



# An Analysis of Urban Flood Resilience Evaluation and Spatio-Temporal Evolution Based on Game-Theoretic Combination Empowerment

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**Abstract.** In order to enhance the resilience of cities in front of flood disaster and improve the efficiency of urban management, the resilience and spatial and temporal evolution of urban flood disaster are studied. Based on the concept of urban resilience, construct urban flood resilience assessment model based on factor analysis-entropy weight method, and use game theory to assign the resilience of flood resilience in 10 years from 2013 to 2022. The results show that the slope, topographic relief and drainage pipe density have significant influence on the resilience level; the resilience level of flood disaster in Ya'an is increasing, but the resilience level of various cities in the region varies; in spatial distribution, the toughness level decreases from central cities to non-central cities. By 2022, all districts and counties will reach medium toughness level by 2022. This study can provide a scientific basis for formulating effective rainstorm and flood disaster risk management measures in Ya'an city.

**Keywords:** Flood disaster, Resilience evaluation, Combination empowerment, Analysis of spatio-temporal evolution.

## 1 Introduction

Global climate change has led to the frequent occurrence of extreme weather and climate phenomena in various places, increasing the possibility of heavy rain in cities, and thus aggravating the risk of flood disaster, and becoming the direct factor causing urban flood disaster. The occurrence frequency of flood disasters accounts for more than 60% of the global natural disasters [1]. In recent years, China has frequently encountered record-breaking extreme precipitation events, leading to floodwater disaster disasters in many cities, bringing a significant impact on the urban operation and the work and life of its citizens, and also revealing the vulnerability of urban systems in the face of such disasters[2]. According to statistics, 38 regional rainstorms occurred in China in 2022, causing 33.853 million people, 171 people, and a direct economic loss of 128.9 billion yuan [3].

A scientific and reasonable risk assessment is crucial to enhance the resilience of cities in response to flood disasters. According to the analysis of the existing research results, domestic and foreign scholars generally use mathematical statistics method [4], index system construction method [5,6], simulation technology [7,8] and spatial analysis[9] means to carry out risk assessment for rainstorm and flood disasters. Benito[10] assessment the risk of flood disaster by integrating historical flood data with geology, history and statistics. Combined with FloodArea inundation model, Li Luan [11] made the GIS platform, and evaluated the method of rainstorm and flood risk regionalization in Wuhu city. Liu Anmengyun [12] used hierarchical analysis method and fuzzy comprehensive evaluation method to carry out rainstorm and flood risk assessment in Xinxiang City, Henan Province and draw the risk distribution map. Nong Yaya [13] conducted risk assessment and risk level classification for rainstorm disasters in Yunnan Province based on the projection pursuit method.

Considering the landform features of Ya 'an, Sichuan and the historical data from 2013 to 2022, this paper evaluates the rainstorm and flood resilience from three dimensions of ecological environment, social system and economic system, and analyzes the temporal evolution of flood resilience, in order to provide solid scientific support for more scientific and effective rainstorm and flood risk management measures.

## 2 Overview of the Study Area and Data Sources

### 2.1 Overview of the Study Area

As shown in Figure 1, Ya 'an city is located at the intersection of the western edge of Sichuan Basin and the eastern foot of Qionglai Mountain, between east longitude 101°56' 26 "to 103°23 '28", north latitude 28°51' 10 "to 30°56'40", with Chengdu in the east, Ganzi Tibetan Autonomous Prefecture in the west, Liangshan Yi Autonomous Prefecture in the south, and Aba Tibetan and Qiang Autonomous Prefecture in the north. It is a key node of the natural transition between Sichuan Basin and the Qinghai-Tibet Plateau. The Dadu River on the south of —and the Qingyi River on the north of the two major water systems, such as two veins of life running through the whole region, endowed Ya'an with rich water resources. Ninety-four percent of the city's land is covered by mountains, with diverse and complex landforms, and topographic features with both windward slope and trumpet effect, making Ya' an a "rain city" with frequent rainstorms. According to statistics, the annual rainfall days can reach 280 days, the rainfall is approaching 3000 mm, the highest annual rainstorm number record is 18 times, and the night rain accounts for more than 70%. In recent years, Ya'an has also been repeatedly hit by earthquakes, such as the "June 1" Lushan earthquake and the "September 5" Luding earthquake in 2022. These natural disasters have further weakened the local geological structure and intensified the risk of meteorological disasters such as floods caused by rainstorms. To sum up, Ya'an city has become a highly representative and practical research area for exploring and studying the resilience of urban flood disasters due to its unique geographical location, frequent rainstorm climate characteristics, complex and susceptible geological structures, and the urgent practical need for building resilient urban strategies.

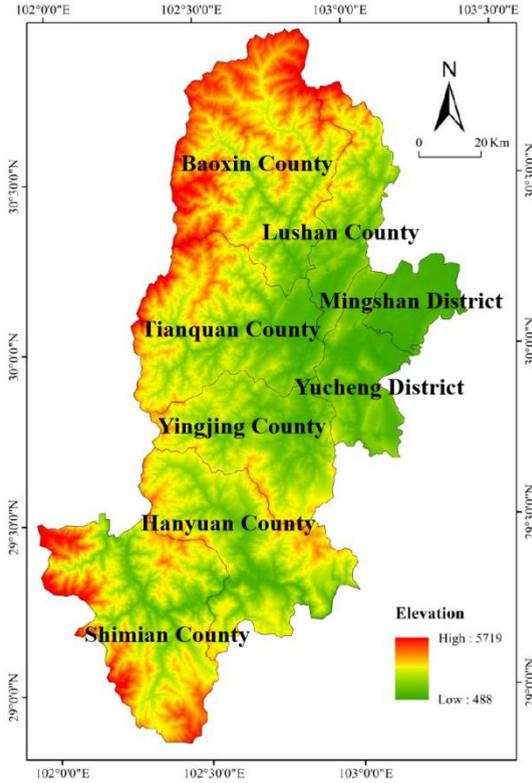


Fig. 1. Overview of the study area

## 2.2 Data Source

Taking 8 counties and districts of Ya'an City, Sichuan Province as the study area, considering the completeness and availability of data, 2013-2022 was selected as the research scope. The data are from Ya'an Statistical Yearbook (2014-2023), China Statistical Yearbook (County and City Volume) (2014-2023), Sichuan Provincial Statistical Yearbook (2014-2023), Statistical Bulletin of National Economic and Social Development and the missing data are supplemented by linear interpolation, average growth rate filling method, and interpolation for adjacent years.

# 3 Construction of the Evaluation System

## 3.1 Construction of the Index System

Flood disaster resilience is a series of ability [14] to resist, absorb and adapt to flood risk in order to keep the main characteristics, structure and key functions unchanged in the face of external flood disaster pressure.

Following the principles of scientificity, comprehensiveness, pertinence and operability, this paper selects resilience evaluation indicators from three aspects of ecological environment, society and economy to demonstrate the resilience level of each urban system when the study area is faced with flood disaster. By carefully sorting out the key evaluation indicators in domestic and foreign literature [15-21] and combining with the actual situation of the research area, the index system consists of 1 target layer, 3 criterion layers, 8 element layers and 20 specific indicators. The specific indicators are shown in Table 1. Among them, the positive indicator indicates that the indicator is positively associated with urban flood disaster resilience, and the growth of this indicator can promote the improvement of the resilience of urban flood disaster; the negative indicator indicates that the indicator is negatively associated with urban flood disaster resilience, and the growth of this indicator will reduce the resilience of urban flood disaster.

### 3.2 Define the Weight of the Evaluation Indicators

#### 3.2.1 Data Processing

In order to ensure that the data of each index is comparable in the calculation, it is necessary to standardize the data of each index to reduce the interference of the index weight and the final evaluation result due to the difference in dimension and the significance of the index. In this paper, the extreme range method is used to standardize the raw data. The normalization formula is as follows:

forward indicators:

$$x'_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \quad (1)$$

Negative indicators:

$$x'_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} \quad (2)$$

In this equation  $x'_{ij}$ , the original  $x_{ij}$  value of the first index  $x_j^{\max}$   $x_j^{\min}$  of the first  $j$  evaluation object, the maximum  $x_j^{\max}$  and minimum value of the first index, is the normalized value. After standardization, the value of each data is between 0 and 1. In order to avoid the impact of zero or negative value in the value, the standardized value is treated with non-negative translation. The translation formula is as follows:

$$x''_{ij} = x'_{ij} + H \quad (3)$$

Where, H is the magnitude of the index translation, presented here by taking 0.001.

**3.2.2 Combination Empowerment Based on Factor Analysis-Entropy Weight Method**

In this paper, factor analysis method and entropy weight method are selected to determine the objective weight of each index of urban flood disaster resilience, and game theory is used to combine each index, so as to ensure the objectivity and accuracy of weight calculation. The steps of determining the comprehensive weight are as follows:

Establish the basic weight vector set:

$$w_q = \{w_1, w_2 \dots w_n\}, q = 1, 2 \dots p \tag{4}$$

Where  $w_q$  is the set of weights determined by the  $p$ th empowerment method,  $n$  is the number of design indicators, and  $p$  is the number of weight-finding methods. In this paper, we mainly  $\alpha = \{\alpha_1, \alpha_2\}$  combine factor analysis method and entropy weight method to solve the comprehensive weight of design index, so  $p=2$ . Let it be the linear combination coefficient, then the linear combination of the two weight vectors is:

$$W = \alpha_1 w_1^T + \alpha_2 w_2^T \tag{5}$$

Based on the idea of game assembly model, two linear combination coefficients are optimized to obtain the most satisfactory weight in  $W$  and establish the objective function:

$$\min \left| \sum_{p=1}^n \alpha_p w_p^T - w_p \right|_2 \tag{6}$$

According to the linear equation, the linear equation of the optimal first derivative condition:

$$\begin{bmatrix} w_1 w_1^T & w_1 w_2^T \\ w_2 w_1^T & w_2 w_2^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} w_1 w_1^T \\ w_2 w_2^T \end{bmatrix} \tag{7}$$

The optimized combination  $\alpha_1$  coefficient  $\alpha_2$  was calculated and normalized:

$$\alpha_1^* = \alpha_1 / (\alpha_1 + \alpha_2) \tag{8}$$

$$\alpha_2^* = \alpha_2 / (\alpha_1 + \alpha_2) \tag{9}$$

Finally, the comprehensive weight of the design index is obtained:

$$W = \alpha_1^* w_1^T + \alpha_2^* w_2^T \tag{10}$$

The specific calculation results are shown in Table 1.

**Table 1.** Evaluation system and index weight of flood disaster resilience in Ya'an

Target layer	The standard layer	Elements layer	Index layer	unit	attribute	weight
Urban flood resilience	Ecological environment resilience	Oro-graphic condition	Average elevation X1	Rice	-	0.0595
			Average slope X2	Linear measure	-	0.1210
			Terrain relief degree X3	Linear measure	-	0.0974
		Meteorologic condition	Annual rainfall X4	Millimetre	-	0.0131
			Annual rainstorm days X5	Sky	-	0.0269
		Biological resources	Forest coverage rate of X6	%	+	0.0117
			Green space area per capita X7	m <sup>2</sup> / person	+	0.0493
		Infrastructure	The density of drainage pipes in the built-up area X8	km/ km <sup>2</sup>	+	0.0737
			Per capita urban road area X9	m <sup>2</sup> / person	+	0.0847
		Social system resilience	Population structure	The permanent resident population density X10	People / km <sup>2</sup>	-
	Urbanization rate is X11			%	-	0.0208
	The registered urban unemployment rate is X12			%	-	0.0455
	Social resources		Number of beds per thousand people in health institutions X13	Zhang / thousand people	+	0.0681
			The basic medical insurance coverage rate X14	%	+	0.0177
	Economic level		Gross regional product of X15	100 million	+	0.0631
			Financial self-sufficiency rate X16	%	+	0.0467
			Per capita GDP X17	Yuan	+	0.0494
			Per capita disposable income X18	Yuan	+	0.0495
			The proportion of tertiary industry production value to GDP X19	%	+	0.0317
	Economic structure	Ratio of per capita deposit balance to per capita consumption expenditure X20	/	+	0.0322	

### 3.3 Urban Flood Disaster Resilience Measurement Model

On the basis of obtaining the weight of each index in Table 1, the weighted comprehensive evaluation method is adopted to calculate the urban flood disaster resilience index, and the calculation formula is as follows:

Resilience index:

$$R_x = \sum_{j=1}^7 w_j x_{ij} \quad (i = 1, 2, \dots, n) \quad (11)$$

$$R_y = \sum_{j=8}^{14} w_j x_{ij} \quad (i = 1, 2, \dots, n) \quad (12)$$

$$R_z = \sum_{j=15}^{20} w_j x_{ij} \quad (i = 1, 2, \dots, n) \quad (13)$$

$R_x$ ,  $R_y$  and  $R_z$  represent the urban flood disaster resilience index of the ecological environment, social system, and economic system, respectively.

Composite resilience index R:

$$R = R_x + R_y + R_z \quad (14)$$

## 4 Results Analysis

### 4.1 Resiliency Level of Flood Disaster in the Study Area

According to the standardized data of the 8 districts and counties in the study area in 10 years, the index weights in Table 1 and the formula (1) to formula (14), the flood resilience index of ecological environment, social system and economic system and the comprehensive resilience index of urban flood in the 8 districts and counties in the study area from 2013 to 2022 were calculated.

### 4.2 Analysis of Resilience of Urban Flood Disasters

#### 4.2.1 Analysis of the Comprehensive Toughness Index

According to the results of the urban flood resilience index in the study area from 2013 to 2022 calculated in the 3.1, the evolution trend of the flood resilience in the 10 years in the study area can be shown in Figure 2.

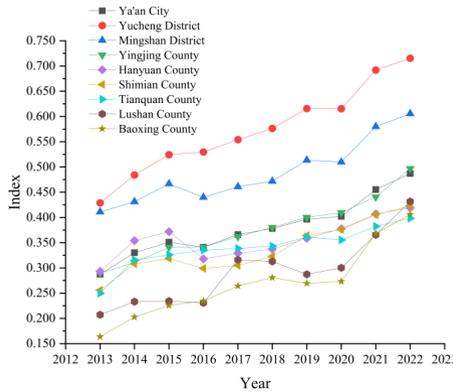
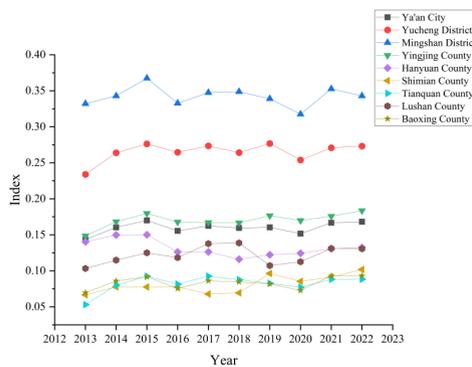


Fig. 2. Changes of flood disaster resilience development in Ya'an city from 2013 to 2022

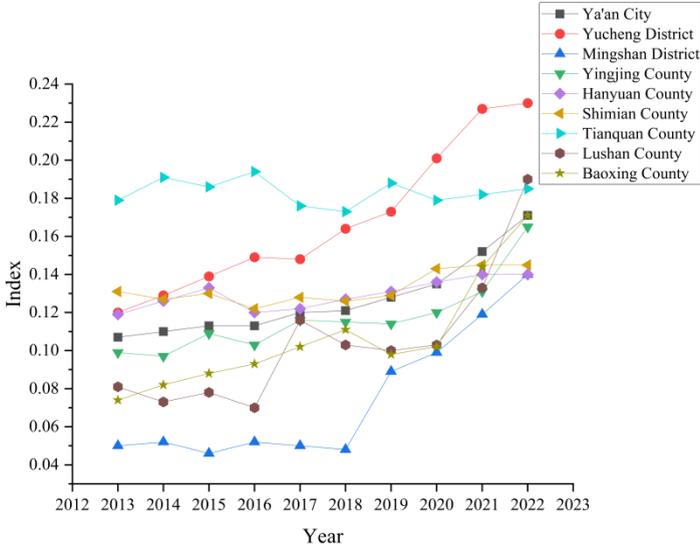
It can be seen from the results that the resilience index of most regions of Ya'an city increased to varying degrees from 2013 to 2022. As the administrative and economic center of Ya'an City, the resilience index of Yucheng District increased steadily from 0.4287 in 2013 to 0.7153 in 2022, an increase of nearly 72%; As the county with relatively weak resilience foundation, the resilience index increased by nearly 150% from 0.1637 in 2013 to 0.4060 in 2022; the resilience index of the other counties also increased significantly in this period. During 2016, many areas of Ya'an city experienced continuous heavy rainfall, and geological disasters such as debris flow occurred in Hanyuan County, Shimian County and Tianquan County, which may be related to the decrease of the toughness index in these areas.

4.2.2 Analysis of the Toughness Index of the Criterion Layer

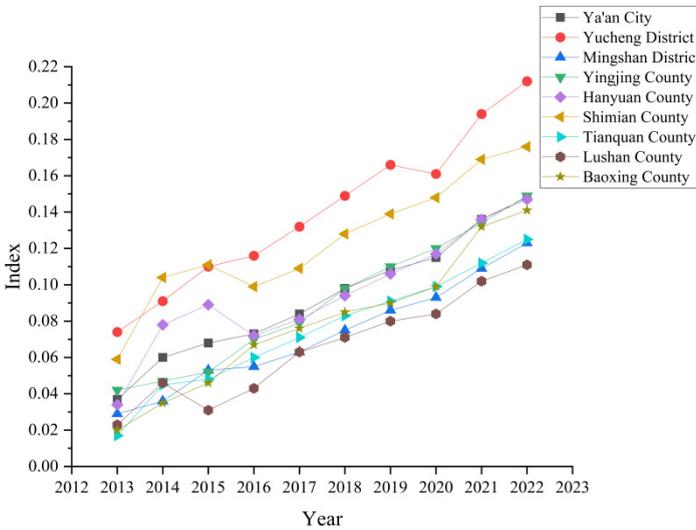
According to the calculation results in Section 3.1, draw the change trend map of the resilience index of the ecological environment, social system and economic system respectively, as shown in Figure 3.



(a) The change trend of the flood toughness index of the ecological environment system



(b) Change trend of the flood resilience index of the social system



(c) Change trend of the flood resilience index of the economic system

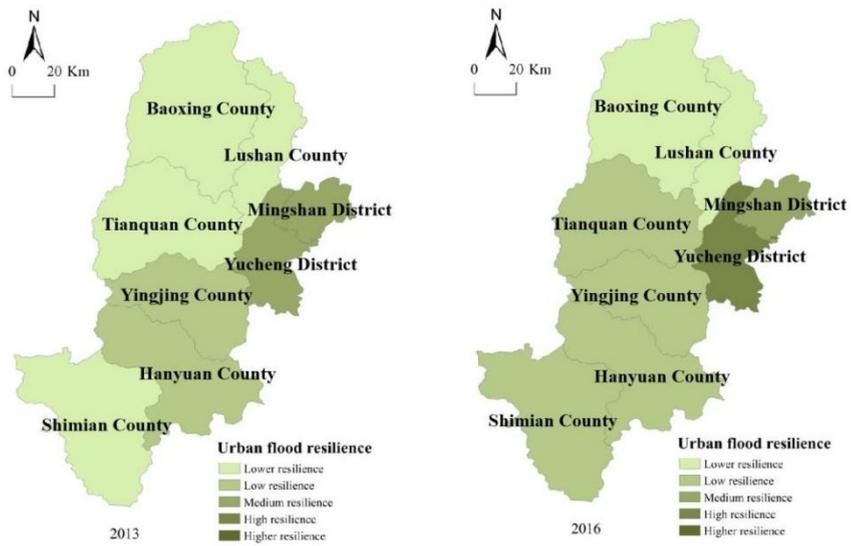
Fig. 3. Trend of flood toughness index of each criterion layer

It can be seen from the change trend chart that the overall ecological environment resilience of Ya'an city is stable, the ecological environment resilience index of Yucheng District and Mingshan District is significantly higher than that of other cities, Shimian County, Tianquan County and Baoxing County are close to each other, and

the ecological environment resilience level is low. The basic value of ecological environment resilience is determined by elevation, slope and topographic fluctuation. The interannual fluctuation is mainly related to rainfall and forest coverage rate. Several cities with low ecological environment resilience have complex terrain and are affected by rainstorm all the year round, which are frequent geological disasters. The overall resilience of the social system is on the rise, the infrastructure is constantly improved in the process of urban construction, the urban drainage network density increases, the evacuation roads are more smooth, and the medical resources are gradually complete. Compared with 2013, the urban resilience of Yucheng District, Mingshan District and Lushan County is significantly enhanced in 2022; as the urban population approaches saturation and the proportion of the population vulnerable to floods increases, the social resilience of Tianquan and ShimCounty fluctuates. The resilience of the economic system is mainly related to the economic level and structure of each city, and the overall economic resilience of Ya'an city shows a significant upward trend.

### 4.3 Analysis on the Spatial Evolution of the Resilience of Urban Flood Disasters

According to the calculation results in 3.1, using natural breakpoint method to the counties of ya'an 2013~2022 urban comprehensive toughness index is divided into low toughness, low toughness, medium toughness, high toughness and high toughness five grades, and using the visualization of ArcGIS representative years (2013,2016,2019 and 2022), the results are shown in Figure 4.



(a) In 2013

(b) In 2016

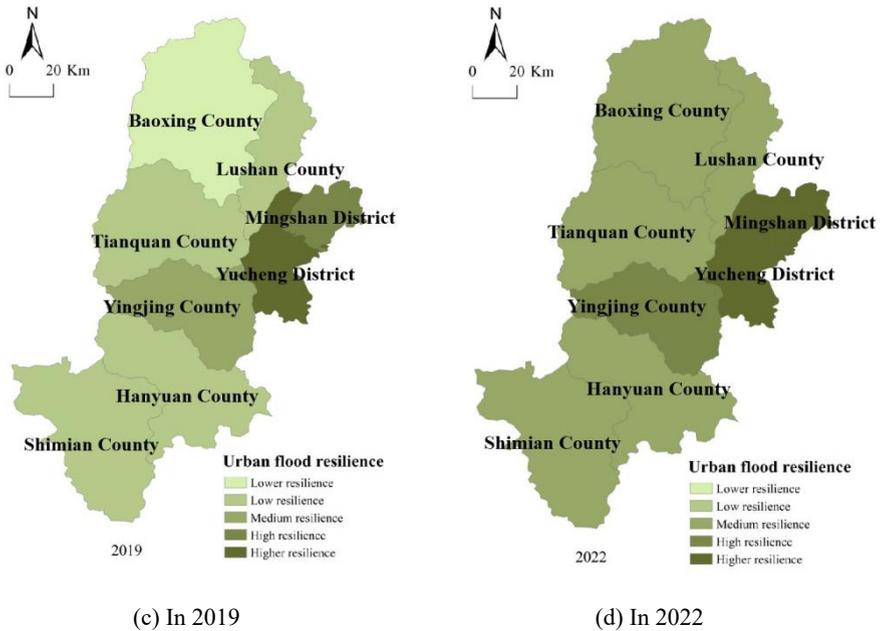


Fig. 4. Spatial distribution of flood disaster resilience in Ya'an City

The analysis results show that in 2022, the districts and counties in Ya'an city have significantly improved in flood disaster resilience compared with 2013, however, there are significant differences and imbalance in the spatial layout. From 2013 to 2022, the toughness level of Yucheng District and Mingshan District has always been in the forefront. The cities with relatively low toughness level are far away from the central city of Ya'an city, showing the spatial structure characteristics of decreasing from central city to non-central city. From 2013 to 2022, the number of high toughness cities and high toughness cities in Ya 'an increased from 2 to 3, and the number of cities with low toughness and low toughness decreased from 6 to 0; by 2022, all districts and counties in Ya' an had reached medium resilience level, indicating that the flood resilience level in Ya'an was significantly improved.

### 5 Conclusion

This paper builds an assessment model of urban flood resilience based on factor analysis-entropy weight method, and uses game theory. Analysis of urban flood resilience in 8 districts of Ya'an from 2013 to 2022, the following conclusions are obtained:

- (1) In terms of the index weight calculation results, slope, topographic fluctuation and drainage pipe density in built-up areas are the main factors affecting the resilience level of urban flood disaster in Ya'an.

(2) In terms of time evolution analysis, the overall flood disaster resilience level in Ya'an city shows an upward trend, and the development of flood disaster resilience level in various cities in the region is quite different, and the fluctuation range is different. Among them, the comprehensive resilience index of flood disaster in Yucheng District is the highest, while Baoxing County increases the most, and it increases the most.

(3) In terms of spatial evolution analysis, the resilience level of flood disasters in Ya'an city has significantly improved, showing the overall spatial structure characteristics of decreasing from central cities to non-central cities, and has reached the medium resilience level by 2022.

According to the above evaluation results of urban flood disaster resilience in Ya'an city, it is suggested to focus on strengthening the construction of flood control facilities in areas with large slope and high topographic relief, and optimize the layout of drainage pipes in the built-up areas to improve the drainage efficiency. At the same time, differentiated improvement strategies should be implemented according to the difference in the resilience level of flood disasters in the region, especially to increase the investment in the weak resilience counties such as Tianquan County and Shimian County. In addition, drawing on the high resilience experience of Yucheng District, promote the construction of the city's flood disaster emergency management system, strengthen the monitoring and evaluation of resilience, ensure the balanced development of flood disaster resilience in all districts and counties, and improve the overall flood resistance ability of Ya'an city. Although this study constructed an urban flood disaster resilience assessment model, it has some limitations. This paper mainly focuses on the analysis of the overall and district and county scales of Ya'an city. The future research can be further expanded to multi-scale spatial analysis, so as to explore the spatial differentiation characteristics of urban flood disaster resilience more carefully, and provide scientific basis for the development of differentiated disaster prevention and mitigation strategies.

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