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Posted Date: April 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9071027/v1>

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Additional Declarations: No competing interests reported.

Analysis Of the Network and Influencing Factors of Urban Resilience: A Case the Chengdu-Chongqing Urban Agglomeration

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Abstract

As a national strategic growth pole, the urban resilience of the Chengdu Chongqing urban agglomeration is related to regional coordination and national security. Based on panel data from 16 cities from 2009 to 2023, entropy weight method, kernel density estimation, social network analysis, and geographic detector were used to explore the spatial correlation characteristics and influencing factors of resilience. Research has found that resilience has improved across the entire region, but at multiple levels of differentiation, with a spatial pattern of "dual core aggregation edge diffusion" and "high outside and low inside" concentric circles; The interconnected network continues to strengthen, the core edge structure weakens, Chongqing and Chengdu dominate resource flow, and the emerging hub transmission function is beginning to emerge, but there are isolated nodes disconnected. Although cohesive subgroups have shifted from fragmentation to functional collaboration, weak connections between subgroups constrain collaborative efficiency. Geographic detectors show that economic, social, and natural factors affect the level of urban resilience, with social and economic interactions having the most significant impact, while natural factors have a weaker direct influence.

Keywords: Urban agglomeration; Urban resilience; Spatial correlation network; Influencing factors; Social network analysis

1. Introduction

Against the backdrop of intensifying global climate change and uncertainty risks, urban resilience has emerged as a core issue in sustainable development. Urban resilience refers to a city's fundamental capacity to maintain functionality, adapt to change, and achieve sustainable development when subjected to external shocks. In recent years, the frequent occurrence of extreme natural disasters worldwide has caused severe destruction and economic losses. As modern cities develop, the interconnections within and between their systems grow increasingly complex. How to withstand shocks after disasters, restore the normal functioning of urban systems, and prepare for future risks has become a major research topic.

Cities are not isolated entities; their capacity to withstand shocks and recover is

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closely tied to their spatial networks. Traditional resilience-building approaches focused solely on individual cities are increasingly inadequate for addressing risks. Therefore, strengthening spatial interconnections among cities within urban agglomeration is crucial for establishing efficient, collaborative regional resilience systems that share risks. However, current research has insufficiently emphasized the interconnected spatial resilience networks within urban agglomeration. At the same time, clarifying the influencing factors and mechanisms of urban resilience in urban agglomerations is a prerequisite for addressing how to enhance urban resilience. Existing studies have predominantly focused on the impact of single factors on the dependent variable within traditional spatial econometric models, with few investigations examining the role of interaction effects among factors.

In summary, existing literature on the spatial network structure of intercity urban resilience within urban agglomerations and its influencing factors has certain limitations. Few studies have examined whether a spatial network structure of urban resilience exists among cities in an agglomeration, and even fewer have employed Geographical detector to investigate the driving factors in Chengdu-Chongqing urban agglomeration. Given that these two issues remain underexplored, this paper combines theoretical and empirical approaches to address the following questions: (1) Does a spatial network structure of urban resilience exist within the Chengdu-Chongqing urban agglomeration, that is, do intercity linkages exist? (2) Do the roles of individual nodes in the urban resilience spatial association network exhibit heterogeneity? (3) What factors influence urban resilience?

This study offers several novel contributions. First, in terms of research perspective, it shifts focus beyond the Yangtze River Delta [1] and Beijing-Tianjin-Hebei [2] regions to examine the Chengdu-Chongqing urban agglomeration—a key area in western China—exploring its evolution through a spatial network lens. Second, in terms of methodology, while previous studies predominantly relied on traditional econometric approaches, this paper integrates interdisciplinary perspectives from economics and sociology. Utilizing ArcGIS and UCINET software, it examines the spatiotemporal evolution and spatial network dynamics of urban resilience, presenting its transformation through multiple dimensions and identifying key influencing factors. Finally, regarding research methodology, earlier studies often measured inter-city connectivity using straight-line distances, which lacked authenticity. This paper employs the shortest highway distances between cities within the Chengdu-Chongqing agglomeration and modifies the gravity model to achieve more precise results.

The structure of this study is as follows: Section 2 presents a comprehensive literature review; Section 3 introduces the research design and methodology; Section 4 analyzes empirical findings; Section 5 discusses the results; and the final section provides a conclusion. The research framework is shown in Figure.1.

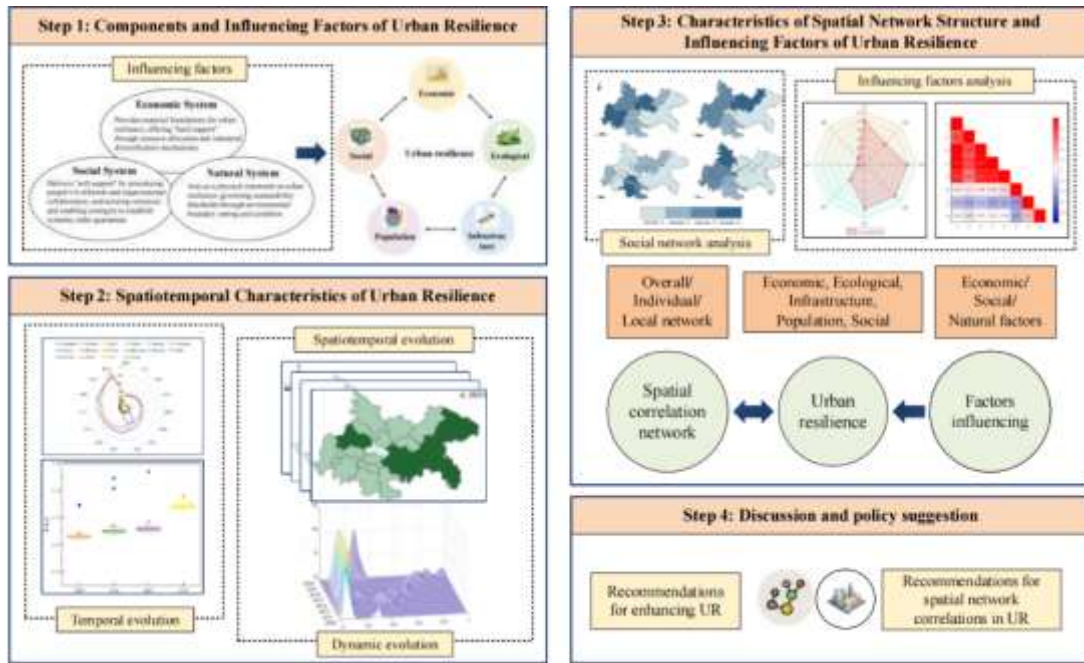


Figure. 1 Research framework

2. Theoretical derivation

2.1 Theoretical framework and research progress on urban resilience

The term “resilience” originates from Latin, meaning to return to its original state. Urban resilience is understood as a city's core capacity to maintain functionality, adapt to change, and achieve sustainable development when subjected to external shocks. As researchers have explored urban resilience, its application has broadened significantly, appearing frequently in disciplines such as economics, sociology, geography, and disaster studies. Each field defines the concept of urban resilience differently. Sociologists argue that cities possess dual attributes: sustainable physical systems and human communities. The planning of physical systems relies on human communities to function effectively [3]. Disaster studies researchers define urban resilience as encompassing four key dimensions: infrastructure resilience, institutional resilience, economic resilience, and social resilience. It represents a city's capacity to promptly resist, withstand, and recover from the impacts of disasters once exposed to society [4]. Geographical researchers view urban resilience as a systemic capability to maintain or rapidly restore functionality and dynamically transform development patterns after experiencing disturbances across spatiotemporal dimensions [5]. Through the above conceptual clarification, urban resilience represents a city's capacity to achieve sustainable development through structural adjustments and resource reallocation when confronting multiple shocks from natural, economic, and social sources.

Reviewing existing literature, research on urban resilience mainly focuses on the following points. One is the comprehensive calculation and spatiotemporal evolution analysis of urban resilience. Combining BP neural network and genetic algorithm to construct an urban resilience measurement model for measuring the resilience of the Chengdu Chongqing urban agglomeration [6]. Measuring the urban resilience of the Yangtze River Delta urban agglomeration from the perspective of coupling

coordination degree. [7]. The level of urban resilience is measured based on the TOPSIS method, Particle Swarm Optimization (PSO), and Extreme Learning Machine (ELM). [8]. Using the entropy weight method to measure the level of urban resilience, and combining it with the spatial hot and cold spot model to study the spatial characteristics of urban resilience [9]. By integrating the Functional Resonance Analysis Method (FRAM), Modified K-shell (MKS) decomposition algorithm, and Bayesian Networks (BNs), the evolution and patterns of urban resilience are revealed. [10]. The second is to further analyze the factors that affect the development of urban resilience based on spatiotemporal evolution. By embedding the "Density-Structure-Function (D-S-F)" framework and combining it with the Geographically Weighted Random Forest (GWRf), this study identifies the influencing factors of urban resilience [11]. Exploring the influencing factors of urban resilience through geographic and time weighted regression models [12]. Through literature review and Delphi method, identify influencing factors under the 4R framework, and use DEMATEL and ISM methods to study their influencing mechanisms [13]. By constructing a five-dimensional indicator system encompassing economic, social, institutional, ecological, and infrastructure dimensions to evaluate urban resilience, and conducts a resilience obstacle factor analysis to provide decision-making support for the construction of resilient cities [14]. The third is the analysis of the resilience spatial correlation network of urban agglomerations. Employing Social Network Analysis (SNA), it reveals the structural characteristics of resilience spatial configuration, and further integrates QAP regression to explore the drivers underlying spatial correlation [15]. Existing literature mostly focuses on the static description of urban resilience, and there is relatively little research on urban resilience from the perspective of potential connections between cities. Moreover, there is little research on the factors affecting urban resilience in the Chengdu Chongqing urban agglomeration using geographic detectors.

2.2 The association and interaction between urban resilience and spatial structure

Urban resilience, as the dynamic equilibrium capacity of complex open systems, emerges and evolves within the organizational framework of spatial structures. Theoretically, the relationship between urban resilience and spatial structure constitutes a bidirectional interactive mechanism of mutual support and synergy.

Spatial structure serves as the foundational carrier of urban resilience. Cities are not isolated systems but rely on spatial structures to achieve coordinated development through factor flows, functional complementarity, and shared risk-bearing. First, spatial linkage expands resilience boundaries. Inter-city spatial connections via transportation networks, industrial collaboration, market exchanges, and ecological co-defense overcome developmental limitations, influencing not only local resilience levels but also surrounding regions. For instance, research on the impact mechanisms of economic restructuring on urban economic resilience, combined with spatial econometric models to decompose effects, reveals that adjustments in industrial, factor, and consumption structures enhance resilience locally while producing varying effects on other cities [16]. Second, network structure determines resilience thresholds. Tighter inter-network connections, higher inter-city link counts, and closer urban associations foster stronger synergies. This enables more effective risk sharing and ecological co-defense, allowing

cities to adapt swiftly to external shocks and achieve sustainable development—thus fortifying urban resilience. For instance, social network analysis of resilience linkages within urban agglomeration along the Yellow River basin revealed increasing network density and connection strength, facilitating frequent resource transfers. This context enables enhanced inter-city coordination and shared risk-bearing [17]. Finally, spatial heterogeneity reflects variations in urban resilience. Spatial structure analysis effectively identifies core and peripheral cities. By integrating city-specific characteristics to develop feasible strategies, this approach improves development trajectories and enhances resilience levels. Urban resilience also influences spatial structures, driving their dynamic evolution. For instance, highly resilient cities catalyze the transformation of surrounding less resilient cities through technological spillovers and industrial collaboration, forming a “one primary, two secondary” spatial linkage structure [18]. The hierarchical structure of urban resilience exhibits dual-core driving patterns, olive-shaped structures, and pyramid-shaped structures [19]. Multidirectional connections between node cities continuously expand horizontally and extend vertically, forming a multi-node, multi-chain spatial association network structure for urban resilience.

2.3 Theoretical analysis of influencing factors of urban resilience

Identifying the full range of factors that influence urban resilience is essential to enhancing it. However, existing studies have predominantly employed spatial panel econometric models to examine the drivers of urban resilience in urban agglomerations, focusing on the marginal effects of individual factors on the dependent variable, with limited attention to the synergistic effects of multi-factor interactions on urban resilience. In reality, the complexity of urban systems is typically shaped by the co-evolution of economic, social, and natural dimensions; it is not a simple linear superposition but is instead characterized by nonlinear relationships generated through interactions among factors. Geographical Detector offers a viable solution by detecting spatial heterogeneity and quantifying the interactive explanatory power of multiple factors on urban resilience. In terms of influencing factors, the STIRPAT model was constructed to study the ecological resilience of the Yangtze River Delta from geographical, economic, and social perspectives [20,21]. Viewing cities as complex systems, the S-DReP framework is constructed to study urban resilience from three aspects: social, economic, and ecological [22]. To explore the role of green infrastructure in promoting resilience of social ecosystems, resilience is assessed from social, economic, and ecological perspectives [23]. The underlying mechanisms are as follows: the economic system provides the material foundation for urban resilience, delivering “hard support” through mechanisms such as resource allocation and industrial diversification; the social system offers “soft support” by focusing on public well-being and organizational coordination to enable resource reallocation and collaboration, thereby ensuring the order necessary for resilience; the natural system constitutes the physical foundation of urban resilience, shaping resilience levels by setting boundary conditions and constraints.

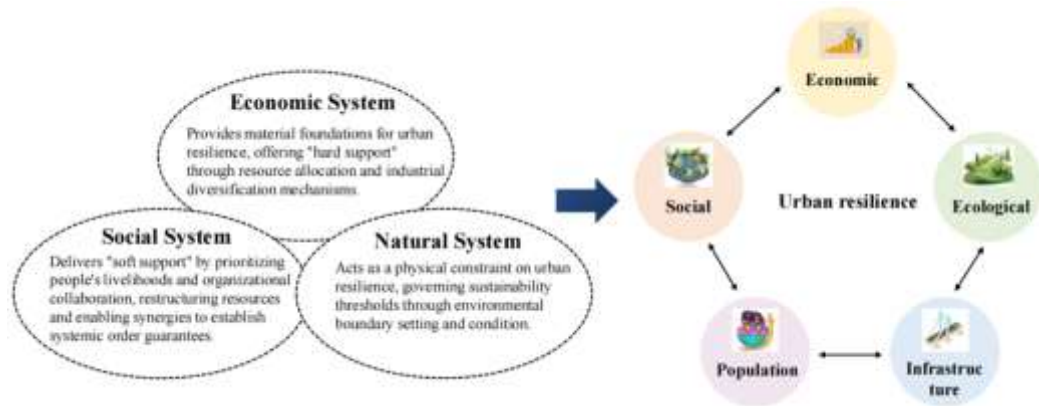


Figure. 2 Theoretical derivation

3. Research design and methodology

3.1 Study area

The study area consists of 16 cities in the Chengdu-Chongqing urban agglomeration, seeing Figure 3. The study period spans from 2009 to 2023, with data sourced from the Statistical Yearbook of Sichuan Province, Statistical Yearbook of Chongqing Municipality, and Statistical Yearbook of Chinese Cities. Missing data were imputed using interpolation methods.

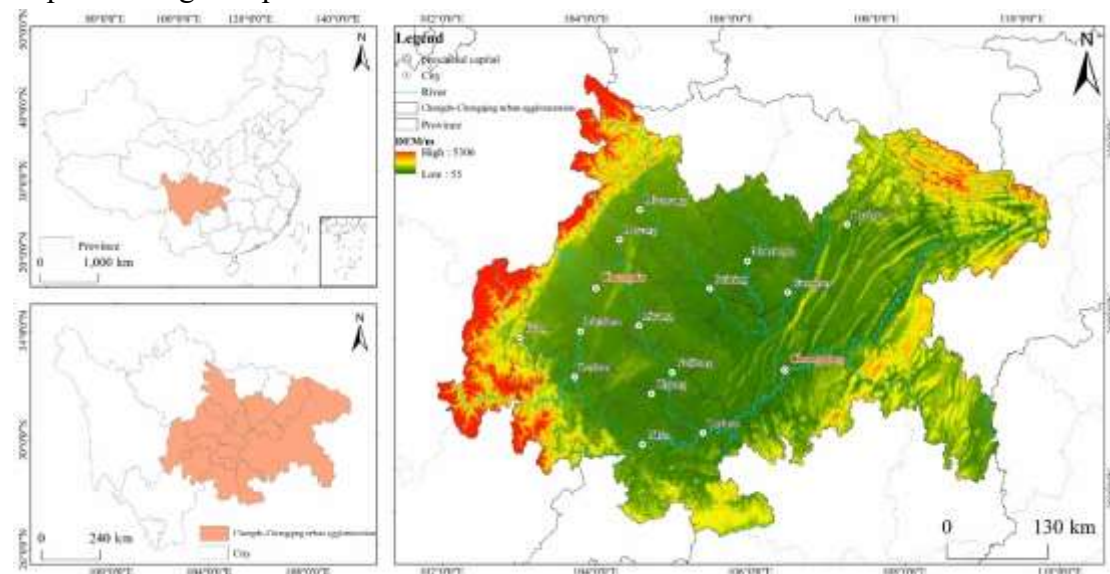


Figure. 3 Research location

3.2 Index system

Urban resilience manifests as the capacity of urban systems to achieve sustainable evolution through structural adjustments and resource reorganization when confronting compound shocks across natural, economic, and social domains. Its assessment cannot rely solely on a single dimension but must integrate the synergistic effects of diverse subsystems-including economic foundations, ecological bases, infrastructure safeguards, population vitality, and social networks-ultimately forming a compound system characterized by “shock resistance, self-repair, and sustainability.” Drawing on the methodologies for constructing urban resilience indicator systems proposed by CUMMING G S et al. [24], Datola G [25] JABAREEN Y [26], Burton C G [27], Cutter

S L [28]and comprehensively considering the development levels of Chinese cities, indicators were selected adhering to principles of systematicity, scientific rigor, representativeness, and accessibility. This study comprehensively constructs the Chengdu-Chongqing urban agglomeration resilience indicator system based on five primary indicators: economic resilience, ecological resilience, infrastructure resilience, population resilience, and social resilience. A total of 20 indicators were selected, as shown in Table 1. Among these, economic resilience provides sufficient momentum for the economic system; ecological resilience ensures sustainability for the ecological system; infrastructure resilience provides disaster resistance for infrastructure; demographic resilience fosters innovation vitality for the population system; and social resilience enhances coordination and cohesion for social governance.

Table 1 Urban resilience indicator system

Criteria layer	Indicator layer	Type	Weight
Economic resilience	GDP per capital	+	0.029
	Disposable income per capital	+	0.026
	Total retail sales of consumer goods	+	0.108
	Tertiary industry share	+	0.014
Ecological resilience	Green coverage rate of built-up area	+	0.004
	Centralized sewage treatment rate	+	0.003
	Sanitary treatment rate of domestic waste	+	0.002
	Industrial sulfur dioxide emissions	-	0.003
Infrastructure resilience	Urban road density	+	0.056
	Mobile phone subscribers at year-end	+	0.091
	Gas coverage rate	+	0.006
	Highway freight volume	+	0.131
Population resilience	Population density	+	0.028
	Number of college students per 10000 people	+	0.054
	Tertiary industry employment share	+	0.206
	Natural population growth rate	+	0.006
Social resilience	Healthcare institution beds	+	0.082
	Urban registered unemployment rate	-	0.012
	Proportion of education expenditure in total fiscal expenditure	+	0.012
	Urban employees covered by basic pension insurance	+	0.129

3.3 Methodology

3.3.1 Core indicator calculation

The selection of urban resilience indicators has been described above. In this research, the entropy method was employed to calculate the weight of each subsystem of urban resilience and its associated indicators. The detailed process is omitted.

3.3.2 Gravity model

Based on the research by Li Z et al. [29], the traditional gravity model was modified. The formula for the modified gravity model is as follows:

$$F_{ij} = K_{ij} \frac{G_i \cdot G_j}{D_{ij}^2}, \quad K_{ij} = \frac{G_i}{G_i + G_j} \quad (1)$$

$$F(i,j) = \begin{cases} 0 & f_{ij} < Y \\ 1 & f_{ij} > Y \end{cases} \quad (2)$$

F_{ij} represents the spatial correlation of resilience between cities i and j , K_{ij} is the gravitational coefficient, G_i and G_j are the resilience values of the two cities, and D_{ij} denotes the distance between them. Early studies used straight-line distance for measurement, which fails to reflect the real distance; this paper measures it by the shortest highway distance between cities in the Chengdu-Chongqing Urban Agglomeration. A spatial correlation network matrix is obtained using a modified gravity model. Using the "mean principle method", binarization is performed with the annual average resilience value Y as the threshold: assign 1 if greater than Y , and 0 otherwise. Since the resilience correlation between cities is directed, the matrix is asymmetric.

3.3.3 Social network analysis

Social network analysis models incorporate "relationships" into economic analysis frameworks, employing data analysis to explore actor behavior and assess individual importance within networks. This paper examines the spatial resilience network of the Chengdu-Chongqing urban agglomeration from three perspectives: holistic, individual, and local network.

(1) Overall network characteristics

Five key indicators are employed to characterize the overall network structure: network density, network connectivity, network efficiency, network hierarchy, and network connectivity number. Network density measures the closeness of connections between nodes; network connectivity number quantifies the number of links between nodes; network efficiency assesses the effectiveness of information transmission within the network; and network hierarchy reflects the hierarchical structure of the network.

$$D = \frac{I}{N(N-1)} \quad (3)$$

$$C = 1 - \frac{V}{\left[\frac{N(N-1)}{2} \right]} \quad (4)$$

In the formula: I represents the actual number of associations within the association network; N denotes the number of nodes in the network; V indicates the number of nodes in the network that cannot establish associations.

(2) Individual network characteristics

This paper employs degree centrality, closeness centrality, betweenness centrality, and core-periphery structure to characterize individual network features. Degree centrality measures a node's importance within the network, with higher values indicating greater prominence; Closeness centrality measures a node's proximity to other nodes; higher values indicate more relationships originating from the node and a more prominent "central actor" status. Betweenness centrality measures a node's bridging role in the network; higher values indicate more elements passing through the node and a more pronounced intermediary effect. Core-periphery analysis is used to identify core and peripheral cities within the resilience spatial network of the Chengdu-Chongqing urban agglomeration.

(3) Local network characteristics

This study employs cohesive clusters to characterize local network features, identifying tightly knit subgroups within the network. Higher density within a cohesive cluster indicates denser connections among its members, reflecting frequent interaction and collaboration.

3.3.4 Geographic detector

Geographical Detector can test the spatial stratified heterogeneity of a single variable and, by examining the coupling of two variables' spatial distributions, detect possible causal relationships between them. Applying this method enables a more robust identification of the explanatory power of each factor on urban resilience in urban agglomerations, thereby revealing the driving mechanisms underlying the spatio-temporal differentiation of urban resilience in the Chengdu-Chongqing urban agglomeration. Accordingly, this study develops an influencing-factor framework from the economic, social, and natural dimensions and specifies the following model; variable definitions are provided in Table 2.

$$RE = f(Economy, Society, Nature) \quad (5)$$

Table 2 Influencing factors of urban resilience

Definition	Explanation	Unit
Economy	Year-end outstanding balance of RMB loans of financial institutions (x1)	100 million yuan
	Share of tertiary industry added value in GDP (x2)	%
	Number of participants in urban employee basic pension insurance (x3)	persons
Society	Science and technology expenditure (x4)	10,000 yuan
	Urbanization rate (x5)	%
Nature	Terrain relief (x6)	meters
	Annual mean temperature (x7)	degrees Celsius
	Annual mean concentration of fine particulate matter (x8)	micrograms per cubic meter

4. Results

4.1 Spatiotemporal characteristics of urban resilience

4.1.1 Temporal evolution trends of urban resilience

Focusing on the period from 2009-2023, this study examines the evolution of urban resilience. As shown in Figure.4. Overall, there are substantial disparities in resilience across regions, with the majority of areas remaining at a relatively low level. Horizontal comparisons indicate that Chengdu and Chongqing consistently lead in resilience, underpinned by their notable advantages in the economy, cultural tourism, and regional development strategies, which provide strong momentum for resilience. Vertical comparisons show that most regions experienced a steady upward trend, with a marked improvement in resilience levels observed in 2023.

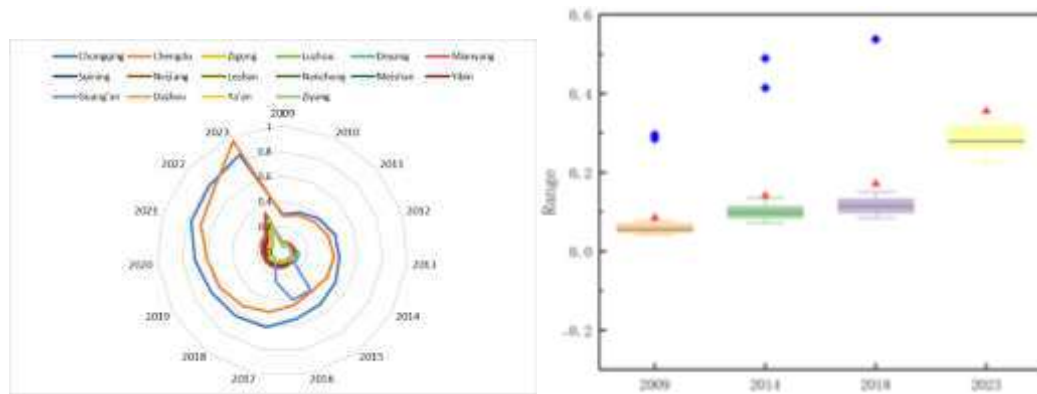


Figure.4 Temporal evolution trends of urban resilience

4.1.2 Spatial evolution trends of urban resilience

Using the natural breakpoint method in ArcGIS software, urban resilience levels are categorized into five zones- low, medium-low, medium, medium-high and high -for visual representation, and choose the years 2009, 2014, 2018, and 2023. This approach analyzes spatial evolution patterns and generates a resilience grading table and visualization map. As shown in Figure.5, the charts reveal significant development disparities among regions in recent years. While most areas show an upward trend in resilience levels, they predominantly remain at low resilience tiers.

Overall, the resilience development of the Chengdu-Chongqing urban agglomeration follows a spatial evolution pattern characterized by “growth pole concentration in the core zone and diffusion-differentiation in peripheral areas.” Chongqing and Chengdu have consistently led in urban resilience development, maintaining a prominent core position. Over time, while other cities have seen improvements in their resilience ratings, they remain at relatively low levels. The disparities between cities are pronounced, reflecting uneven development and a spatial manifestation of the Matthew Effect: “the strong grow stronger, the weak remain weak.”

By year: In 2009, resilience levels were relatively uniform across cities, with Chongqing and Chengdu leading. By 2014, a pattern of “initial dual-core clustering with emerging core-periphery differentiation” emerged. Chongqing and Chengdu exhibited moderate resilience, while all other cities remained at low resilience levels. By 2018, Chongqing and Chengdu exhibited higher resilience, with intensified core polarization, though the overall pattern remained dominated by isolated dual-core clusters. By 2023, Chongqing and Chengdu achieved high resilience, with enhanced resilience in the “intermediate zone” between the dual cores. Surrounding cities also showed gradual development, yet the overall distribution exhibited a concentric pattern of “higher resilience externally, lower internally,” gradually forming a layered development trend.

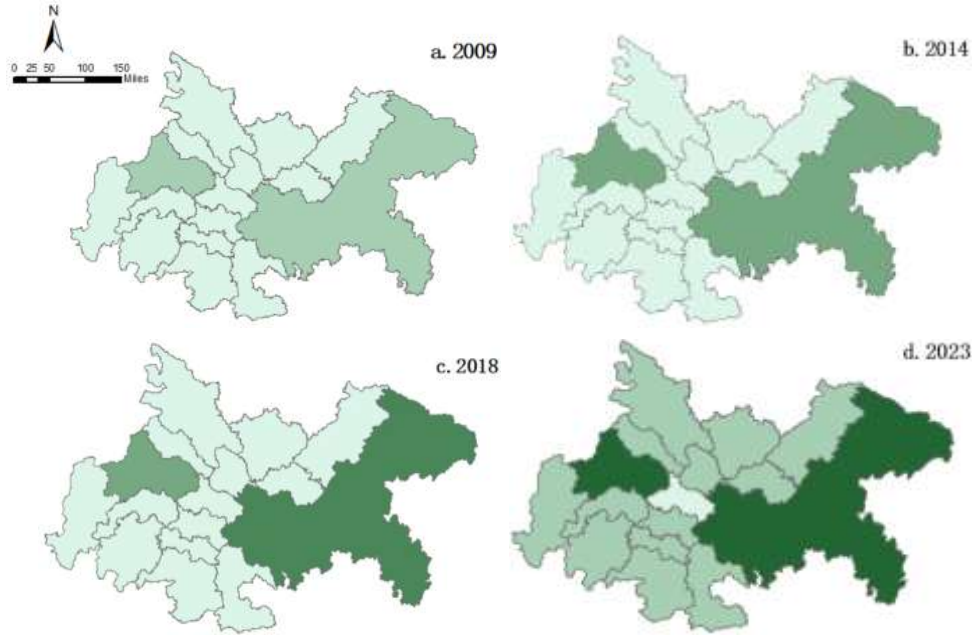


Figure.5 Spatial evolution trends of urban resilience

4.1.3 Dynamic evolution of urban resilience

This study employs nonparametric kernel density estimation (KDE) and uses 2009, 2014, 2018, and 2023 as time benchmarks. As shown in Figure.6, from the perspective of curve position, the curves shift progressively to the right, indicating a gradual rise in the overall level of urban resilience; from the perspective of peaks, the curves evolve from narrow peaks to broader peaks and exhibit multiple peaks, reflecting the emergence of multipolar differentiation; from the perspective of distribution tails, the presence of long right tails suggests substantial disparities in resilience across regions and heterogeneity in capabilities.

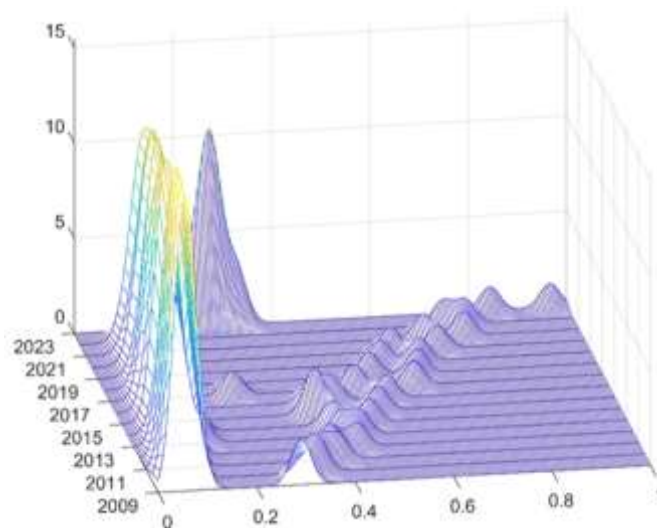


Figure.6 Dynamic evolution trends of urban resilience

4.2 Spatial correlation network analysis of urban resilience

To better analyze the spatiotemporal evolution patterns of resilience connections within the Chengdu-Chongqing urban agglomeration, this study constructs spatial association networks for urban resilience at three levels: the overall network, individual

nodes, and local regions. By integrating resilience with urban network structures, it aims to enhance inter-city connectivity and coordination, thereby elevating the cluster's overall resilience.

4.2.1 Overall network structure characteristics

Using UCINET software, we constructed a network association structure diagram for 2023 and calculated the network structural characteristics during the study period. As shown in Figure.7. Network density, which measures the closeness of connections between nodes, showed an upward trend during the study period, increasing from 0.208 to 0.25. The number of network relationships also rose, growing from 50 to 60. This trend was particularly pronounced between 2018 and 2023, primarily driven by the 2020 establishment of the Chengdu-Chongqing Economic Circle, which facilitated resource flows between cities and strengthened spatial connections. These findings indicate that spatial connections in urban resilience within the Chengdu-Chongqing urban agglomeration are steadily strengthening. However, overall connectivity remains relatively low: while the maximum possible number of relationships among all cities is 240 (16×15), the highest observed network relationship count during the sample period was only 60. This suggests that current resilience-related interactions between cities are loosely connected, indicating substantial potential for enhancing spatial network ties within the agglomeration. Network relationship degree calculations show a consistent value of 1 from 2009 to 2023, indicating strong spatial connectivity in resilience among Chengdu-Chongqing cities, with pronounced spatial correlation and spillover effects. Network degree, reflecting hierarchical structure, decreased from 0.486 in 2014 to 0.125 in 2023, signifying a flattening network hierarchy. Urban development no longer relies on monopolistic growth at single points but shifts toward hub-based collaborative development. The influence of core nodes gradually radiates to secondary and peripheral cities, breaking the “core-periphery” constraints and evolving toward a favorable trend of equalization and parity. Network efficiency, measuring the effectiveness of information transmission, remains stable at around 0.8, indicating relatively stable inter-network connections.

In summary, this article believes that the implementation of government policies, the reconstruction of the industrial chain, and the free flow of factors have led to a relatively low level of spatial connectivity in the Chengdu Chongqing urban agglomeration, but overall, it is continuously strengthening its connections with cities. The connections between networks are relatively stable and gradually breaking the "core periphery" shackles, promoting coordinated development between cities.

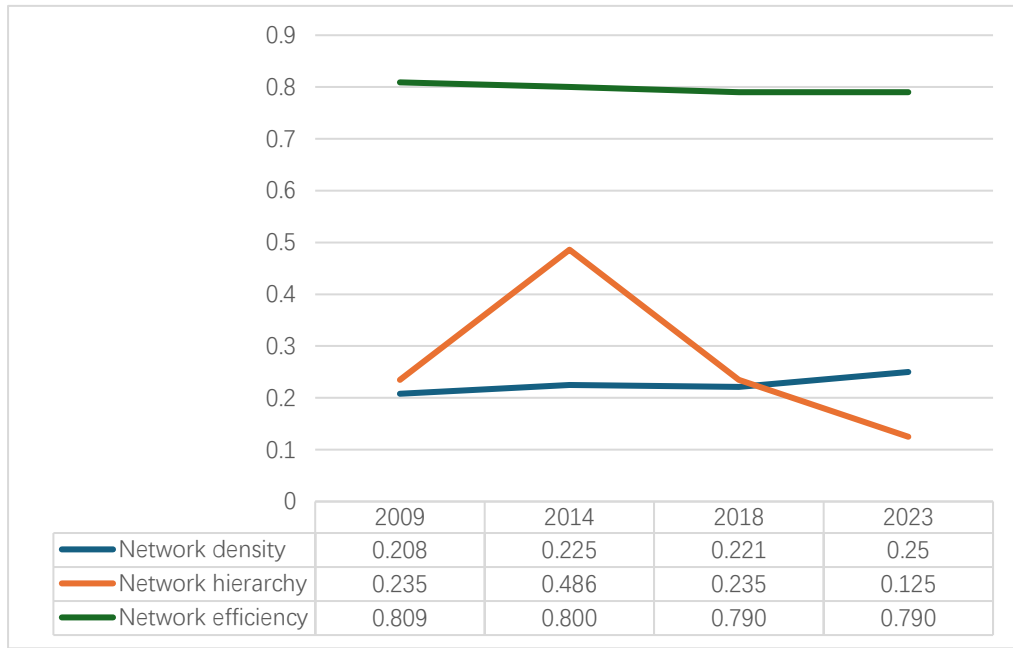


Figure.7 Overall network structure characteristics

4.2.2 Individual network structure characteristics

The overall network structure analysis can only broadly reveal the spatial network characteristics of urban resilience within the Chengdu-Chongqing urban agglomeration, failing to reflect the status and role of individual cities within the network. Therefore, this section conducts an individual network structure analysis using mean values as a reference. Network centrality analysis is performed by measuring degree centrality, betweenness centrality, closeness centrality, and core-periphery analysis to reveal the role of each city in constructing the spatial association network of urban resilience. As shown in Table 3. Due to space constraints, only the results for 2023 are presented for selected procedures.

Table 3 Individual network structure

	Degree Centrality		Betweenness Centrality	Closeness Centrality	
	Out-degree	In-degree		Out-degree	In-degree
Chongqing	2	10	53.00	30.61	75.00
Chengdu	7	13	109.83	35.71	88.23
Zigong	6	4	17.83	36.58	42.85
Luzhou	5	3	0.00	35.71	32.60
Deyang	2	2	0.00	27.77	50.00
Mianyang	2	2	0.00	27.77	50.00
Suining	3	1	0.00	31.91	25.42
Neijiang	6	4	13.50	36.58	41.66
Leshan	4	4	22.33	32.60	53.57
Nanchong	4	2	20.00	32.60	33.33
Meishan	4	4	2.33	31.25	53.57
Yibin	5	3	0.00	35.71	32.60
Guang'an	2	2	26.00	25.86	45.45
Dazhou	1	0	0.00	31.25	6.25
Ya'an	3	3	0.00	30.00	51.72
Ziyang	4	3	21.16	34.88	51.72

(1) Degree centrality analysis

Degree centrality measures a node's importance within a network; a higher degree centrality indicates a more prominent position. Given the directed nature of resilience connections within the Chengdu-Chongqing urban agglomeration, degree centrality is divided into out-degree centrality and in-degree centrality. Out-degree centrality represents the number of connections a node actively establishes with other nodes, while in-degree centrality reflects the number of connections initiated by other nodes toward that node. During the observation period, both in-degree and out-degree showed minimal variation among cities, with most values clustering near the mean. Analyzing out-degree reveals that Chengdu, Zigong, Luzhou, Neijiang, Nanchong, and Yibin exhibit out-degrees above the mean. This indicates these cities demonstrate greater proactivity within the network, actively engaging in external interactions and facilitating industrial radiation. Regarding in-degree, only Chongqing and Chengdu exceeded the mean, indicating these cities possess the strongest attractiveness within the network. Other cities send the most connection signals to them, making them resource hubs with advantages in factor aggregation and inter-city dependency. Analyzing by city: Chongqing exhibits relatively high in-degree but low out-degree, suggesting it tends toward “passive connectivity” rather than “active connectivity”; Chengdu exhibits high both inbound and outbound connectivity, positioning it as both an “active contributor” and a “core hub.” In contrast, Suining, Dazhou, and Ya'an display low inbound and outbound connectivity. Due to their greater distance from the “dual-core” cities, the latter's driving influence is limited. Combined with their own developmental shortcomings, these cities can only passively receive connections from

others and are unable to actively pursue collaborative development with neighboring regions.

(2) Proximity to centrality analysis

Proximity to centrality measures a node's closeness to other nodes. Higher values indicate greater relationship generation and more prominent status as a “central actor.” During the observation period, cities within the Chengdu-Chongqing urban agglomeration exhibited comparable levels of out-proximity to centrality, all clustering near the mean. This suggests each city maintains effective connections with others and possesses strong proactive networking capabilities. However, significant variations exist in the cities' in-centrivity levels. Only Chongqing, Chengdu, Deyang, Mianyang, Leshan, Meishan, Guang'an, and Ziyang exhibit in-centrivity values above the mean. This highlights their more pronounced status as “central actors,” with other cities demonstrating greater willingness to establish relationships with them. This phenomenon stems from these cities' superior efficiency in facilitating flows with others, coupled with their robust capacity to acquire resources. Chongqing and Chengdu exhibit the highest in-degree centrality values, further underscoring their core positions. Conversely, cities like Dazhou display extremely low in-degree centrality, with values significantly below the average. This indicates that Dazhou, constrained by its economic development level and geographical location, functions as a peripheral actor within the network.

(3) Intermediary Centrality Analysis

Intermediary centrality measures a node's role as a bridge within a network. Higher values indicate greater flow of elements through the node and more pronounced intermediary effects. Based on the results from the observation period, the top five cities ranked by intermediary centrality in overall development trends are: Chengdu, Chongqing, Guang'an, Ziyang, and Zigong. Cities exceeding the average intermediary centrality for the year include Chongqing, Chengdu, Neijiang, and Ziyang. This indicates these cities effectively connect with others in constructing spatial networks for urban resilience, serving as “bridges” in spatial relationships. Cities with an intermediary centrality of 0, such as Luzhou, Deyang, Mianyang, Suining, Meishan, Yibin, Dazhou, and Ya'an, exhibit low control capacity within the network and show insignificant connections with other cities. Chongqing and Chengdu, as the two cities with the highest intermediary centrality during the study period, accounted for 49.3% (2009), 70.1% (2014), 53.7% (2018), and 57.2% (2023) of the total intermediary centrality. This demonstrates their core status and control power, as well as their pivotal role as the most important “bridges.” Meanwhile, cities like Neijiang, Nanchong, and Guang'an have seen steadily rising intermediary centrality values in recent years, gradually emerging as new intermediary nodes. Conversely, weak intermediaries/non-intermediaries such as Luzhou, Deyang, Mianyang, Suining, Yibin, and Ya'an exhibit extremely limited intermediary functions. Comparative analysis across cities reveals pronounced regional patterns of control and subordination. The uneven distribution of intermediary centrality among cities may hinder effective inter-city development and cooperation. Moving forward, intermediary cities at all tiers should align with regional development strategies: Secondary intermediary cities should enhance connectivity

with others through infrastructure and industrial chains to amplify their intermediary value. Weak intermediary cities must define their local development positioning, identify their strengths, and proactively seek connections and collaborations with other cities. Only then can the Chengdu-Chongqing urban agglomeration advance toward a more scientifically sustainable spatial network development that fosters urban resilience.

(4) Core-periphery analysis

To accurately identify core and peripheral cities within the Chengdu-Chongqing urban agglomeration resilience spatial network, the Core/Periphery model in UCINET was applied to analyze the resilience spatial network. As shown in Table 4. The models from 2009, 2014, 2018, and 2023 yielded model fit indices of 0.584, 0.64, 0.604, and 0.503 respectively, indicating overall high fit. This confirms the Chengdu-Chongqing agglomeration exhibits a distinct “core-periphery” network structure. Five major core cities (Chongqing, Chengdu, Zigong, Luzhou, Neijiang) and eleven peripheral cities were identified. Among these, Chongqing and Chengdu serve as the “dual cores” of the Chengdu-Chongqing region, while other core cities are embedded within the core network based on geographical proximity. The core-periphery density matrix reveals that the core zone maintains consistently high-intensity connections at 0.7, reflecting tight inter-city interactions that act as a “stabilizer” within the resilience network. Connections from the core zone to the periphery have generally increased, enhancing its radiating influence and strengthening the “core-periphery” synergy within the resilience network. Connections from the periphery to the core zone exhibit greater volatility. Meanwhile, internal connections within the periphery remain persistently low, indicating weak interactions among peripheral cities.

Table 4 Core edge density matrix

Year	2009		2014		2018		2023	
	Core area	Peripheral area	Core area	Peripheral area	Core area	Peripheral area	Core area	Peripheral area
Core area	0.7	0.127	0.75	0.164	0.7	0.145	0.7	0.218
Peripheral area	0.364	0.082	0.4	0.073	0.418	0.073	0.364	0.127

4.2.3 Local network structure characteristics

Clustering sub-groups reflect the phenomenon of small regional clusters forming within the entire network due to close connections. This paper employs the CONCORE method in UCINET to analyze the distribution of clustering sub-groups within the network, using a maximum cut depth of 2 and a convergence criterion of 0.2. It explores the “small group” phenomenon within the spatial resilience network of the Chengdu-Chongqing urban agglomeration during the study period.

As shown in Table 5 and Figure.8, identical colors denote the same cohesive cluster. In 2009, except for the third cluster being divided by the fourth, the spatial organization capacity of other clusters was relatively strong, forming independent clusters. The network density of cohesive clusters was relatively low in the initial year, with only one cluster reaching 0.5. By 2014, spatial self-organization capacity improved, with no fragmentation observed among clusters, all forming distinct small groups. Internal

network density values showed some optimization, with three clusters exceeding 0.5. By 2018, except for the third cluster being divided by the fourth and the first cluster by the second, the spatial organization capacity of the remaining clusters strengthened, forming independent clusters. Internal network density decreased due to differentiation. By 2023, spatial self-organization capacity improved, with no fragmentation between clusters, all forming independent small groups. The cohesive subgroup network density remained relatively low. Although visualization diagrams showed internally formed independent subgroups, the connections between them were loose. In summary, spatial reorganization further optimized during the observation period, transitioning from “fragmented isolation” to “functional synergy.” Disconnections between subgroups disappeared, but issues of insufficient collaboration efficiency and weak inter-subgroup connections persisted.

Table 5 Cohesive subgroup network density

Subgroup	2009				2014				2018				2023			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	0	0	0.33	0.16	0.5	0.25	0.16	0	0.5	0.03	0	0.07	0.45	0	0.12	0
2	1	0.33	0.27	0	0.62	1	0.16	0	0.23	0.2	0	0	0.2	1	0.3	0
3	1	0.05	1	0.05	0.41	0	0.43	0	0.28	0	1	1	0.08	0.1	0.8	0.2
4	0.5	0	0.33	0.23	0.5	0	0.08	0.33	0.28	0	1	0	0	0	0.2	1

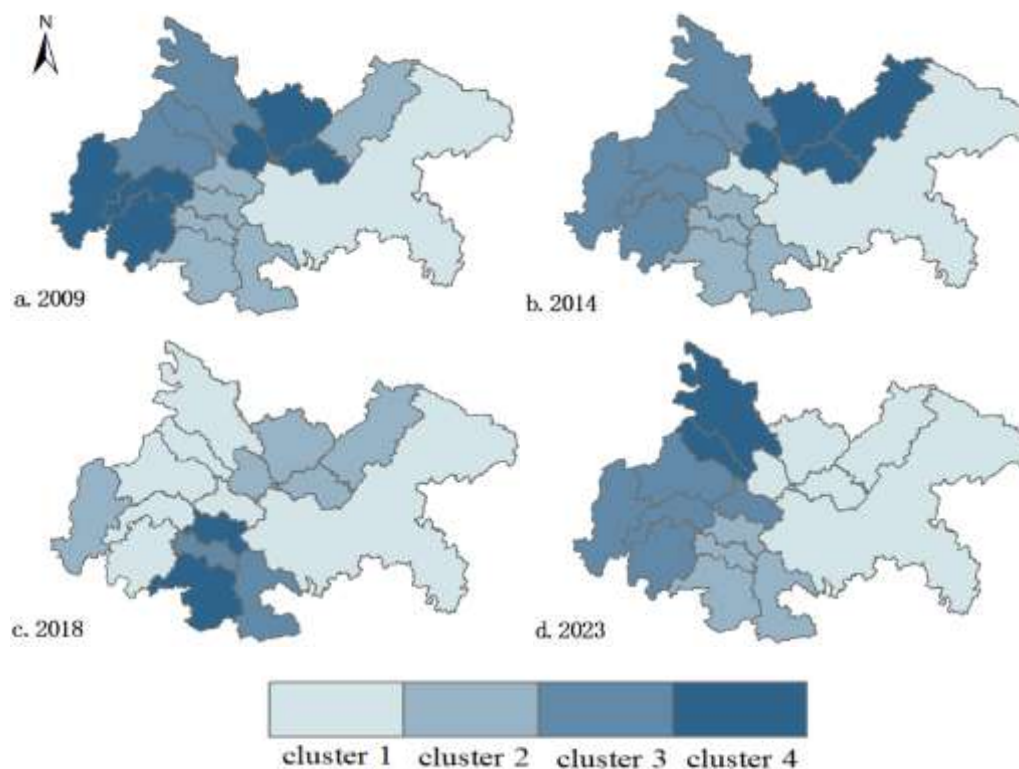


Figure.8 Cluster diagram of urban resilience spatial connectivity cohesion

4.3 Analysis of factors influencing urban resilience

To identify the key factors influencing urban resilience, this study focuses on the year 2023, categorizing independent variables into three major groups-economic, social,

and natural-with secondary indicators designated as x1–x8, while the dependent variable is urban resilience. The analysis explores the explanatory power of individual factors and their interactions on urban resilience.

4.3.1 Factor detection

As shown in Figure.9. Overall, urban resilience is primarily driven by social factors, supported by economic development, and constrained by natural foundations. Social factors exert the strongest influence on urban resilience, encompassing livelihood security, technological empowerment, and resource integration, with all q values exceeding 0.97. Among them, x1 emerges as the most influential single factor, with a q value of 0.98, demonstrating that finance directly, comprehensively, and instantaneously enhances urban resilience by improving anti-shock capacity and accelerating recovery and reconstruction. However, its influence is slightly weaker than that of natural factors, suggesting that the natural environment serves primarily as a foundational constraint on urban resilience, with limited direct impact. Regional terrain complexity, climate change, and air quality-though influential-can be mitigated through environmental governance and industrial upgrading, thereby reducing their direct effect on urban resilience.

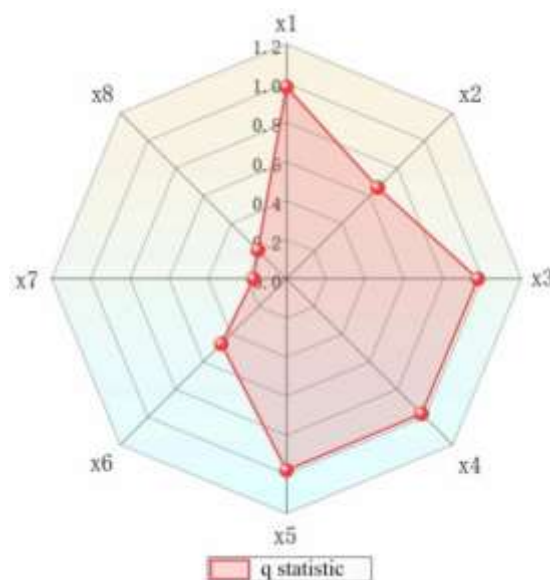


Figure.9 Factor detection

4.3.2 Interaction detection

The results of factor interaction detection in Figure.10 reveal that the interaction between x1 and x3 exhibits the strongest synergistic effect, with a q value of 0.99, indicating that the interplay between financial support and social security has the most significant impact on urban resilience. Meanwhile, the interactions between x6-x8 and other variables are relatively weak, suggesting that the explanatory power of interactions between natural environmental factors and economic or social factors for urban resilience is limited. This may stem from the inherently weak direct influence of natural factors on urban resilience. Excluding natural factors, interactions between economic and social factors demonstrate a pronounced impact on urban resilience, as these two dimensions form an integrated system of shared resources and joint risk-

bearing. The economy provides material foundations and capacity, while society ensures stability, order, and human capital. Together, they create a reinforcing loop-supporting each other against shocks and accelerating recovery collaboratively.

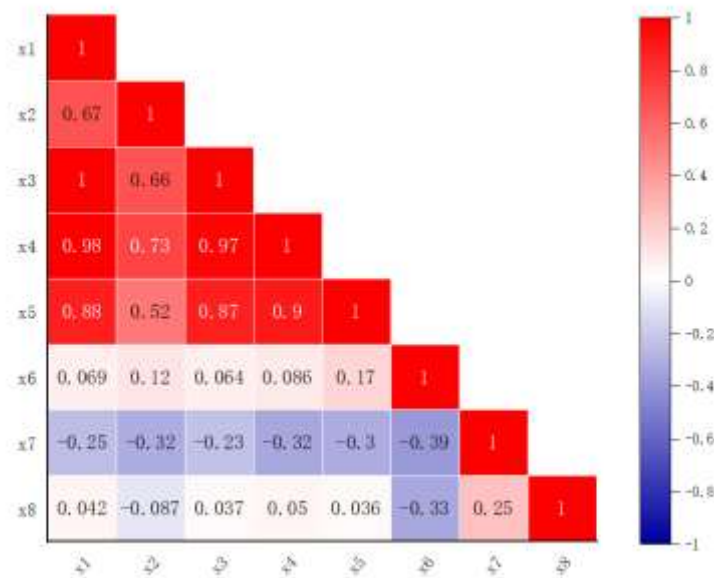


Figure.10 Interaction detection

5. Discussion

5.1 Spatial network characteristics and impact mechanisms of urban resilience

The "core periphery" structure of the urban resilience network in the Chengdu Chongqing urban agglomeration has weakened, but isolated nodes still exist. The main reasons can be analyzed from three aspects: firstly, government planning and regional cooperation. The transportation and industrial cooperation promoted by the government has strengthened the connection between the two core cities of Chengdu and Chongqing and other cities. For example, the integration of high-speed rail networks and industrial chains has helped cities such as Yibin and Mianyang integrate into their development. However, due to remote geographical locations or limited resources, peripheral cities such as Ya'an and Dazhou still find it difficult to fully benefit, resulting in uneven network development. Secondly, there is an imbalance in the flow of resources. Funds and technology are overly concentrated in Chengdu and Chongqing. This gap makes it easier for core cities to attract businesses and talents, while peripheral cities can only assume low value-added roles, creating a situation where the strong become stronger. The third factor is the influence of geographical conditions. Terrain differences also shape differences in urban resilience. Low altitude areas such as the Chengdu Plain facilitate the construction of dense roads and high-rise buildings, making them more resilient to disasters; However, due to the complex terrain and high infrastructure investment costs, it is difficult for cities in the western Sichuan Plateau to deeply participate in the regional network. The impact mechanism of urban resilience is influenced by a combination of economic, social, and natural factors. Except for the

relatively small effect of nature as a constraint, the influence of the other two parts is more significant.

5.2 Path to enhancing urban resilience

Based on the research results, this article proposes the need to construct a gradient development system of "core secondary edge". Core cities should strengthen their radiation function and establish a cross regional resource coordination mechanism. For example, establishing an industrial spillover mechanism, grasping the laws of factor flow and industrial division of labor, and driving the rapid development of surrounding cities in the central city. Chongqing focuses on expanding its automotive parts manufacturing and electronic information processing industries to neighboring areas; Chengdu is transferring high-end equipment development and clinical transformation of biomedicine to cities such as Deyang, Meishan, and Ziyang, clarifying the division of labor boundaries between core city research and development and secondary city manufacturing.

Activate the transmission node function of secondary hubs and strengthen network connectivity capabilities. For example, further encryption of the comprehensive transportation network, such as the Chengdu Mianyang Lego double track railway and the construction of the Chongqing Kunming high-speed railway, can achieve direct high-speed rail connections between core cities and secondary cities, improving traffic efficiency. Cultivate characteristic industrial clusters and leverage the advantages of industrial intermediaries. For example, supporting the construction of a "National Advanced Materials Industry Base" in Mianyang, relying on leading enterprises such as Changhong and Jiuzhou to provide material industry chains to other peripheral cities.

Edge cities clearly define the positioning of "characteristic response" and actively integrate into the resilience network. For example, Ya'an should rely on its giant panda national park and ecological advantages to focus on developing ecotourism, jointly build the "Chengya Ecological Health Road" with Chengdu, and undertake the spillover demand of Chengdu's health industry; Guang'an leverages its location advantage adjacent to Chongqing to undertake labor-intensive industries such as automotive parts processing, and build a Chongqing industrial synergy base.

5.3 Limitations and future research directions

Regarding the limitations of this study, firstly, the indicator system for evaluating urban resilience can be expanded. This study comprehensively measures the resilience level of the Chengdu Chongqing urban agglomeration through five dimensions - economy, ecology, infrastructure, population, and society, totaling 20 indicators. However, as a complex system, the evaluation indicators of urban resilience are far beyond these five systems. Future research can measure urban resilience from multiple perspectives. Secondly, in terms of data selection, this study is mainly based on macro level data and lacks micro level urban data. In the future, such data can be obtained through more advanced geographic data mining techniques [30].

6. Conclusion

This study examines the spatiotemporal dynamics of urban resilience in the Chengdu-Chongqing urban agglomeration, its spatial network characteristics, and influencing factors. The conclusions are as follows:

(1) The spatiotemporal dynamics of urban resilience reveal a gradual increase in resilience levels over the study period, though multi-tiered differentiation persists. Cities outside the core exhibit relatively low resilience, with significant disparities between urban centers. Overall, the spatial evolution follows a pattern of “growth poles clustering in the core while peripheral areas undergo diffusion and differentiation,” alongside a concentric distribution characterized by “higher resilience outward and lower inward,” gradually forming a layered development structure.

(2) Analysis of the spatial network structure of urban resilience reveals that, within the overall network, spatial interconnections among cities remain at a relatively low level but are steadily strengthening, gradually breaking the “core-periphery” constraints. Within individual networks, spatial connectivity between core-core and core-periphery nodes is gradually increasing, while connections between periphery-core and periphery-periphery nodes remain weak, hindering inter-network interaction. Core cities exhibit greater initiative, while secondary nodes are gradually emerging as bridges connecting cities. However, isolated nodes remain disconnected. Within local networks, spatial reorganization has further optimized connections, eliminating fragmentation between subgroups. Nevertheless, collaboration efficiency remains insufficient, and links between subgroups are weak.

(3) Findings regarding influencing factors indicate that: Urban resilience is shaped by economic, social, and natural factors. The social subsystem serves as the core driving force, and its interaction with the economic subsystem amplifies overall resilience. In contrast, the natural subsystem functions as a foundational boundary condition, exerting only limited direct influence.

Author Contributions:

ZiYu Luo: Conceptualization, Investigation, Methodology, Software, Writing(original draft).

QinLong Hu: Supervision, Review, Editing.

All authors reviewed the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Data availability statement: All data generated or analysed during this study are included in this published article [and its supplementary information files].

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