Postprint: Spatial Network Structure of Urban Resilience in Three Major Urban Agglomerations in the Yellow River Basin

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Abstract

Against the backdrop of increasing risk complexity and regional synergy, investigating the organizational modes of multi-center, multi-level, multi-node resilient spatial network structures holds practical significance for urban agglomeration resilience construction, risk prevention, and sustainable development. Grounded in social network theory and taking the three major urban agglomerations in the Yellow River Basin as case studies, this research employs a modified gravity model to calculate spatial correlation relationships in urban resilience development, and subsequently utilizes social network analysis to examine the structural characteristics of resilience spatial correlation networks in the three major urban agglomerations of the Yellow River Basin. The results demonstrate that: (1) Urban resilience levels in the three major urban agglomerations of the Yellow River Basin exhibit a growth trend, resilience network connection intensity is gradually strengthening, and the overall resilience network is becoming increasingly perfected. (2) The spatial correlation network of resilience levels among the three major urban agglomerations in the Yellow River Basin is becoming increasingly close-knit, with provincial capital cities demonstrating prominent radiation effects and dominant positions, yet inter-subgroup development remains unbalanced. The three major urban agglomerations in the Yellow River Basin have formed a typical networked spatial pattern: the Shandong Peninsula urban agglomeration has developed a "one primary, two secondary" resilient spatial network pattern with the provincial capital Jinan as the central origin point and the coastal cities of Qingdao and Yantai as secondary centers radiating and driving the entire agglomeration; the Central Plains urban agglomeration has formed a radial resilient spatial network pattern centered on Zhengzhou, with peripheral cities such as Kaifeng and Luoyang serving as secondary centers; and the closely connected regions within the Guanzhong Plain urban agglomeration primarily exhibit a "dual-core" resilient spatial network pattern linking the provincial capital Xi'an and Xianyang.

Study on the Spatial Network Structure of Urban Resilience in the Three Major Urban Agglomerations of the Yellow River Basin

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Abstract

In the context of escalating risks and regional synergy, exploring multi-center, multi-level, and multi-node organizational models for resilient spatial networks holds practical significance for the resilience building, risk prevention, and sustainable development of urban agglomerations. Based on social network theory, this study examines the three major urban agglomerations in the Yellow River Basin as a case study. Using a modified gravity model to measure spatial correlations in urban resilience development, social network analysis is employed to investigate the structural characteristics of the resilience spatial association network. The results indicate that: (1) The resilience level of cities in the three major urban agglomerations of the Yellow River Basin shows an upward trend, with strengthening network connections and an increasingly robust overall resilience network. (2) The spatial connectivity network among the three urban agglomerations is becoming increasingly tight, with provincial capitals demonstrating prominent radiation effects and dominant positions, though development among subgroups remains unbalanced. The three urban agglomerations have formed typical network-style spatial patterns: the Shandong Peninsula urban agglomeration has developed a "one primary and two secondary" resilient spatial network with Jinan as the central node and Qingdao and Yantai as secondary centers; the Central Plains urban agglomeration has formed a "radial" resilient spatial network with Zhengzhou at the center and Kaifeng, Luoyang, and other cities as secondary centers; and the Guanzhong Plain urban agglomeration exhibits a closely connected "dual-core" resilient spatial network linking the provincial capital Xi'an with Xianyang.

Keywords: spatial network structure; urban resilience; gravity model; social network analysis

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1. Study Area Overview

The Yellow River Basin refers to the entire geographical and ecological region influenced by the Yellow River water system and its tributaries. The basin is primarily divided into three major urban agglomerations, whose population and economic indicators account for 85%-96% of the entire Yellow River Basin.

Specifically, the three major urban agglomerations—the Shandong Peninsula, Central Plains, and Guanzhong Plain—account for 77%-89% of all urban agglomerations in the basin and 73%-83% of the entire Yellow River Basin, representing key development areas. Using these three major urban agglomerations as the primary lever to promote overall resilience development in the Yellow River Basin is essential. Therefore, this study selects the Shandong Peninsula urban agglomeration, Guanzhong Plain urban agglomeration, and Central Plains urban agglomeration as research objects (Figure 1).

[Figure 1: see original paper]

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2. Data and Methods

2.1 Data Sources

Data were obtained from authoritative government sources, including the *China Statistical Yearbook*, *China Tourism Statistical Yearbook*, *National Economic and Social Development Bulletins*, *China Environmental Statistical Yearbook*, and provincial statistical yearbooks from 2012 to 2021, ensuring scientific validity.

2.2 DPSR Model and Indicator System Construction

Urban resilience refers to a city's capacity to fully mobilize and utilize economic, social, organizational, ecological, and infrastructure resources, while broadly engaging individuals, communities, social organizations, and governments to collectively demonstrate multiple response capabilities including prevention, resistance, recovery, learning, adaptation, and transformation. Through literature review, we find that both reflexivity and responsiveness in resilience characteristics emphasize crisis learning and emergency response capabilities; flexibility, redundancy, and robustness refer to systems and resources that can withstand risks and promote recovery through alternative solutions; and inclusiveness and integration involve good governance and effective management processes.

The DPSR (Driving forces-Pressure-State-Response) model introduces the core driving forces of system development into the framework, enhancing the dynamic logic of the system. This study employs DPSR model thinking to dynamically and relationally analyze the process of urban resilience under disturbance through four causal chain forces: "Driving forces-Pressure-State-Response." Specifically, as urbanization and socioeconomic levels continuously improve, long-term driving forces such as ecological resources, technological innovation, and urbanization create pressure on resource environments and socioeconomic development. These pressures cause the urban system state to react, prompting human responses to urban disaster risks through measures that enhance urban resilience and risk resistance capacity. This model analyzes the internal relationships among economic, social, environmental, and political elements from a dynamic perspective.

Based on the connotation of urban resilience and existing research, and following principles of scientific validity, objectivity, independence, and data availability, this study constructs an urban resilience evaluation indicator system for the Yellow River Basin urban agglomerations using the DPSR model (Table 1).

[Figure 2: see original paper]

Table 1 Evaluation indicator system of urban resilience based on the DPSR model

Category	Indicator	Description
Driving Forces	Economic development drivers	Tertiary industry added value, fixed asset investment growth rate, number of patent authorizations
	Social development drivers	Urbanization rate, population growth rate, per capita disposable income of urban residents
Pressure	Economic-social pressure	General public budget expenditure, foreign trade dependence, population density
	Ecological resource pressure	Waste gas emissions, energy consumption per unit GDP
State	Urban environmental resources	Per capita urban green space, proportion of days with good air quality
	Urban economic-social status	Urban water penetration rate, gas penetration rate, average wages of employees
	Urban infrastructure status	Built-up area drainage pipe density, per capita urban road area, internet penetration
Response	Resistance and recovery capacity	Number of hospital beds per thousand people, proportion of social security in public budget expenditure

Category	Indicator	Description
	Adaptation capacity	Per capita financial institution deposits, sewage treatment rate, harmless treatment rate of domestic waste

2.3 TOPSIS Entropy Weight Method

The entropy weight method is an objective weighting approach that determines indicator weights based on sample data distribution, providing a basis for multi-indicator comprehensive evaluation. The TOPSIS method can fully utilize data information to comprehensively and objectively demonstrate differences among evaluation indicators. This study combines entropy weight method with TOPSIS: using entropy method to determine weights and TOPSIS to calculate scores and rankings.

(1) Standardize the indicator data. For m evaluation units and n indicators, let x_{ij} be the value of indicator j for unit i:

Positive indicators: $y_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} + 1$

Negative indicators: $y_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}} + 1$

where y_{ij} is the standardized value, $x_j^{\min}$ and $x_j^{\max}$ are the minimum and maximum values of indicator j.

(2) Calculate the ratio p_{ij} of indicator j for unit i:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}}$$

(3) Calculate the entropy value e_j of indicator j:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}), \quad 0 \leq e_j \leq 1$$

(4) Determine indicator weight w_j:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)}, \quad j = 1, 2, \ldots, m$$

(5) Construct the weighted normalized matrix Z, where w_j is the weight determined by the entropy method:

$$Z = (z_{ij})_{n \times m}, \quad z_{ij} = w_j \times y_{ij}$$

(6) Determine the maximum Z^+ and minimum Z^- values in the matrix:

$$Z^+ = (\max z_{i1}, \max z_{i2}, \dots, \max z_{im})$$
$$Z^- = (\min z_{i1}, \min z_{i2}, \dots, \min z_{im})$$

(7) Calculate the distance D_i^+ to the maximum value and D_i^- to the minimum value:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (Z_j^+ - z_{ij})^2}$$
$$D_i^- = \sqrt{\sum_{j=1}^{n} (Z_j^- - z_{ij})^2}$$

(8) Calculate the final score (evaluation index) S_i:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

2.4 Modified Gravity Model

To accurately and objectively reflect the intensity of inter-city resilience connections, this study modifies the traditional gravity model by using the entropy method to calculate comprehensive resilience development scores for each city, which serve as the "mass" in the model. The modified urban resilience model is:

$$G_{ij} = k_{ij} \times \frac{M_i M_j}{d_{ij}^2}$$

where G_{ij} represents the gravitational force of urban resilience development from city i to city j; M_i and M_j are the "mass" values (comprehensive resilience scores) of cities i and j; d_{ij}^2 is the geographical distance between the two cities; and k_{ij} is the contribution rate of city i to city j's resilience.

2.5 Social Network Analysis Method

The social network model uses "nodes" as research objects, constructing a network through "nodes" and "links" formed based on specific relationships. Compared with other quantitative analysis methods, social network analysis offers significant advantages in accurately depicting various relationships within networks and effectively reflecting overall network structure characteristics and individual positions within the network. This study constructs an urban agglomeration resilience relationship network, treating each city's resilience level as a node and their interaction relationships as links. The analysis focuses on three perspectives: overall network, individual network, and spatial block model to examine the structural characteristics of the resilience network in the three major urban agglomerations.

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3. Results and Analysis

3.1 Overall Development Trends of Resilience in the Three Major Urban Agglomerations

Based on entropy method calculations and TOPSIS evaluation, Table 2 shows the resilience development levels of the three major urban agglomerations from 2012 to 2021. The resilience levels exhibit a fluctuating upward trend with clear growth momentum, though development remains unbalanced, forming a spatial distribution pattern of "higher in the east, lower in the west" and "higher in the south, lower in the north."

Table 2 Resilience development trends of the three major urban agglomerations in the Yellow River Basin from 2012 to 2021

Year	Shandong Peninsula	Central Plains	Guanzhong Plain
2012	[value]	[value]	[value]
…	…	…	…
2021	[value]	[value]	[value]

Using dichotomized matrices, social network analysis tools were employed to obtain network density and relationship numbers for the three urban agglomerations (Table 3). Network density results show a differentiation pattern of "Central Plains > Shandong Peninsula > Guanzhong Plain." Specifically, from 2012 to 2021, the Shandong Peninsula urban agglomeration's network connections became increasingly tight, gradually stabilizing. After the implementation of urban agglomeration development plans, resilience connections among nodes intensified, and the allocation efficiency of diverse capital, information, and human resources improved. The Central Plains urban agglomeration's network density increased from [value] to [value], becoming the fastest-growing among the three, with increasingly complex networks and stronger inter-city resilience connections. The Guanzhong Plain urban agglomeration experienced some decline, partly due to geographical constraints resulting in relatively lagging socioeconomic development compared to the other two agglomerations, and partly because Xi'an's radiation effect on distant cities like Qingyang and Yuncheng remains weak.

Table 3 Network density and number of network relationships

Urban Agglomeration	2012 Network Density	2021 Network Density	Network Relationships
Shandong Peninsula	[value]	[value]	[value]
Central Plains	[value]	[value]	[value]
Guanzhong Plain	[value]	[value]	[value]

3.2 Spatial Network Structure Analysis of Resilience

3.2.1 Analysis of Resilience Connection Strength Based on the modified gravity model, the spatial network connection intensity matrices were calculated for 2012, 2016, and 2021. Using ArcGIS natural breaks classification, connection intensity was divided into five levels to map the spatial network patterns (Figure 3). Overall findings show: (1) Both network density and connection intensity are increasing, with resilience connections strengthening and resource flows becoming more frequent. (2) Regional differences in connection intensity are significant, with higher intensity mainly between core cities and between provincial capitals/sub-provincial centers and their surrounding cities, while connections with distant cities remain weak. (3) The Shandong Peninsula has formed a "one primary and two secondary" pattern centered on Jinan with Qingdao and Yantai as secondary centers. The Central Plains exhibits a "radial" pattern with Zhengzhou at the center and Kaifeng, Luoyang as secondary centers. The Guanzhong Plain shows a "dual-core" pattern linking Xi'an and Xianyang.

[Figure 3: see original paper]

3.2.2 Overall Network Structure Features Network density reveals overall network characteristics—the higher the density, the more connections among nodes and the tighter the relationships. UCINET analysis shows that from 2012 to 2021, all three urban agglomerations experienced increased network density, indicating gradually strengthening resilience connections. However, development remains unbalanced, with core cities showing strong radiation effects while peripheral cities lag behind.

3.2.3 Individual Network Structure Features Individual network features identify nodes that play bridging roles, measured through degree centrality. Higher degree centrality indicates greater direct connection potential and stronger control over other nodes. Calculations for 2012-2021 reveal three categories:

Resilience-enhancing type: Qingdao, Luoyang, and Xianyang show the largest increases in degree centrality, gradually becoming important central cities. Cities like Dongying, Linyi, Xuchang, Zhumadian, and Tongchuan also show significant growth, indicating they are receiving spillover effects from core cities and transitioning from periphery to core.

Resilience-stable type: Jinan, Zhengzhou, and Xi'an maintain absolute core positions as provincial capitals with abundant resources, strong risk response capabilities, and significant spatial network influence.

Resilience-declining type: Several cities in the Shandong Peninsula (Zibo, Jining, Rizhao) and a few in the Central Plains (Anyang) and Guanzhong Plain (Weinan) show declining centrality, indicating insufficient secondary nodes to buffer and coordinate development, highlighting regional imbalance.

[Figure 4: see original paper]

3.2.4 Spatial Plate Analysis Block model analysis classifies cities with similar connection strengths into plates (sub-networks). Results for 2021 show distinct spatial clustering characteristics (Figure 5). The Shandong Peninsula divides into four plates: Plate 1 centered on Jinan, Plate 2 with Jinan's peripheral cities, Plate 3 centered on coastal Qingdao, and Plate 4 as remaining peripheral cities. The Central Plains forms four plates: Plate 1 centered on Zhengzhou, Plate 2 on Kaifeng, Plate 3 on Luoyang, and Plate 4 on Xuchang. The Guanzhong Plain forms three plates: Plate 1 centered on Xi'an and surrounding cities, Plate 2 as Shangluo alone, and Plate 3 as remaining peripheral cities.

[Figure 5: see original paper]

Plate relationship analysis: Using plate density matrices (Table 4), we find all plates within each agglomeration have densities exceeding the overall network density, indicating increasingly close intra-plate relationships. The Shandong Peninsula's Plate 3 (Qingdao, Yantai) shows the highest and fastest-growing density. The Central Plains' Plate 3 (peripheral areas like Nanyang) has overcome previous isolation. However, some plates remain isolated with low inter-plate connectivity, such as Plate 4 in the Central Plains (Xuchang, Luohe) and Plate 3 in the Guanzhong Plain (Qingyang, Linfen), which contribute little to overall network construction.

Table 4 Resilience network density matrix and image matrix of the three major urban agglomerations

Network Density Matrix	Simplified Resilience Network Diagram
[Matrix data]	[Diagram description]

Conclusion

The three major urban agglomerations in the Yellow River Basin have gradually formed tightly clustered network groups within plates, enhancing overall risk resistance and recovery capacity. Inter-agglomeration connections have created closely linked network plates that can quickly integrate resources and leverage complementary mechanisms during crises. However, peripheral cities in edge plates have poor self-response capabilities and struggle to obtain resources from core plates due to communication barriers, limiting overall network effectiveness against external disturbances.

To enhance resilience network levels, the Yellow River Basin urban agglomerations should focus on narrowing inter-city gaps and reducing polarization effects by constructing a resilience development pattern of "multi-point interaction, point-to-line, line-to-surface, and integrated line-surface linkage."

For the Shandong Peninsula, Jinan and Qingdao should strengthen their "dual-core" functions, promote integrated development, and build a resilience development circle. Supporting cities like Zibo and Weifang should be enhanced through infrastructure connectivity to create tight industrial and innovation chains, while "bridge" cooperation between Linyi and Tai'an should share urban functions with the dual cores.

The Central Plains should leverage Zhengzhou's "米"-shaped transportation network to promote secondary node cities along each axis (Handan, Shangqiu, Zhoukou, Luoyang) and increase disaster prevention investment to build "sponge cities."

Xi'an should utilize its "Belt and Road" node advantage to expand economic-technical cooperation, establish free trade zones, and enhance radiation effects. Secondary centers like Baoji and Weinan should be cultivated through policy guidance and resource optimization to reduce core city pressure and form a multi-level, efficiently coordinated resilience network.

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Note: Figure translations are in progress. See original paper for figures.