Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-8, August 2025
DOI: 10.53469/jrse.2025.07(08).09

Evaluation of Infrastructure Resilience and Analysis of Obstacle Factors in Northeast Sichuan Economic Zone

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Abstract: ***Based on the PSR framework, an infrastructure resilience evaluation model was developed to study the development of infrastructure resilience in the Northeast Sichuan Economic Zone from 2014 to 2023. Using factor analysis and entropy value methods, along with game theory, the weights of each evaluation indicator were determined. The results were visualized using ArcGIS, and the obstacle degree model was used to identify key constraining factors. The findings indicate that the overall infrastructure resilience in the northeast Sichuan economic zone is on the rise. The 'Dual-core' development pattern of Nanchong and Dazhou is evident, with significant differences in infrastructure resilience levels between cities. The main obstacles to enhancing infrastructure resilience in the study area include industrial structure, energy supply, terrain slope, and population distribution.***

Keywords: Infrastructure resilience, PSR model, Spatio-temporal evolution analysis, Obstacle factors**.**

1. Introduction

In the current era of rapid urbanization, cities are grappling with various "urban ills" such as traffic congestion, worsening environmental pollution, and increasingly scarce resources [1]. The emergence of these issues has significantly increased the uncertainty risks faced by urban infrastructure. As a material support system that ensures orderly social production activities and normal daily life operations, infrastructure encompasses municipal public works facilities like transportation, postal services, water supply, and power supply, along with various service facilities meeting public needs[2]. Its importance is self-evident. In December 2024, the General Office of the Central Committee of the Communist Party of China and the State Council issued the "Opinions on Promoting New Urban Infrastructure Construction to Build Resilient Cities" [3], proposing to build an intelligent and efficient new urban infrastructure system. This aims to continuously enhance the resilience of urban facilities in terms of management, spatial configuration, and safety development. For the Northeast Sichuan Economic Zone, conducting a deep analysis of the current status of regional infrastructure development based on resilience concepts and accurately identifying obstacles in its development process holds crucial theoretical and practical significance. Domestic and international studies on urban infrastructure resilience evaluation analyze practical issues from multiple perspectives, primarily optimizing existing model tools for the resilience evaluation system. Xu Xiujuan constructed an urban infrastructure evaluation index system from two aspects: the hard environment system and the soft environment system, using catastrophe level method and entropy value method to assess spatial differences in urban infrastructure construction [4]. Wang et al. developed a three-tiered evaluation index system for urban-rural infrastructure disparity, employing the coefficient of variation method to analyze infrastructure gradient differences across 26 provinces [5]. Liao et al. proposed resilience enhancement strategies for existing and new urban underground infrastructure from five dimensions: facilities, management, culture, economy, and intelligence [6]. Jiang et al. conducted research on urban transportation infrastructure resilience in the Yangtze River Delta region and provided corresponding optimization recommendations [7]. Current domestic studies on urban infrastructure resilience still face issues such as single-dimensional perspectives and insufficient specificity. To address these challenges, this study evaluates urban infrastructure resilience levels in Sichuan's northeastern economic zone using the PSR evaluation model, while applying the obstacle model to analyze influencing factors. The findings aim to provide evidence-based support for infrastructure development measures in the northeastern Sichuan region.

2. Research Basis

2.1 Research Area Profile

The Northeast Sichuan Economic Zone, encompassing five cities-Dazhou, Bazhong, Nanchong, Guangyuan, and Guang 'an-serves as a vital corridor connecting southwestern and northwestern China while bridging western regions with central areas. As a key economic pillar in Sichuan Province's socioeconomic development framework, this region features predominantly hilly terrain with complex geological conditions. Its resource capacity remains limited, intensive utilization persists, and natural hazards like landslides and mudflows occur frequently, placing significant pressure on urban infrastructure systems. Moreover, the area grapples with severe soil erosion and formidable ecological restoration challenges. Most zones are designated as national restricted development zones, imposing strict constraints on large-scale industrialization and urbanization. Given its strategic location at the convergence of Sichuan, Chongqing, Shanxi, and Gansu provinces, coupled with complex topography presenting both construction challenges and resource potential, selecting this region for urban infrastructure resilience evaluation proves crucial. This research aims to explore infrastructure adaptation and recovery capabilities under unique geographical conditions and disaster risks, thereby ensuring sustainable regional development. The topographic profile of the Northeast Sichuan Economic Zone is illustrated in Figure 1.

2.2 Data Sources

The research data was sourced from publicly available materials including the China County City Statistical Yearbook (County and City Volume), local statistical yearbooks, and district-level National Economic and Social Development Statistical Bulletins. As some 2024 data was not yet released during the study period, we selected the 2014-2023 time frame to ensure data integrity, accessibility, and methodological rigor. For missing data points, we applied linear interpolation and average growth rate estimation techniques to scientifically supplement the information.

3. Evaluation System Construction

3.1 Index System Construction

Based on the research of domestic and foreign scholars and practical research content, this paper constructs an infrastructure resilience evaluation index system for northeast Sichuan economic zone based on pressure, state and three dimensions from the PSR evaluation model [8]-[10], and selects 23 specific indicators such as annual number of rainstorm days, road network density and per capita GDP, as shown in Table 1.

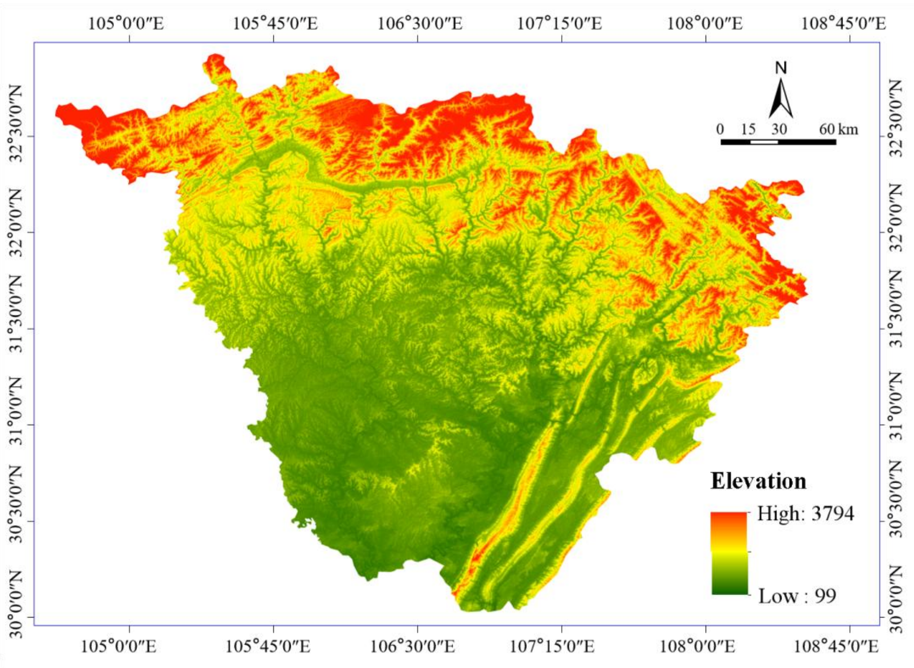


Figure 1: Topographic profile of the study area

Table 1: Infrastructure resilience evaluation index system of Northeast Sichuan Economic Zone

Target layer	Criterion layer	Element Layer	Serial Number	Index Layer	Unit
Infrastructure Resilience	Pressure	Natural pressure	X1	Number of rainy days per year	Day
			X2	Terrain relief amplitude	m
			X3	Average grade	Degree
		Artificial pressure	X4	Density of population	People/km^2
			X5	Urbanization rate	%
			X6	Total wastewater discharge	kt
			X7	Sulfur dioxide (SO2) emissions	t
	State	Traffic system	X8	Road network density	km/km²
			X9	Road area per capita	m^2/people
		Energy supplies	X10	Water supply	Million m³
			X11	Gas and natural gas supply	t
		Water supply and drainage system	X12	Built-up area water supply pipeline density	km/km^2
			X13	Built-up area drainage pipeline density	km/km^2
		Ecological environment	X14	Per capita green area	m^2/people
			X15	Built-up area greening overjet rate	%
			X16	Comprehensive utilization rate of industrial waste	%
	Response	Economic level	X17	Per capita GDP	Yuan
			X18	General budget revenue of local finance	100 million
			X19	The proportion of science and technology expenditure in local fiscal expenditure	/
		Medical facilities	X20	Number of hospital beds per 10,000 population	Per 10,000 people
			X21	Number of health technical personnel per 10,000 Homo sapiens	people
		Communication facility	X22	Mobile phone penetration rate	Per 100 people
			X23	Number of internet broadband access subscribers	Ten thousand households

3.2 Index Weights

Currently, the most widely used methods for determining indicator weights primarily include subjective weighting approaches such as Analytic Hierarchy Process (AHP), Expert Rating Method, and G1 method, along with objective weighting methods like Entropy Value, CRITIC method, and Variance Coefficient method. Given the multidimensional and dynamic nature of urban infrastructure resilience evaluation, to ensure scientific rationality in weight allocation, factor analysis [11]-[12] and entropy value [13] are employed through game theory to further determine the weights of each evaluation indicator.

3.2.1 Index weights based on factor analysis

Factor analysis is fundamentally about extracting common key factors from numerous raw variables based on their correlations, efficiently integrating them to achieve data “Dimensionality reduction” while preserving information and enhancing the rigor and practicality of data analysis [14]. After standardizing the original indicator data, KMO tests and Bartlett’s test are conducted to determine whether the data is suitable for factor analysis. Typically, a KMO value above 0.7 and a Bartlett test p-value below 0.05 indicate significant correlations between variables, confirming the validity of factor analysis. The weight calculation follows formula (1).

$$\omega_j^{'} = \frac{P_k \beta_j}{\sum_{j=1}^{n} P_k \beta_j} \tag{1}$$

In this formula, $\omega_j^{`}$ is the indicator weight value, P_k is the variance contribution rate after factor rotation, and β_j is the factor score coefficient of each index.

3.2.2 Index weight based on entropy method

As an objective weighting method, the basic principle of entropy value method is to calculate the information entropy value of each index first, and then determine the weight of each index according to the degree of dispersion of index data reflected by entropy value [15]. The calculation formula is as follows:
Calculating the proportion of the i-th city under the j-th index:

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}} \tag{2}$$

Computing the entropy value of the j-th indicator in year t:

$$e_j = -k \sum^{\Sigma ij} \quad \frac{1}{ln\, m} P_{ij} ln \tag{3}$$

Calculate the coefficient of variation of index j:

$$g_j = 1 - e_j \tag{4}$$

Obtain the weight of indicator j in year t

$$\omega_j = \frac{g_j}{\Sigma g_j} \tag{5}$$

3.2.3 Game theory-based combined weighting

Game theory aims to minimize the dispersion among weights obtained through different methods by optimizing a strategic balance. This process allows for the identification of an equilibrium state among competing weighting schemes, thereby deriving the optimal composite weight for each indicator [16,17]. The specific steps for determining the combined weights using the game-theoretic approach are as follows:

Establish a basic weight vector set:

$$\omega_q = \{\omega_1, \omega_2 ... \omega_n\}, q = 1,2...p \tag{6}$$

$\alpha = \{\alpha_1, \alpha_2\}$ as the linear combination coefficients, then the linear combination of the two weight vectors is:

$$\omega = \alpha_1 \omega_1^T + \alpha_2 \omega_2^T \tag{7}$$

Establish the objective function:

$$min \,|\sum_{p=1}^{n} \alpha_p \omega_p^T - \omega_p|_2 \tag{8}$$

Transform the objective function into a system of linear equations that optimizes the first-order derivative conditions:

$$\begin{bmatrix} \omega_1\omega_1^T & \omega_1\omega_2^T \\ \omega_2\omega_1^T & \omega_2\omega_2^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \omega_1\omega_1^T \\ \omega_2\omega_2^T \end{bmatrix} \tag{9}$$

Obtain the optimized combination coefficients and perform normalization processing on them:

$$\alpha_1^* = \alpha_1/(\alpha_1 + \alpha_2) \tag{10}$$
$$\alpha_2^* = \alpha_2/(\alpha_1 + \alpha_2) \tag{11}$$

Finally, the comprehensive weights of the design indicators are obtained:

$$\omega = \alpha_1^* \omega_1^T + \alpha_2^* \omega_2^T \tag{12}$$

According to formula (1-12), the specific weight calculation results are obtained, as shown in Table 2.

Table 2: Game theory-based combination weighting results

Index	ω_1	ω_2	ω
X1	0.0397	0.0180	0.0222
X2	0.0457	0.0467	0.0500
X3	0.0515	0.0899	0.0856
X4	0.0462	0.0620	0.0589
X5	0.0476	0.0286	0.0322
X6	0.0364	0.0203	0.0222
X7	0.0485	0.1052	0.1034
X8	0.0348	0.0176	0.0211
X9	0.0438	0.0308	0.0311
X10	0.0462	0.0681	0.0678
X11	0.0376	0.0822	0.0756
X12	0.0173	0.0086	0.0111
X13	0.0461	0.0274	0.0322
X14	0.0360	0.0351	0.0400
X15	0.0494	0.0131	0.0144
X16	0.0359	0.0098	0.0133
X17	0.0419	0.0255	0.0311
X18	0.0552	0.0450	0.0511
X19	0.0300	0.1194	0.1100
X20	0.0571	0.0261	0.0333
X21	0.0566	0.0543	0.0511
X22	0.0469	0.0274	0.0322
X23	0.0494	0.0388	0.0411

3.3 Infrastructure Resilience Index

Based on the indicator weights calculated in Section 3.2, a weighted comprehensive evaluation method was employed to compute the resilience indices for the three dimensions of infrastructure resilience—pressure, state, and response—as well as the overall composite resilience index.

(1) Computing the Comprehensive Resilience Index of Computing Infrastructure, the calculation formula is:

$$R_{\lambda i} = \sum_{j=1}^{23} \omega_j \, C''_{\lambda_{ij}} \quad (13)$$

(2) Calculate the resilience index for each dimension, the calculation formula is:

$$P_{\lambda i} = \sum_{j=1}^{7} \omega_j \, C'_{\lambda ij} \quad (14)$$

$$S_{\lambda i} = \sum_{j=8}^{16} \omega_j \, C'_{\lambda ij} \quad (15)$$

$$V_{\lambda i} = \sum_{j=17}^{23} \omega_j \, C'_{\lambda ij} \quad (16)$$

Here, $P_{\lambda i}$ represents pressure resilience index、$S_{\lambda i}$ represents state resilience index、$V_{\lambda i}$ represents response resilience index.

3.4 Obstacle Degree Model

The Obstacle Degree Model [18-20] was applied to analyze the primary factors hindering infrastructure resilience in the Northeastern Sichuan Economic Zone. The calculation formula is as follows:

$$O_{i\,j} = \frac{\omega_j \times (1 - C'_{\lambda ij})}{\sum_{j=1}^{n} \omega_j \times (1 - C'_{\lambda ij})} \quad (17)$$

Here, O_{ij} is the obstacle degree of the i-th index in the j-th year, ω_j is the weight of the index, and $C'_{\lambda ij}$ is the value of the index after standardization.

4. Results and Analysis

4.1 Temporal Evolution of Infrastructure Resilience

Based on Equations (13) -(16) presented in Section 3.3, this study conducted a temporal analysis of the overall infrastructure resilience index and the three dimension - specific indices (pressure, state, and response) for the Northeastern Sichuan Economic Zone over the period 2014 -2023.

4.1.1 Comprehensive resilience index analysis

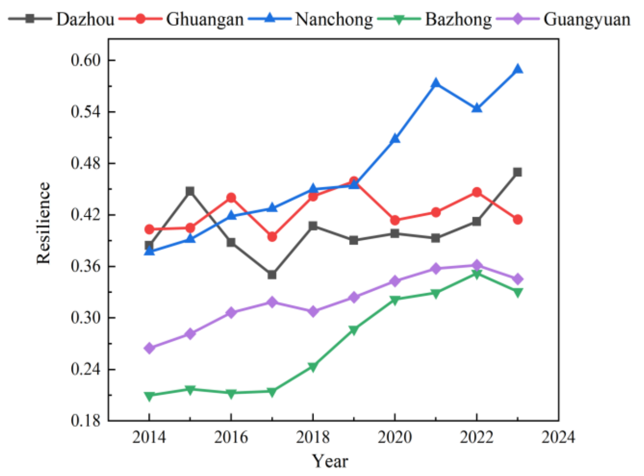


Figure 2: Temporal Trends in Comprehensive Infrastructure Resilience Index in the Northeastern Sichuan Economic Zone (2014-2023)

The comprehensive infrastructure resilience indices of the five cities were visualized using Origin 2024, as shown in Figure 2. The results reveal a clear upward trend in the overall infrastructure resilience across the region during the study period.

Among the cities, Nanchong and Bazhong exhibited the most substantial increases, both exceeding 55%. Although Guang'an showed the smallest improvement, with an increase of only 2.28%, its overall resilience level remained consistently higher than that of Bazhong and Guangyuan throughout the study period.

Dazhou demonstrated a moderate growth of approximately 30%, characterized by significant fluctuations in the early years, followed by a stable middle phase and a sharp increase in the later years. Overall, Dazhou's resilience level was also higher than that of Bazhong and Guangyuan during most of the observed timeframe.

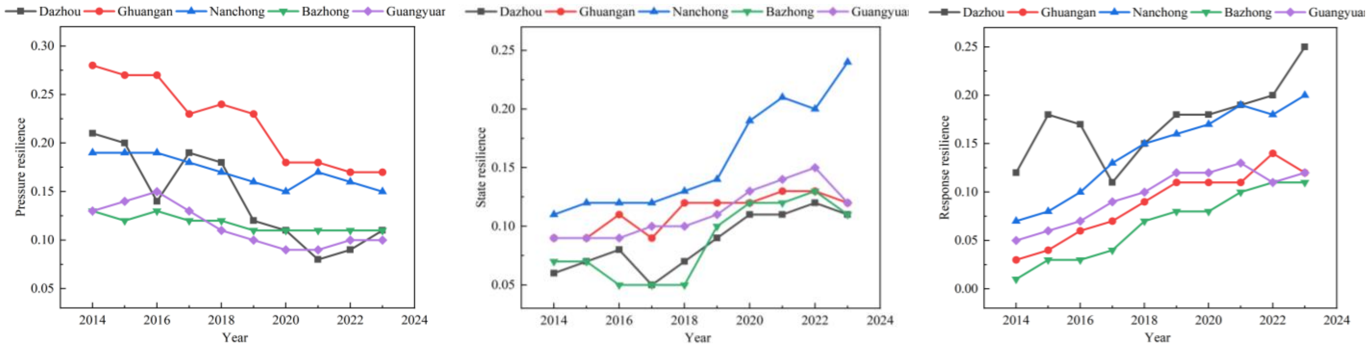
4.1.2 Analysis of dimension-wise resilience indices

To further investigate the temporal evolution of infrastructure resilience in the Northeastern Sichuan Economic Zone, this section analyzes the changes in resilience indices across the three PSR dimensions: pressure, state, and response.

Pressure resilience reflects the stress exerted on urban infrastructure systems due to natural and anthropogenic factors. Natural pressure is primarily influenced by local topography and climatic conditions, while anthropogenic pressure is closely related to urban population density and industrial activity. As illustrated in Figure 3(a), the pressure resilience levels of the five cities in the region exhibited a downward trend over the period 2014 -2023. Based on supporting indicator data, this decline suggests that population growth and industrial expansion have been effectively managed across the region, thereby alleviating pressure on infrastructure systems. Notably, Guang'an experienced the most significant reduction in pressure, although it still remains among the higher-pressure cities compared to its peers.

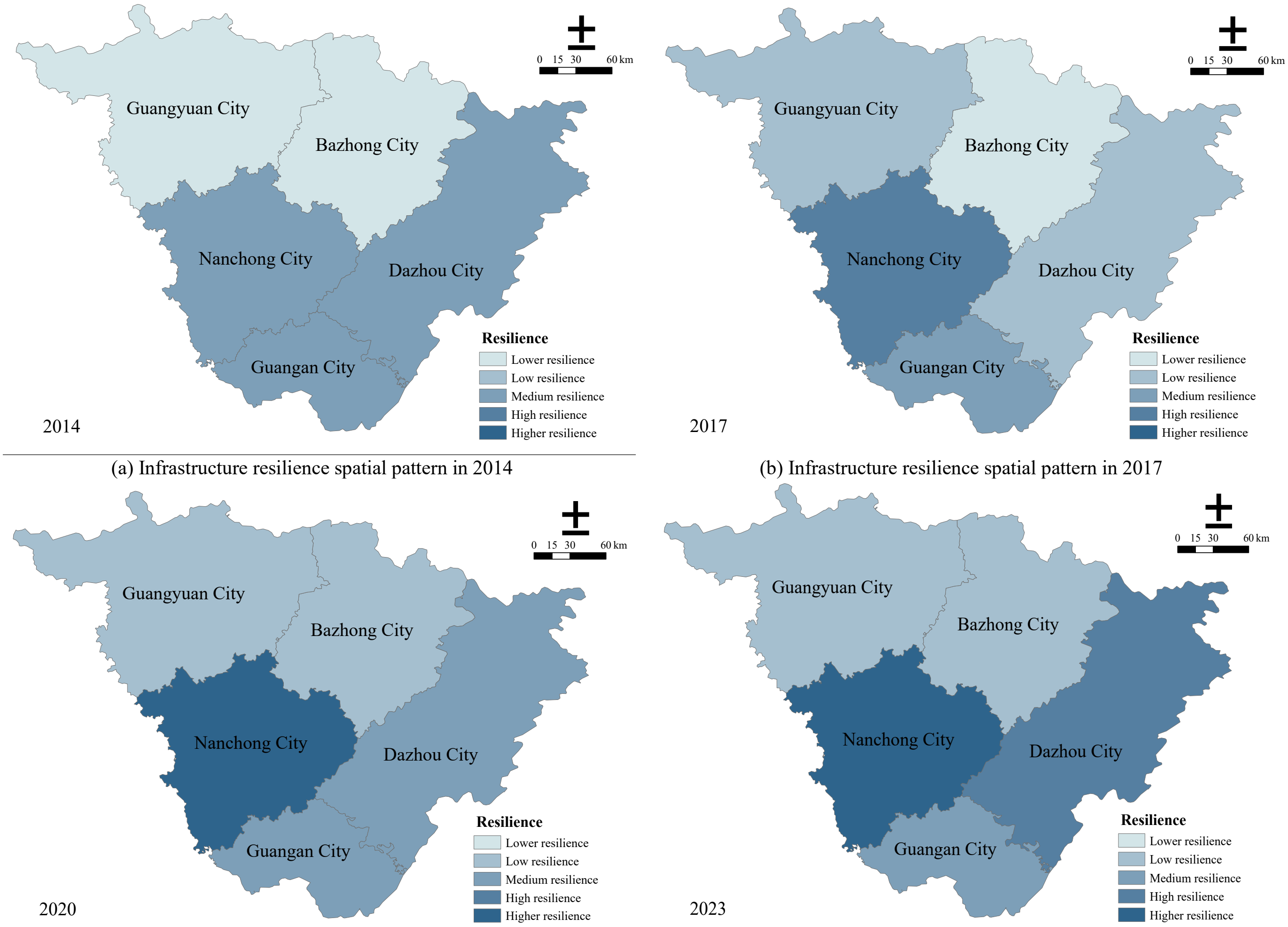
State resilience represents the ability of infrastructure systems to withstand external shocks or disturbances. As shown in Figure 3(b), the overall state resilience level in the Northeastern Sichuan Economic Zone increased steadily during the study period. In particular, Nanchong exhibited a substantial improvement in state resilience in the later years, indicating significant achievements in infrastructure construction and system robustness. In contrast, the development of state resilience in the other cities remained relatively consistent and closely aligned.

Response resilience reflects the capacity of urban infrastructure systems to recover from disruptions and respond to external challenges. According to Figure 3(c), response resilience levels across the region showed a marked upward trend. Dazhou and Nanchong consistently demonstrated higher response resilience compared to the other cities. This pattern is likely linked to the Development Plan for the Northeastern Sichuan Economic Zone, which outlines a "dual-core and three-belt" strategic development structure. By designating Nanchong and Dazhou as regional centers, this framework has led to a positive spillover effect that has enhanced infrastructure responsiveness in these key cities.



(a) Temporal Evolution of Stress Resilience (b) State Resilience Temporal Evolution (c) Resilience response temporal evolution

Figure 3: Temporal Evolution of Infrastructure Resilience Across the Pressure, State, and Response Dimensions



(a) Infrastructure resilience spatial pattern in 2014 (b) Infrastructure resilience spatial pattern in 2017

(c) Infrastructure resilience spatial pattern in 2020 (d) Infrastructure resilience spatial pattern in 2023

Figure 4: Spatial Patterns of Infrastructure Resilience in the Northeastern Sichuan Economic Zone (2014, 2017, 2020, and 2023)

4.2 Spatial Evolution of Infrastructure Resilience

To analyze the spatial dynamics of infrastructure resilience in the Northeastern Sichuan Economic Zone, spatial visualization was conducted using ArcGIS for the years 2014, 2017, 2020, and 2023, as shown in Figure 4. The Jenks Natural Breaks Classification method was adopted to categorize resilience levels into five classes: low, relatively low, moderate, relatively high, and high, as presented in Table 3.

Table 3: Urban Vulnerability Index Classification Criteria

Rank	*Lower resilience*	*Low resilience*	*Medium resilience*	*High resilience*	*Higher resilience*
Resilience Index	≤0.2648	0.2648 - 0.3614	0.3614 - 0.4231	0.4231 - 0.4696	≥0.4696

As illustrated in Figure 4(a), in 2014, Guangyuan and Bazhong were classified as low-resilience cities, while Nanchong, Guang'an, and Dazhou exhibited moderate resilience levels. By 2017, Bazhong remained at a low resilience level, but the other cities had all reached at least a moderate level, with Nanchong advancing to a relatively high resilience status, indicating growing spatial disparities across the region. In 2020, Nanchong achieved a high level of infrastructure resilience, and the number of low-resilience cities in the study area dropped to zero. By 2023, Dazhou also progressed to a relatively high resilience level, forming a "Dual-core" resilience development structure with Nanchong. These two cities demonstrated significantly higher resilience levels compared to the surrounding municipalities. Overall, infrastructure resilience development across cities in the Northeastern Sichuan Economic Zone showed substantial heterogeneity. Guangyuan and Bazhong lagged behind the other cities in terms of infrastructure improvement. Both are located at the northeastern periphery of Sichuan Province, geographically distant from the province's core economic zones. Their limited economic scale and relatively simple industrial structure have constrained infrastructure investment and development, thereby inhibiting resilience enhancement. Conversely, Nanchong and Dazhou, as the core cities of the region's "dual-core" development strategy, benefit from stronger economic capacity, a diversified industrial base, and critical positions as transportation hubs. These advantages enable greater financial investment, stronger industrial support, and more efficient resource allocation, thus promoting more robust and resilient infrastructure systems.

4.3 Obstacle Factor Analysis

The obstacle degree model was employed to identify and analyze the primary factors hindering infrastructure resilience in the Northeastern Sichuan Economic Zone.

4.3.1 Dimension-level obstacle analysis

Based on Equation (17), the obstacle degree of each indicator and the proportional contribution of each dimension to the overall obstacle level were calculated, as illustrated in Figure 5.

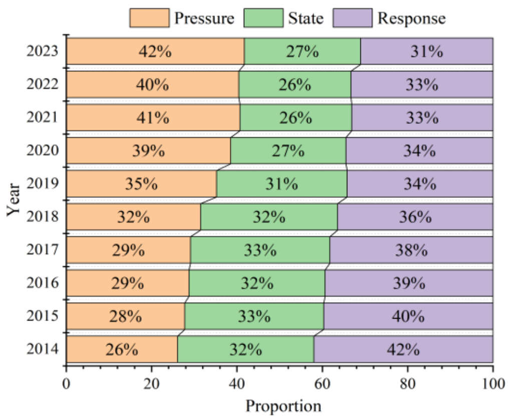


Figure 5: Obstacle Degree Levels of Pressure, State, and Response Dimensions in the Northeastern Sichuan Economic Zone (2014-2023)

During the period from 2014 to 2023, the Northeastern Sichuan Economic Zone experienced increasing natural pressure due to the frequent occurrence of extreme weather events. Concurrently, the continuous economic development of cities in the region led to intensified industrial activities, further exacerbating the pressure on infrastructure systems. The contribution of the pressure dimension to the overall obstacle degree exhibited a marked upward trend, rising from 26% in 2014 to 42% in 2023, thereby becoming the dominant constraint hindering infrastructure resilience improvement in the region.

4.3.2 Indicator-level obstacle analysis

Using the year 2023 as an example, the primary obstacle factors affecting infrastructure resilience in the Northeastern Sichuan Economic Zone were identified based on the calculated obstacle degrees, as presented in Table 3. The top six indicators with the highest obstacle degrees were: sulfur dioxide (SO_2) emissions (X7), the proportion of science and technology expenditure in local government budgets (X19), the supply of gas (natural gas and coal gas) (X11), average terrain slope (X3), total water supply (X10), and population density (X4). Sulfur dioxide (SO_2) emissions reflect the region's energy consumption patterns and industrial structure. Excessive emissions may indicate a reliance on high-pollution energy sources and traditional industries, thereby hindering the development of resilient infrastructure. Addressing environmental pollution and optimizing industrial composition are critical for mitigating this constraint. Investment in science and technology plays a pivotal role in enhancing infrastructure resilience by supporting advancements in construction technologies, smart monitoring systems, and emergency response capabilities. The availability of water and gas resources represents the foundational support for critical urban infrastructure systems such as heating, power supply, and transportation. Insufficient energy and water supply directly weakens system stability and adaptability. Average terrain slope reflects the complexity of the region's physical geography. Steeper terrain increases construction difficulty and cost, and complicates maintenance and management efforts, collectively lowering infrastructure resilience. Population density reflects the intensity of infrastructure demand. In highly populated areas, the pressure on transportation, water supply, electricity, and drainage systems is significantly higher, necessitating more robust and resilient infrastructure to ensure stable urban functioning.

Table 4: Obstacle degree of infrastructure resilience indicators in the Northeast Sichuan Economic Zone in 2023

Dimension	*Index*	*Obstacle degree*
Pressure	X1	1.82%
	X2	3.85%
	X3	**7.85%**
	X4	**5.76%**
	X5	4.66%
	X6	1.00%
	X7	**16.81%**
	X8	1.68%
State	X9	2.20%
	X10	**6.34%**
	X11	**8.57%**
	X12	0.70%
	X13	2.47%
	X14	4.08%
	X15	0.43%
	X16	0.74%
Response	X17	0.96%
	X18	4.46%
	X19	**16.54%**
	X20	1.81%
	X21	3.78%
	X22	0.93%
	X23	2.56%

5. Conclusion

This study constructs an infrastructure resilience evaluation model for the Northeastern Sichuan Economic Zone based on the Pressure-State-Response (PSR) analytical framework, incorporating three core dimensions: pressure, state, and response. A combined weighting approach-integrating factor analysis and the entropy method-was applied and further refined using game-theoretic optimization to ensure objectivity and robustness in the assignment of indicator weights. Spatial distribution patterns of infrastructure resilience were visualized through ArcGIS, while the obstacle degree model was employed to systematically identify the principal limiting factors hindering resilience enhancement. The major findings of the study are summarized as follows:

(1) Temporal analysis reveals that the overall infrastructure resilience level in the Northeastern Sichuan Economic Zone has exhibited a steady upward trend from 2014 to 2023. However, significant disparities exist among cities in terms of growth magnitude and fluctuation patterns. Notably, Nanchong demonstrated the most substantial improvement in resilience, whereas Bazhong and Guangyuan still exhibit considerable potential for enhancement.

(2) Spatial analysis indicates that the overall resilience level across the region has improved substantially during the study period, forming a “dual-core” development pattern centered on Nanchong and Dazhou. Nevertheless, the spillover effect of this pattern remains limited. By 2023, only Nanchong and Dazhou had attained high resilience levels, while the remaining cities still ranked at moderate or lower levels of resilience.

(3) Obstacle degree analysis identifies the pressure dimension as the primary constraint on infrastructure resilience improvement in the region. Key inhibiting factors include sulfur dioxide (SO_2) emissions, the proportion of science and technology expenditure in local government budgets, the supply of gas and water resources, average terrain slope, and population density. These indicators substantially affect infrastructure resilience and should be addressed through targeted policy measures such as industrial restructuring, increased investment in science and technology, and optimized population spatial planning.

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