilience of floods, while sufficient revenue can guarantee disaster prevention and mitigation projects and emergency response capacity building, enhancing resilience. Residents in areas with low per capita disposable income are less resilient to disasters, and are prone to falling into a cycle of poverty and reduced resilience, while residents in areas with higher incomes have stronger self-help and recovery capabilities, which promotes resilience. In the future, the study area should focus on the improvement of response and resilience, promote sound and sustainable economic development, scientifically and rationally plan the population distribution pattern, vigorously strengthen the construction and improvement of urban disaster prevention and resilience infrastructure, and simultaneously increase the protection of the water system and restoration of investment.

5. Conclusion

Based on the PSR evaluation framework, this study constructed a flood resilience evaluation index system for northeastern Sichuan from the three dimensions of pressure, state and response, adopted the entropy method for index assignment, used ArcGIS to visualize the level of urban flood resilience in northeastern Sichuan, and used the barrier degree model to further identify the key obstacle factors that affect the enhancement of urban flood resilience in northeastern Sichuan.

The results indicate that a comprehensive analysis of spatiotemporal evolution and obstacle factors reveals an overall upward trend in flood resilience in northeastern Sichuan, albeit with significant fluctuations and variations among cities. Nanchong and Guang'an exhibit relatively high comprehensive resilience indices, while Guang'an, Dazhou, and Bazhong still show considerable potential for improvement. Spatially, the region demonstrates a characteristic "low in the north, high in the south" pattern, with all five cities reaching a medium resilience level by 2023. River density, average slope, and population density are identified as key constraining factors for resilience enhancement. Future efforts should prioritize strengthening flood control infrastructure in steep and topographically complex areas, rationally planning population distribution, and improving urban water system management to systematically enhance regional flood resilience.

Based on the empirical conclusions of the assessment of urban flood resilience in northeastern Sichuan, there are significant differences in flood resilience development in the region; special construction funds should be increased for the cities lagging behind in flood resilience development, focusing on the improvement of the urban drainage network renovation, flood control levee reinforcement, the layout of emergency shelters, and other engineering measures, to promote the modernization of the emergency management system of floods and disasters, and to comprehensively enhance the disaster-resistant capacity of the northeastern region of Sichuan. northeastern region of Sichuan Province. This paper focuses on the evaluation of urban flood resilience in northeastern Sichuan, and subsequent research can expand the resilience analysis framework under the perspective of disaster chain, integrate geographic information system technology, and analyze the interaction mechanism of topography, land use, population flow and other factors on flood resilience, so as to provide more targeted scientific analysis for the development of differentiated "one-city-one-policy" disaster prevention planning. It provides more targeted scientific support for the differentiated formulation of "one city, one policy" disaster prevention planning, and helps build a new paradigm for the safe development of resilient urban agglomerations.

Acknowledgements

This work was financially supported by the Sichuan Education Informatization Application and Development Research Center (Grant No. JYXX202503), the Sichuan Provincial Education Development Research Center (Grant Nos. CJF25101 and CJF24050), and the Scientific Research Fund Project of Chengdu Agricultural College (Grant No. 25BS09).

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