



# The spatial correlation network structure and its formation mechanism of urban high-quality economic development: a comparative analysis from the Yangtze River Economic Belt and the Yellow River Basin in China

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## Abstract

In the context of regional integration, it is more than crucial to compare and analyze the spatial correlation network structure and formation mechanism of high-quality economic development in the Yangtze River Economic Belt and the Yellow River Basin urban cities as an attempt to strengthen collaborative work on high-quality economic development in both river basins. The paper measured high-quality economic development of the Yangtze River Economic Belt and the Yellow River Basin from 2010 to 2021. Then, it employed social network analysis and the QAP method to study the network structure's characteristics and formation mechanism. The conclusion of the research illustrates a few points clearly that first, the high-quality economic development of the two rivers presents a complex and multithreaded network structure. Although the network structure is hold at a comparatively stable state, the correlation degree needs improvement. Second, cities such as Chongqing, Wuhan, Hefei, Nanjing, Hangzhou, Shanghai, and Changsha and cities like Zhengzhou, Xi'an, Luoyang, Yulin, Hulunbuir, Ordos, and Nanyang are at the very central as well as central position of the network. The spatial correlation networks of the Yangtze River Economic Belt and the Yellow River Basin can be divided into four plates: "agent plate," "main outflow plate," "bidirectional spillover plate," and "main inflow plate." Third, reverse geographical distance and differences in the digital economy attach great significance to the spatial correlation networks of the two basins. The difference in urbanization level makes significant impacts only on the spatial correlation network of the Yangtze River Economic Belt, while the difference in environmental regulation and material capital accumulation only significantly influences the spatial correlation network of the Yellow River Basin.

**Keywords** High-quality economic development · Social network analysis · QAP method · Spatial correlation network

## Introduction

Since the initiation of the reform and opening up, China has witnessed constant and rapid growth in economy, propelling it to become the world's second-largest economy, right after the United States (Wang et al. 2023). This has been widely recognized as the "Chinese economic miracle."

However, over the recent years, both China's domestic and international economic landscapes have been dynamically evolving. Internally, it faces downward pressure, while externally, the environment is complex and challenging. The shortcomings of the traditional model that relies on factors and investment-driven growth have become increasingly apparent (Sun and Jiang 2021). These encompass issues of diminished economic efficiency, substantial environmental pollution, and insufficiently coordinated regional development, all of which have impeded the potential sustaining the Chinese economy. Addressing these concerns, during the 19th National Congress, China pinpointed an accurate and staple fact that "the Chinese economy has transitioned from a phase of high-speed growth to a phase of high-quality development (HQD)" (Hong et al. 2022). This means that, a

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traditional method as it is, the extensive development model has become obsolete and washed out by the time (Chen et al. 2020), and achieving HQD is the primary task for China's current economic advancement (Nair et al. 2021; Yuan et al. 2023).

The Yangtze River and the Yellow River, two mother rivers of the Chinese nation positioned in the southern and northern regions of China, has spanned three primary terrain of eastern, central, and western China (Ji and Zhang 2023). These regions hold significance as key economic areas, ecological safeguards, and conduits. For future HQD, with unique locational advantages and enormous development potential, the Yangtze River Economic Belt (YREB) and the Yellow River Basin (YRB) ecological protection and HQD have been proposed and elevated to national major strategies. The strategic positioning is a crucial benchmark for governing major rivers, a vital barrier for national ecological security, and an important experimental zone for HQD (Liu et al. 2023a). However, there are still many issues in the YREB and the YRB, such as substantial pollution emissions, vulnerable ecological environment, and notable environmental risks. Therefore, relying on the “big rivers and great rivers” implements the national major development strategy, and exploring the HQD paths that align with local characteristics has become an indispensable decision to be made by both regions to pursue high-quality economic development (HQED).

With the continuous deepening of regional integration, the spatial correlation between cities has transcended the traditional linear model, gradually displaying a non-linear spatial structure characterized by a complex network pattern. Therefore, promoting the urban HQED through cross-regional collaboration has become a critical path for the country to achieve a HQD strategy. Against this background, this paper quantifies and analyzes the HQED of the YREB and the YRB based on scientific measurements. From a spatial correlation perspective, it compares and analyzes the network structures of HQED in cities within these two regions. And the paper explores the network formation mechanisms in the two rivers. The aim of this paper is to comprehend the similarities and differences in HQED between YREB and the YRB, providing a theoretical basis to formulate collaborative and regionally tailored paths for elevating the HQED of these two major river basins.

## Literature review

Currently, research on HQED can be classified, in a general way, into two main aspects: first, a study on the connotation of HQED. There has yet to be a consensus in the academic community on the definition of the connotation of HQED, but the core idea is the same. It can be summarized

as follows (Gao and Ke 2020): Firstly, the ultimate goal of HQD is to progressively tackle the challenges of imbalanced and insufficient development, while satisfying the increasing demands of the population for an improved quality of life (Luo and Qu 2023). Secondly, the five fundamental principles of HQD are innovation, coordination, green, opening, and sharing (Liu and Hu 2021). These principles must be pursued simultaneously, and the core driving force of HQD mainly focuses on innovation. Thirdly, the fundamental embodiment of HQD lies in various aspects such as products and services, structural efficiency, demand and supply, and circulation and distribution. Fourthly, HQD must be sustainable, continuously optimizing various relationships throughout its development process (Chen et al. 2023a).

Second is a quantitative study of HQED. This area of study is divided into three parts: (1) study on measuring HQED. There still needs to be more consensus in the academic community, and a unified evaluation system still needs to be established. Some scholars only rely on a sole indicators to assess the level of HQED like total factor productivity (Chen et al. 2023b; Qiu et al. 2023), per capita GDP (Han et al. 2022), and energy-efficient total factor productivity (Li and Liao 2022; Wang et al. 2021), as proxy variables for HQED. In fact, HQED has rich connotations, covers multiple aspects of economic development, and is inclusive and diverse. These indicators only depict the economic situation from one dimension, which is highly biased and cannot reveal the complete picture of HQED. However, a multidimensional composite indicator system possesses the preponderance to avert the one-sidedness of single indicators with predominant ability in fulfilling the research purpose. Meanwhile, the system outperforms the other ones with its abundant connotations, extensive indicators, and intuitive processes. Therefore, scholars widely adopt a multidimensional composite indicator system. Based on their knowledge of the connotation of HQED, scholars have set up different evaluation systems according to their research purposes. For example, Yang et al. (2021) constructed evaluation criteria for provincial HQD in China in terms of 3 aspects: ecological efficiency, economic productivity, and structure. Guo et al. (2023) built an evaluation instrumentality for urban HQED in China based on five dimensions, ranging from industrial structure, total factor productivity, technological innovation, and ecosystem to residents' living standards. Li and Wang (2023) have proposed another set of criteria for HQED in Liaoning Province based on three dimensions: production quality, living quality, and ecological quality. However, with the introduction of “guiding HQED with new development ideas,” the five development ideas are gradually becoming the mainstream for measuring HQED (Lu et al. 2019). Many researchers such as Song et al. (2022), Zha et al. (2022), and Wan et al. (2023) have measured the level of HQED using five development ideas. (2) Spatial

analysis of HQED. Building on the measurement of HQED, many scholars have also incorporated spatial factors into studying spatial patterns and influencing factors of HQED. Scholars use the Moran's  $I$  to explore the evolving spatial pattern of HQED (Sun et al. 2021), employing kernel density estimation and Markov matrix to study the dynamic evolution of HQED (Chen et al. 2020b). Some other scholars utilized Theil index (Guo et al. 2020), Gini coefficient (Wang et al. 2023), and their decomposition to study the distribution characteristics of regional differences, and examined the convergence mechanism of HQED with models such as  $\sigma$  convergence,  $\beta$  convergence, club convergence, and spatiotemporal  $\beta$  convergence (Lv and Cui 2020). However, these studies mainly focus upon "attribute data" and overlook the examination of "relationship data." Therefore, Wang et al. (2022) have investigated correlation network of HQED in Chinese provincial regions based on relationship data and found that there is a robust spatial correlation relationship among HQED, with variations in the network position and role played by each area. (3) Study on the influencing factors of HQED. This aspect mainly explores the impact of different factors on HQED. For example, Wang et al. (2022) used the QAP method to study the formation mechanism of the regional correlation network of HQED in China's provinces. The results show that regional differences in human capital, urbanization level, financial technology, and environmental regulation will directly cause differences in HQED between regions, with human capital differences contributing more than 90%. Chen et al. (2021) analyzed the current situation and influencing factors of HQED in 286 cities in China and found that industrial structure positively impacts HQED. The degree of impact shows a distribution pattern of low in the west and high in the east. Song et al. (2022) believe that environmental regulation has an inverted "U"-shaped effect on the HQED of local and neighboring areas, and the improvement of the advanced level of industrial structure has a positive impact on the HQED of local and neighboring areas. In addition, Peng et al. (2023) selected the elderly care industry as the research object. They found that the higher the level of digital economy in an area, the higher its level of HQD, which means that the development of the digital economy can significantly promote the improvement of the level of HQD.

Focusing on the river basin level, considerable research has been carried out on this subject to date. HQED of the YREB and the YRB. This research mainly focused on evaluation of the HQD of different regions, spatial analysis, and influencing factors (Han et al. 2022). For example, Zhang et al. (2022) measured HQD in the YREB based on the five development ideas. They then analyzed the spatiotemporal characteristics of HQD using standard deviation ellipse analysis. Zheng and He (2022) assessed the level of HQED in the Chengdu-Chongqing Economic Zone based

on the new development ideas. Spatial-temporal features and key influencing factors have been explored under the help of kernel density estimation and SDM. Chen et al. (2022) employed entropy method, Moran's  $I$ , and GWR to analyze the spatial characteristics and affecting factors of HQED in seven city clusters in the YRB. Having taken different elements into consideration, including essential development, social outcomes, and ecological outcomes, Shi et al. (2021) carefully measured HQED in the cities of the YRB. Then, they analyzed the dynamic evolution patterns and characteristics of upstream, middle, and downstream cities in the YRB using kernel density estimation and Markov chain analysis. In addition, extensive research has also been conducted on regions such as the heartland of the YRB urban agglomeration (Fang and Zhu 2020) and heartland of the YREB (Ma and Huang 2023).

In summary, the existing literature has made valuable explorations in terms of relevant theories, measurements, and temporal and spatial variations of HQED. However, this study identifies several shortcomings in current research at the river basin level by comparing the differences in research content at the national and river basin levels. (1) Existing literature mainly focuses on studying HQED in a single river basin, lacking comparative analysis among different river basins. (2) The construction of evaluation systems for HQED in river basins is limited to a single "quality" aspect, neglecting the examination of economic growth "quantity." (3) Research on spatial characteristics of HQED in river basin cities mainly relies on attribute data and overlooks the advantages of "relational data" in identifying spatial correlations. Considering these shortcomings, this study makes three marginal contributions: (1) This study takes the cities in the YREB and the YRB as research subjects, considering the dialectical relationship between the quantity and quality of HQED; it breaks through the measurement system that focuses solely on quality. It unifies the rational growth of quantity with the steady improvement of quality. Using the objective weighting method, it measures the level of HQED across six dimensions: economic growth, innovation, coordination, environmental sustainability, openness, and sharing. (2) Starting from relational data and in accordance with a modified gravity matrix, a spatial correlation network for HQED in basin cities is constructed. Social network analysis (SNA) methods are used to analyze the spatial network structure characteristics of HQED. It primarily concentrates on examining the particular "status" and "role" of each city within the network. (3) The QAP model is utilized to delve into the impact mechanisms of disparate factors on the differences in HQED among cities. This effectively avoids the problem of biased statistical test results caused by multicollinearity among variables.

## Methodology and data

### Indicator selection

Pan et al. (2021) pointed out that HQED can be identified as the transition from rapid economic development to medium-speed growth. However, we should be wary of the “middle-income trap” of inefficient development. Economic growth remains essential for measuring HQED and plays a primary role. On the other hand, Ren and Wen (2018) emphasize that HQD embodies the new development ideas. As the primary driving force, innovation needs to stimulate the vitality of HQD further. As an intrinsic characteristic, coordination needs to strengthen the holistic nature of HQED. As a universal form, green development needs to promote the construction of a HQED institutional system. As an essential path, openness demands a new structure of opening up. Sharing, as the fundamental goal, requires enhancing the supply capacity of public services. Therefore, achieving HQED requires the integration of rational growth in quantity and steady improvement in quality. In this regard, this paper combines economic growth with the new development ideas (Guo and Sun 2023; Huang et al. 2022), considering the hierarchy and availability of process and outcome indicators of economic development. A more well-rounded and objective evaluation index system has been set up for HQED, consisting of 6 primary indicators, including economic growth, innovative, coordinated, green, open development, and shared development, as well as 20 secondary indicators including economic foundation, economic vitality, and innovation input, and 26 tertiary indicators including per capita real GDP, science expenditure intensity, and urban development structure (Table 1).

## Methodology

### Objective weighting method

To address the issue of subjective randomness (Guo et al. 2023), this study employs the objective weighting method (CRITIC method and CANTILLET method) to evaluate the indicator system for HQED. The CRITIC method ( $W_1$ ) considers both the variability and conflicts of indicators, which helps avoid the shortcomings of ignoring the data attributes in indicator evaluation. Based on this, the CANTILLET method is combined to obtain comprehensive objective weights. The CANTILLET method ( $W_2$ ) combines information content weighting with correlation weighting to effectively overcome the shortcomings of neglecting data correlation. The formula is as follows:

$$H_i = \sum_{j=1}^n (0.5W_1 + 0.5W_2)X_{ij} \quad (1)$$

where  $H$  is the HQED index and  $X$  is the tertiary indicator value.

### Modified gravitational model

Currently, two main methods for determining spatial relationships are VAR model and modified gravitational model (Gao et al. 2023; Huo et al. 2022). However, VAR models are susceptible to the choice of lag order, leading to potential inaccuracies in representing the network structure (Rios and Gianmoena 2018). Therefore, this study utilizes a modified gravity model to set up the spatial correlation network. The formula is as follows:

$$R_{ij} = K_{ij} \frac{\sqrt[3]{G_i P_i H_i} \sqrt[3]{G_j P_j H_j}}{(D_{ij})^2}, K_{ij} = \frac{H_i}{H_i + H_j} \quad (2)$$

where  $R$  represents the strength of association,  $K$  represents the gravity coefficient,  $G$  represents the actual GDP,  $P$  represents the permanent population, and  $D$  represents the geographical distance.

### SNA method

#### 1. Overall network structure characterization index

The paper examines the overall network structure features using four distinct indicators: network density, connectedness, hierarchy, and efficiency (Bai et al. 2020; Zhang and Yao 2023). Among these, network density reflects the compactness of the entire network structure. Network connectedness reflects the accessibility among cities within the spatial correlation network. Network hierarchy refers to the measurement of uneven accessibility among cities within a network. Network efficiency, on the other hand, signifies the efficiency of connectivity among cities in a spatial correlation network. A higher number of connections between cities results in a more stable network but lower network efficiency. The specific calculation formula can be found in the provided reference (Liu et al. 2023).

#### 2. Individual network structure characterization index

Individual network structural features are explored using three indicators: degree, closeness, and betweenness centrality. Among these, degree centrality measures the centrality of a city within the network. Closeness centrality characterizes the extent to which a city is “independent” from other cities’ control. Betweenness centrality reflects a city’s ability to control other cities (Wang and Liu 2023). Detailed formulas can be found in reference (Liu et al. 2023a).

**Table 1** Indicator system for evaluating HQED

Primary indicators	Secondary indicators	Tertiary indicators	Measuring method
Economic growth	Economic foundation	Per capita real gdp Per capita fiscal revenue	Real GDP/resident population Fiscal general budget revenue/GDP
	Economic vitality	Market potential	Retail sales of consumer goods/resident population
Innovative development	Innovation input	Economic growth rate	Real GDP growth rate
		Research and development investment intensity Science expenditure intensity	Internal expenditure on Research and development /GDP Expenditure on science finance/general budget expenditure
	Innovation output	Patents per capita	Number of patents authorized/resident population
	Innovation potential	Per capita enrollment in higher education	The count of individuals currently registered in general higher education institutions for their studies/resident population
Coordinated development	Regional coordination	Urban development structure	Urban GDP/basin GDP
	Urban and rural structure	Rural and urban income structure	Per capita disposable income of (urban/rural residents)
	Industrial coordination	Secondary and tertiary industry gaps	Value added of (tertiary/secondary industry)
	Financial coordination	Share of deposit and loan	deposit and loan balance/GDP
Green development	Environmental governance	Green coverage ratio	Green coverage ratio in built-up area
		Domestic waste disposal rate	Non-hazardous domestic waste disposal rate
	Environmental pollution	Wastewater discharge per unit GDP Smoke emissions per unit GDP SO <sub>2</sub> per unit GDP	Industrial wastewater discharge/GDP Industrial soot emissions/GDP Total industrial SO <sub>2</sub> /GDP
Open development	Foreign investment dependency	The degree to which foreign capital is utilized in economic activities	Actual utilization of foreign capital/GDP
	tourism openness	Inbound tourism contribution	Inbound tourism revenue/GDP
	Dependence on foreign trade	The role of imports and exports in the overall economic contribution	Total imports and exports/GDP
Shared development	Social security	Per capita social security expenditure	Fiscal expenditure on social security and employment/resident population
	Information sharing	Internet penetration rate	Internet broadband access users/total households
	Medical sharing	Number of practicing physicians per capita	Number of practicing (assistant) physicians/resident population
	Transportation sharing	Per capita road area	Road area/resident population
	Education sharing	Density of primary and secondary schools	Number of general secondary schools and general elementary school/area of administrative area
	Cultural sharing	Per capita public library collection	Public library collection/resident population

## Block model analysis

The block model is a prominent approach used to analyze the clustering properties of intricate spatial networks (Yu et al. 2022). It is a model for revealing network positions and conducting descriptive analyses of social roles (Wang et al. 2022). After studying the methodology of Bu et al. (2020), the paper uses the UCINET software and the CONCOR

method to divide the YREB and the YRB into four types of plates: “agent plate,” “main outflow plate,” “bidirectional spillover plate,” and “main inflow plate.” The main inflow plate acts as a recipient of relationships not only from cities within the same plate but also from other plates, with a significantly higher number of received relationships compared to send out. The main outflow plate on the other hand sends out more relationships than it receives. The bidirectional

spillover plate both receive and send relationships, but in terms of received relationships, the relationships sent out by cities within the plate itself are the majority. The agent plate shares common properties with the bidirectional spillover plate, but this plate exhibits a higher degree of interconnectedness with other plates in the network.

## The QAP method

In the study of the underlying mechanism of the spatial network for HQED in the YREB and the YRB, all variables are relational data. Therefore, there is multicollinearity among these variables, and traditional statistical methods cannot be used to analyze their relationships (Huo et al. 2022). The QAP method, based on relational data, is a non-parametric method that does not assume independence among independent variables, effectively tackle with the phenomenon of multicollinearity among uncertainties. Therefore, this study chooses QAP correlation and regression analysis to look into the networks' formation mechanism. This method is based on the permutation of matrix data, calculating correlation coefficients through repeated sampling, and performs non-parametric tests to compare the values of two relationship matrices (He et al. 2020).

Building upon the studies by Wang et al. (2022) and (Zheng and He 2022), this study selects reverse geographical distance (RGD), industrial structure difference (IS), urbanization level difference (URL), environmental regulation difference (ER), digital economy difference (DE), material capital accumulation difference (MCA), and government intervention degree difference (GID) as influencing factors, and establish the QAP method. The exact formula is provided as follows:

$$H = f(\text{RGD}, \text{IS}, \text{URL}, \text{ER}, \text{GID}, \text{DE}, \text{MCA})$$

where inverse spatial distance between cities represents RGD. IS represents the quotient of value added from the secondary industry to GDP. URL is determined by quantifying the degree of urbanization within a given area. ER entails analyzing the frequency at which environmental protection terminology appears in local government work reports. GID is measured using the ratio of government fiscal expenditure to GDP. DE is represented by the digital inclusive finance index. MCA is determined by the ratio of fixed asset investment to GDP.

The differences matrix of all indicators, except for  $D$ , is constructed using the standard practice in the academic community. The data from the last year of the research period is selected, and the absolute difference values between each city are used to establish the differences matrix for each indicator.

## Data sources and processing

The research period for this paper spans from 2010 to 2021, focusing on 189 cities within the the YREB and YRB. The data utilized in this article were sourced from the “China City Statistical Yearbook,” statistical yearbooks of various provinces (prefecture-level cities), CEIC database, China Research Data Services Platform (CNDRS), “China Environmental Statistical Yearbook,” “China Urban Construction Statistical Yearbook,” authorized statistical reports from diverse provinces, (prefecture-level cities), and government administrative reports. To address the issue of missing data, we employed the sliding average method to fill gaps.

## Results

### Measurement of HQED in the YREB and the YRB

From a basin-wide perspective (Fig. 1), the level of HQED in the YREB increased from 0.274 to 0.387 from 2010 to 2021, while the level of HQED in the YRB increased from 0.258 to 0.371. Both basins showed a stable upward trend in HQED. Throughout this period, the level of HQED in the YREB remained higher than that in the YRB, with a difference of 0.016 in both 2010 and 2021, and the overall gap remained unchanged. This is mainly due to the higher degree of openness in the YREB and the earlier start of ecological civilization construction, which has led to significant achievements in HQED. However, the YRB faces more severe problems, such as geographical disadvantages, inconvenient transportation, fragile ecological environment, and water scarcity, resulting in a lag in overall HQED.

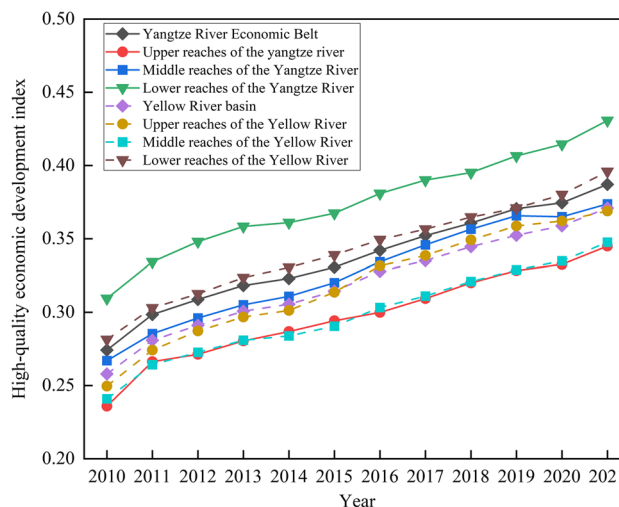


Fig. 1 Trends of HQED in the YREB and YRB from 2010 to 2021

Internally within the basins (Fig. 1), the overall pattern of HQED in the YREB shows a trend of upstream < midstream < downstream, showing an east-high and west-low spatial distribution pattern. However, the overall pattern of HQED in the YRB is midstream < upstream < downstream, displaying a spatial distribution pattern of low in the central region and high on both sides. Compared with the YREB, the HQED of the YRB's middle reaches and the YREB's upper reaches are similar, and both are far behind other areas. This is because many cities in the middle reaches of the YRB and the upstream regions of the YREB are resource-based cities. The “resource curse” phenomenon has caused many problems such as economic and industrial decline, weakened factor agglomeration capacity, environmental damage, and infrastructure backlog, thereby hindering the HQED of these two regions.

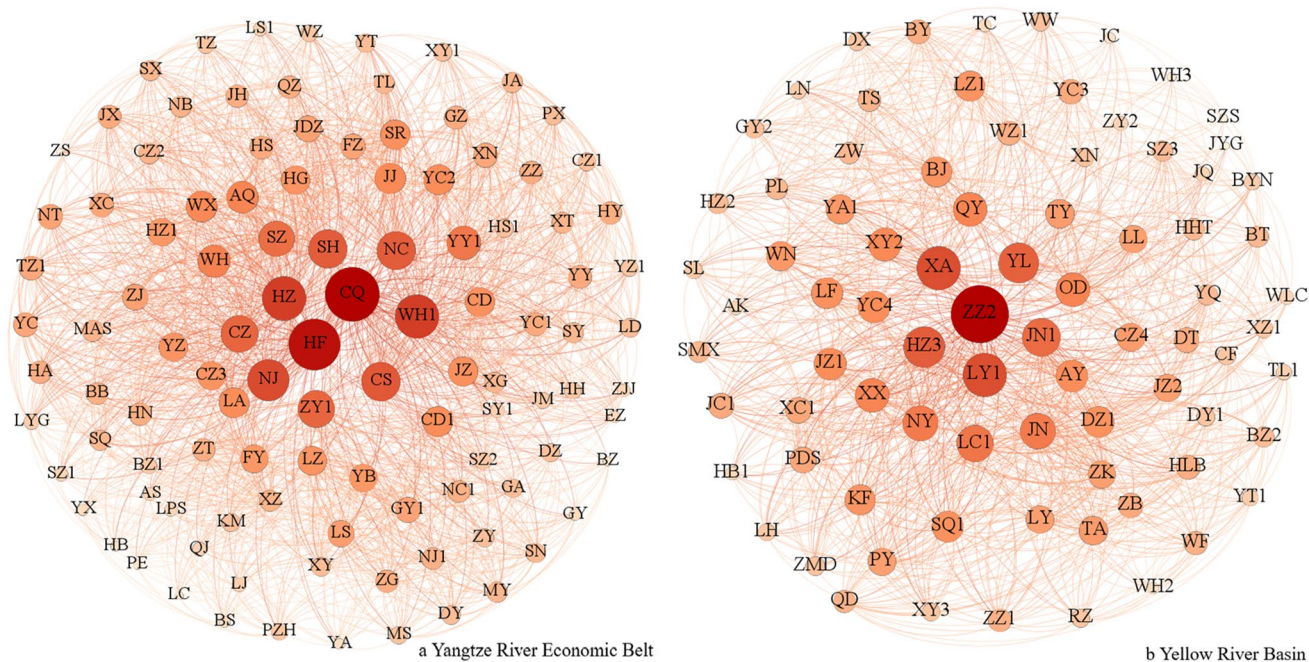
### Network construction

In this study, the gravity matrix for HQED in the YREB and the YRB was computed using Formula (2). The spatial correlation network was visualized using Gephi. Due to the network's stability, no substantial alterations were observed in the overall structure of the network throughout the study period. Therefore, this paper exclusively focuses on presenting the spatial network in 2021. (Fig. 2). The spatial correlation between the YREB and the YRB for HQED has surpassed the simple “neighborhood” relationship in geographical terms, gradually revealing a complex and

multithreaded network structure. Furthermore, this validates the importance of investigating relationship data.

### Overall network structure characteristics

Network relationships and network density of the YREB and the YRB have slightly decreased from 2010 to 2021, but overall, they remain stable (Table 2). In 2021, the network relationship of the YREB and the YRB was 2232 and 1354, respectively, which still has a significant gap with the upper limit of potential network connections (11,556 and 6480). It indicates that the HQED of the YREB and the YRB has yet to reach the optimal spatial correlation state, and their spatial correlation networks need to be further strengthened (Gao et al. 2023). The network connectedness has been consistently one during the sample period, indicating no isolated cities in the HQED of the YREB and the YRB. Every city within the respective spatial correlation network is linked either directly or indirectly to other cities, displaying good connectivity and robustness network. The network hierarchy has always been 0, signifying that the spillover relations between cities in the YREB and YRB are symmetrical, without a strict hierarchical network structure. The network efficiency of the YREB and the YRB has slightly decreased, with the network efficiency being around 0.764 and 0.7373, respectively. This indicates multiple overlapping phenomena of spatial spillover, and the network stability is high (Wang and Liu 2023). From the perspective of network density, connectedness, hierarchy, and efficiency, the network



**Fig. 2** Network structure of HQED

**Table 2** Network relationships, density, and efficiency from 2010 to 2021

Year	YREB			YRB		
	Relationships	Density	Efficiency	Relationships	Density	Efficiency
2010	2243	0.1941	0.7651	1360	0.2099	0.7386
2011	2249	0.1946	0.7637	1361	0.2100	0.7383
2012	2241	0.1939	0.7648	1357	0.2094	0.7389
2013	2236	0.1935	0.7648	1361	0.2100	0.7377
2014	2235	0.1934	0.7642	1361	0.2100	0.7373
2015	2238	0.1937	0.7637	1354	0.2090	0.7380
2016	2235	0.1934	0.7644	1357	0.2094	0.7370
2017	2238	0.1937	0.7637	1356	0.2093	0.7361
2018	2244	0.1942	0.7628	1353	0.2088	0.7367
2019	2243	0.1941	0.7634	1356	0.2093	0.7358
2020	2233	0.1932	0.7637	1352	0.2086	0.7370
2021	2232	0.1931	0.7637	1354	0.2090	0.7364

indicators of HQED in the YREB and the YRB remained relatively stable from 2010 to 2021.

### Individual network structure characteristics

Since the networks of HQED in the YREB and the YRB remained relatively stable, this paper presents the city's in-degree, out-degree, degree, closeness, and betweenness centrality for the year 2021 (Table 3 and 4).

Forty-six cities in the YREB have a degree centrality higher than the average. Among them, the top ten cities in degree centrality are Hefei, Chongqing, Wuhan, Nanjing, Hangzhou, Shanghai, Suzhou, Nanchang, Changzhou, and Changsha. These cities hold central positions in the network of HQED in the YREB, maintaining numerous spatial correlations with other cities. The reasons behind this lie in their status as provincial capitals or key cities in the Yangtze River Delta (YRD) city cluster. They possess a strong economic foundation, strategic geographic locations, and convenient transportation. This enables a continuous influx of capital and talent from other cities. Moreover, as regional hub cities, they drive the development of other cities in the region. The bottom ten cities in terms of ranking are Zhoushan, Huaibei, Bazhong, Lincang, Ezhou, Yuxi, Suzhou, Puer, Guangyuan, Qujing, and Liupanshui. Most of these cities are situated in the upper regions of the YREB, in relatively remote geographical locations, leading to challenges in communication with other cities. Consequently, the spatial correlations in terms of HQED between these cities and others are relatively weak.

There are 34 cities in the YRB with a node degree centrality exceeding the average value. Among them, the top ten cities in terms of node degree centrality are Zhengzhou, Xi'an, Yulin, Luoyang, Heze, Jinan, Jining, Hulunbuir, Liaocheng, Anyang, and Ordos. These cities have a relatively high degree centrality and are positioned at the

networks' center for HQED in the YRB. This is due to their central position within various city clusters, being transportation hubs with convenient access, facilitating connections with other regions. The bottom ten cities, except for Shizuishan, Wuhai, Jiayuguan, Tongchuan, Jinchang, and Ankang in the upper reaches of the YRB, are all located in the downstream area. This indicates that central cities possess a strong capability to attract production factors from other cities. During the process of HQED, a large portion of production resources from other cities flows into these central cities.

In addition, calculating the in-degree and out-degree found that cities located at the network center have significantly higher receiving relationships than overflow relationships. In contrast, the receiving relationships of edge cities are significantly lower than overflow relationships. This indicates that central cities have a solid ability to attract production factors from other cities. In the process of HQED, production resources from other cities will flow into the center in large quantities.

The mean closeness centrality in the network of HQED in the YREB is 46.6198, with a maximum value of 64.4578 and a minimum value of 37.2822. In the YRB, the mean closeness centrality in the network of HQED is 53.1431, with a maximum value of 76.1905 and a minimum value of 42.3280. Overall, the networks of HQED in the YREB and YRB are in a relatively balanced state.

The top ten cities with high closeness centrality in the YREB are Wuhan, Chongqing, Hefei, Changsha, Ganzhou, Suizhou, Ji'an, Shiyan, Xiangyang, Jingmen, and Xiaogan. Similarly, the top ten cities with high closeness centrality in the YRB are Zhengzhou, Xi'an, Luoyang, Yulin, Hulunbuir, Ordos, Nanyang, Jinzhong, Taiyuan, and Changzhi. This suggests that these cities possess a high capacity to establish rapid connections with other cities within the HQED network and demonstrate strong resource acquisition



**Table 3** Network’s in-degree, out-degree, and degree centrality in 2021

YREB			YRB						
City	In-degree	Out-degree	City	Degree	City	In-degree	Out-degree	City	Degree
CQ	52	31	HF	49.53	ZZ2	55	16	ZZ2	68.75
HF	49	30	CQ	49.53	XA	38	17	XA	48.75
WH1	49	20	WH1	45.79	LY1	35	20	YL	47.50
NJ	47	19	NJ	43.93	HZ3	34	18	LY1	46.25
HZ	45	24	HZ	42.06	JN	32	14	HZ3	42.50
SH	45	17	SH	42.06	JN1	31	18	JN	40.00
SZ	45	13	SZ	42.06	YL	31	20	JN1	40.00
CZ	40	20	NC	38.32	AY	29	13	HLB	38.75
CS	40	23	CZ	37.38	LC1	29	18	LC1	38.75
WX	39	13	CS	37.38	XY2	28	15	AY	37.50
NC	35	27	WX	36.45	XX	28	16	OD	37.50
CD1	34	17	ZY1	36.45	NY	26	20	XY2	37.50
YY1	33	23	WH	33.64	DZ1	25	16	NY	36.25
ZY1	33	27	LA	32.71	JZ1	25	17	JZ2	35.00
JJ	31	21	CD1	31.78	OD	24	20	LF	35.00
GY	9	17	MS	18.69	YQ	8	21	ZMD	21.25
HB	9	15	SN	18.69	AK	7	14	DY1	20.00
PZH	9	24	YA	18.69	SZS	7	7	WLC	20.00
SZ2	9	24	ZY	18.69	TC	7	13	AK	18.75
YX	9	17	LPS	16.82	WH2	7	12	RZ	18.75
BZ	8	15	QJ	16.82	WLC	7	15	SL	18.75
SY1	8	22	GY	15.89	JC	6	12	WH2	18.75
YT	8	28	PE	15.89	WH3	6	10	YT1	18.75
YA	7	18	SZ1	15.89	XY3	6	20	JC	17.50
ZJJ	7	21	YX	15.89	ZY2	5	17	LH	17.50
BS	6	20	EZ	14.95	CF	3	23	HB1	16.25
LJ	6	24	LC	14.95	HLB	2	31	TC	16.25
LC	6	16	BZ	14.02	JYG	2	12	JYG	15.00
PE	6	17	HB	14.02	JQ	2	20	WH3	13.75
ZS	5	15	ZS	14.02	TL1	2	21	SZS	11.25
Mean	21	21	Mean	25.04	Mean	17	17	Mean	28.18

Due to limited space, this article only displays the top 15 and last 15 centrality rankings

capabilities, playing the role of “central actors.” Cities with closeness centrality below the mean have a relatively weaker ability to acquire resource elements within the network. They are less influenced by the HQED of other cities, playing the role of “peripheral actors” in the network of both the YREB and the YRB.

The mean values of betweenness centrality in the networks of HQED for the YREB and the YRB are 1.5775 and 2.1542, respectively, showing significant polarization. In the YREB, 29 cities have betweenness centrality greater than the mean, accounting for about 80.78% of betweenness centrality in the YREB. Similarly, in the YRB, 34 cities have betweenness centrality greater than the mean, accounting for about 82.33% of betweenness centrality in the YRB. This indicates that these cities have a strong dominance over the flow of resources such as talents, information, funds,

and technology within the network. They possess a strong capacity to foster connections among other cities, occupying a central position and serving as key intermediaries and bridges within the network. Mainly, cities such as Chongqing, Wuhan, Changsha, Hefei, Nanchang, Xiangyang, Zunyi, Fuyang, Shangrao, and Hangzhou in the YREB, as well as Xi’an, Zhengzhou, Luoyang, Yulin, Nanyang, Ordos, Jiaozuo, Linfen, Qingyang, and Heze in the YRB, are located in the center of urban clusters. Due to their special geographic locations, they serve as key intermediaries and facilitators for elevating the flow of resource elements from downstream to upstream areas, playing a role in ‘connecting the east and west, unifying the south and north (Gao et al. 2023).

However, the remaining cities with betweenness centrality in the YRE and YRB account for only 19.22% and

**Table 4** Network’s closeness centrality and betweenness centrality in 2021

YREB				YRB			
City	Closeness	City	Betweenness	City	Closeness	City	Betweenness
WH1	64.458	CQ	26.549	ZZ2	76.190	XA	9.793
CQ	58.470	WH1	12.128	XA	65.574	ZZ2	8.771
HF	57.838	CS	9.554	LY1	65.041	LY1	8.532
CS	57.838	HF	9.185	YL	65.041	YL	7.581
GZ	57.527	NC	6.280	HLB	62.016	NY	6.161
SZ2	56.316	XY	5.891	OD	61.069	OD	5.530
JA	55.155	ZY1	5.562	NY	60.606	JZ1	5.331
SY1	54.592	FY	5.377	JZ2	60.150	LF	5.313
XY	54.592	SR	5.195	TY	60.150	QY	5.003
JM	54.315	HZ	4.426	CZ4	60.150	HZ3	4.694
XG	54.315	KM	3.922	DT	58.394	TY	4.676
NC	53.769	GY1	3.376	HZ3	58.394	CZ4	4.672
YY1	53.500	SY1	3.289	LF	58.394	JN1	4.500
HZ	53.234	YC1	3.070	BT	57.971	SQ1	4.433
NJ	52.970	AQ	2.979	AY	57.143	LZ1	4.391
KM	39.630	MY	0.063	ZW	47.337	DX	0.203
MS	39.630	GA	0.059	ZB	47.337	DY1	0.140
SX	39.630	SN	0.053	BZ2	46.784	AK	0.120
SZ1	39.630	EZ	0.046	GY2	46.512	BZ2	0.115
SN	39.630	YA	0.045	WW	46.512	WH3	0.100
YA	39.630	YX	0.045	QD	45.455	RZ	0.073
ZY	39.630	DY	0.042	WF	45.455	YT1	0.064
HB	39.338	LJ	0.028	WH3	45.198	LH	0.060
LPS	39.338	HB	0.018	DX	44.944	SZS	0.058
QJ	39.338	ZY	0.018	JC	44.944	JQ	0.054
GY	39.194	GY	0.011	DY1	44.444	HB1	0.051
PE	39.194	BS	0.011	WH2	43.956	TC	0.020
YX	39.194	ZS	0.009	YT1	43.956	WH2	0.004
LC	39.051	PE	0.002	RZ	42.781	JYG	0.000
ZS	37.282	LC	0.000	SZS	42.328	TL1	0.000
Mean	46.620	Mean	1.577	Mean	53.143	Mean	2.154

Due to limited space, this article only displays the top 15 and last 15 centrality rankings

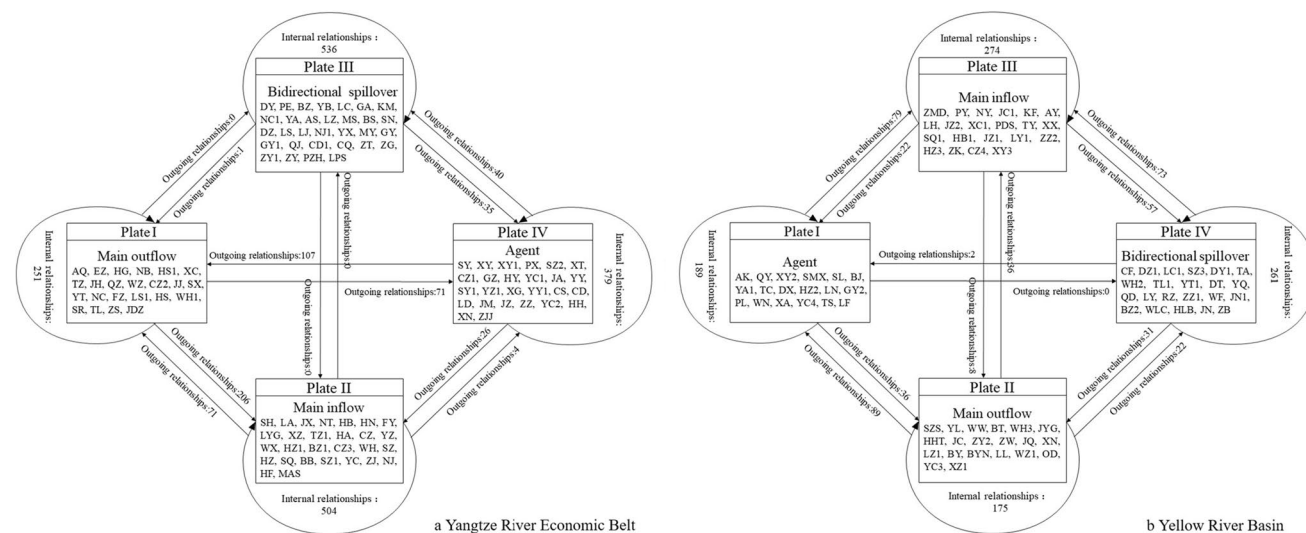
17.67% of the entire basin, respectively. Most of the cities are situated at the upper reaches of the basin or far from the river channel area. They have very weak control and influence on the HQED of other cities. In the network, they are in a “dominated” and peripheral position. Therefore, in the future, it is essential to enhance the optimization of the network structure in the YREB and the YRB, breaking the imbalanced state between them in controlling resource elements.

**Spatial clustering characteristics**

To further explore the internal structural state of HQED network in the YREB and the YRB, as well as the roles and positions of each member in the correlation network, this study used the CONCOR method to analyze their spatial

clustering characteristics. Therefore, this study utilizes UCINET to partition the YREB and the YRB into four plates, and analyze the spatial interaction relationships of these four plates (Fig. 3).

There are 2232 correlation relationships among the 108 cities in the YREB, with 1670 correlation relations within the plates and only 562 correlation relationships between plates. Similarly, there are 1354 correlation relationships among the 81 cities in the YRB, with 889 correlation relationships within the plates and only 445 correlation relationships between plates. This indicates that the HQED spatial correlation between the YREB and the YRB mainly exists within the plates, showing a “local agglomeration” characteristic. Although the correlation relations between plates are relatively few, they should not be ignored, as they still exhibit a “global correlation” characteristic overall.



**Fig. 3** Spatial correlation among the four plates in 2021

Analyzing the YREB, the initial plate demonstrates a notable disparity with a significantly higher count of outgoing relationships (277) compared to incoming relationships (180), designating it as the main outflow plate. The second plate has a much lower number of outgoing relationships (76) compared to incoming relationships (232); it belongs to the main inflow plate. The third plate has a similar number of outgoing (36) and incoming (40) relationships, with the highest properties of internal relationships; it goes to the bidirectional spillover plate. The fourth plate has 173 outgoing and 110 incoming relationships, with a comparatively lower ratio of internal relationships within the network; it belongs to the agent plate. Looking at the YRB, the first plate has 115 outgoing and 113 incoming relationships, with a comparatively lower ratio of internal relationships; it belongs to the agent plate. The second plate exhibits a significantly higher number of outbound interrelationships (147) compared to incoming relationships (75); it belongs to the main outflow plate. The third plate has a much lower number of outgoing interrelationships (87) compared to incoming relationships (188); it belongs to the main inflow plate. The fourth plate has 106 outgoing and 79 incoming relationships, with a relatively higher proportion of internal relationships; it belongs to the bidirectional spillover plate. Among them, the fourth plate of the YREB and the first plate of the YRB both belong to the agent plate, serving as the link for element communication. The cities in the agent plate are mostly located in the middle reaches, with a special geographical position. They play a vital role in transmitting resources and elements between the downstream and upstream areas. At the same time, they are also closely connected internally, facilitating communication. This makes them serve as the link.

Based on the spatial interaction relationships of each plate, this study further calculated the network density. If the density of a specific plate exceeded the overall density of the network, it was assigned a value of 1; otherwise, it was assigned 0. On this basis, an image matrix for HQED was obtained (Table 5). The probability values on the main diagonal of the image matrix are 1, indicating a significant correlation between HQED within a plate and showing an apparent “club” effect. In addition, within the YREB, only the plate I had spatial overflow to the plate III. Similarly, within the YRB, only the plate I had spatial overflow to the plate III and the plate II had spatial overflow to the plate I. There were no overflow relationships between the other plates, indicating that the YREB and the YRB have not yet formed a coordinated effect of “A game of chess for the entire river basin.”

**QAP analysis**

**Correlation analysis**

The formation mechanism of the network between the YREB and the YRB’s HQED is accurately identified, which is of great significance for constructing a network of correlated interactions for coordinated improvement of HQED in river basins. However, due to the fact that both the correlation matrix of the HQED space and the variable matrix are relational data matrices, using traditional statistical methods to test causal relationships will inevitably lead to bias due to the presence of multicollinearity. Thus, this study employs the non-parametric method known as QAP to empirically investigate the factors that influence the formation of the spatial correlation network for HQED in the YREB and the

**Table 5** Density matrix and image matrix

Plate	YREB				YRB			
	I	II	III	IV	I	II	III	IV
Density matrix								
I	0.496	0.320	0.000	0.119	0.618	0.100	0.209	0.000
II	0.112	0.667	0.000	0.005	0.247	0.461	0.086	0.050
III	0.001	0.000	0.576	0.043	0.058	0.019	0.652	0.123
IV	0.179	0.036	0.050	0.583	0.005	0.070	0.158	0.565
Image matrix								
I	1	1	0	0	1	0	1	0
II	0	1	0	0	1	1	0	0
III	0	0	1	0	0	0	1	0
IV	0	0	0	1	0	0	0	1

YRB. QAP correlation analysis is employed prior to conducting QAP regression analysis to assess the correlation between the spatial correlation network and the influencing factors. This analysis helps determine the suitability of QAP regression analysis by evaluating the strength of the relationship between the network and the influencing factors.

This study obtains QAP correlation results through 5000 random permutations (Table 6). The table points out evidently that seven factors, including reverse geographic distance, industrial structure difference, urbanization level difference, environmental regulation difference, digital economy difference, material capital accumulation difference, and government intervention degree difference, have passed the test at a significance level of 5%, indicating significant correlations with the formation of the associated network for HQED in the YREB and the YRB. Specifically, the correlation coefficients of reverse geographic distance for the YREB and the YRB are positive. In contrast, the correlation coefficients of the other factors are negative, implying a positive correlation between reverse geographic distance

and the spatial correlation network for economic development and a negative correlation between the other factors and the spatial correlation network for HQED. However, correlation does not imply regression relationships, and the impact of regional differences in variables on network needs to be further compared through study.

**Regression analysis**

The QAP regression results in this study were obtained through 5000 random permutations (Table 6). The overall fit levels of the regression equations for the YREB and the YRB were 0.490 and 0.431, respectively. This means that 49.0% and 43.1% of the spatial correlation relations between the HQED of the YREB and the YRB can be explained by seven factors: reverse geographic distance, differences in digital economy, urbanization level, environmental regulations, material capital accumulation, industrial structure, and government intervention.

**Table 6** Results of QAP correlation and regression analysis

Variable	YREB		YRB		YREB		YRB	
	Correlation	P value	Regression	P value	Correlation	P value	Regression	P value
RGD	0.696***	0.000	1.300***	0.000	0.647***	0.000	1.241***	0.000
DE	-0.193***	0.000	-0.080**	0.014	-0.047**	0.011	-0.139**	0.025
URL	-0.056***	0.001	0.334***	0.000	-0.102***	0.000	-0.035	0.613
ER	-0.033**	0.026	-0.070	0.229	-0.057***	0.003	0.173***	0.001
MCA	-0.081***	0.000	-0.021	0.306	-0.151***	0.000	-0.103***	0.000
IS	-0.051***	0.001	0.004	0.628	-0.102***	0.000	0.000	0.959
GID	-0.064***	0.000	0.002	0.981	-0.126***	0.000	-0.121	0.187
R <sup>2</sup>	—	—	0.490	—	—	—	0.431	—
Adj R <sup>2</sup>	—	—	0.490	—	—	—	0.431	—

The symbols \*\*\*, \*\*, and \* represent significance at the 1%, 5%, and 10% levels, respectively. *RGD* reverse geographical distance, *DE* digital economy difference, *URL* urbanization level difference, *ER* environmental regulation difference, *MCA* material capital accumulation difference, *IS* industrial structure difference, *GID* government intervention degree difference

Specifically, (1) the regression coefficients for reverse geographic distance were all significantly positive, indicating that reducing geographic distance is beneficial for forming a spatial correlation network for HQED between cities. This result is consistent with the commonly held view in the academic community (Bai et al. 2020; Wang and Liu 2023). Due to the existence of the first law of geography (the closer the distance between cities, the greater the spatial correlation) (Joo et al. 2017), geographical proximity can facilitate in-depth communication and cooperation for HQED between cities, reduce transaction costs of resource elements, and improve resource utilization efficiency (Wang 2023). It can maximize the spatial spillover effect of urban HQED and effectively promote the formation of its spatial network of relationships.

(2) The regression coefficients for differences in the digital economy were all significantly negative, indicating that more minor differences in the digital economy between cities make it easier to form a correlation relation. The reason is that, under the backdrop of big data, the narrowing of digital economic disparity can effectively improve the efficiency of information dissemination and diffusion, expand the geographic scope of information overflow, and break the spatial constraints of knowledge, technology, and other information (Ferreira et al. 2019). Thereby, the HQED gap between cities is narrowed through the imitation and diffusion effects of “promoting catching up theory” (Franco and Keun 2021), making the spatial connections between cities closer.

(3) The regression coefficient of urbanization level difference is only significantly positive in the YREB, indicating that the urbanization gap has widened, which can strengthen the spatial connection for HQED in the YREB, and He and Xu (2023) have also reached the same conclusion. The reason is that the difference in urbanization level is usually complementary to the difference in human capital accumulation, especially against the backdrop of the continuous exacerbation of the development gap in the new urbanization of the YREB. The talent war has further led to the “plunder” of large cities and the “loss” of small cities. Leading cities are more likely to use the first-mover advantage to generate a “siphon effect” on population and resources (Wang et al. 2022), thereby promoting the formation of spatial connectivity for HQED in the cities of the YREB. But the regression coefficient of the urbanization level difference is not significant in the YRB, which is determined by the level of new urbanization of the cities in the YRB. According to the research by Wang et al. (2016), there are significant differences in the new urbanization among cities in the YREB, while in the YRB, apart from the cities in the Shandong Peninsula urban agglomeration at a relatively high level and some cities in Henan at a moderate level, the vast majority of the remaining cities are at low or very low levels. It indicates

that there is not much disparity in the new urbanization of the YRB, with most cities at a lower level. At the same time, according to the centrality analysis, the driving effect and spillover effect of the cities in the Shandong Peninsula urban agglomeration are not significant. Therefore, the disparity in urbanization level in the YRB is relatively small, and it fails to generate a siphon effect or “drip effect” to enhance the spatial correlation between cities (Zhang and Wen 2022), resulting in the regression coefficient of the urbanization level difference in the YRB not being significant.

(4) The regression coefficient of environmental regulations difference is only significantly positive in the YRB, indicating that the greater the environmental regulation differences, the more helpful it is for the formation of the spatial correlation of HQED among cities in the YRB. The reason is that the YRB is ecologically fragile, and its cities with higher levels of HQED tend to have stronger environmental regulations as well, while the environmental access threshold for social development in low-developed cities is relatively low, forcing polluting enterprises to transfer to these areas to some extent (Zhang and Yao 2023), thereby promoting closer regional connections. This result is consistent with the “pollution haven hypothesis” (enterprises in heavily polluted industries tend to establish themselves in areas with relatively low environmental standards (Dou and Han 2019)). But the regression coefficient of environmental regulation difference in the YREB is not significant.

(5) The regression coefficient of material capital accumulation difference is only significantly negative in the YRB, indicating that the smaller the difference in material capital accumulation between cities in the YRB, the easier it is to form a correlation relationship (Qian et al. 2018). The reason is that the material capital accumulation is reflected in the construction of infrastructure, especially in the construction of transportation infrastructure. The underdevelopment of transportation infrastructure in the upper and middle reaches of the YRB increases its fixed asset investment. It can narrow the gap in transportation infrastructure between the upper and middle reaches and the lower reaches, accelerating the flow of resources and factors of production between cities and weakening path dependence in the transformation process of relatively low-developed cities (Wang et al. 2022), thereby facilitating the establishment of connections between cities in the YRB. But the regression coefficient of material capital accumulation difference in the YREB is not significant.

From (4) and (5), it can be seen that the environmental regulation and material capital accumulation differences have only had a significant impact on the YRB but not the YREB. It is mainly determined by the regional characteristics of the two major rivers. The resources, environment, geography, and transportation factors of the YRB are significantly different from those of the YREB. The

construction of ecological civilization in the YRB started relatively late (Liu et al. 2023a), and its main characteristics include a fragile ecological environment, water resource shortage, and backward infrastructure. In particular, there are tightening constraints on resources, and lack of ecosystem restoration in the upper reaches of the Yellow River, serious soil erosion in the middle reaches, problems of low quality, and inefficiency are prominent, and a strong industrial foundation in the lower reaches, which has formed competitive industrial clusters. This ecological difference has led to significant differences in environmental regulation intensity between the upper, middle, and lower reaches of the Yellow River, which is prone to creating a pollution haven effect, thereby promoting spatial connection between cities in the YRB. However, the economic development level of the YREB is relatively high, the ecological civilization construction started early, the infrastructure is sound, and there are significant achievements of HQD. It makes the overall environmental regulation of the YREB strong, the transportation network developed (especially shipping); it is difficult to produce pollution haven effects and further weaken path dependence, causing both factors to have no further impact on the formation of spatial correlation of the YREB.

(6) The regression coefficient of industrial structure difference is not significant in both the YREB and the YRB, indicating that the industrial structure differences have not affected the formation of HQED spatial correlation in the YREB and the YRB, which is consistent with the research results of Dong and Li (2022) and Zhang and Yao (2023). This paper believes that the reasons for this result may be the following two points: (1) This is determined characteristics by the “marriage of families with similar social status” in regional economic spatial correlation in China, and spatial spillover effects are more likely to occur in cities with similar social status (Huo et al. 2022). Therefore, similar industrial structures are more likely to generate spatial spillover effects, while the existence of industrial structure differences is not conducive to generating spatial spillover effects, thus failing to impact the formation of spatial correlation between cities. (2) According to a study by Gao et al. (2023), cities with the same industrial agglomeration types, due to similar development patterns, have unimpeded city-to-city communication and cooperation, making it easier to form spatial correlation relationships. However, the existence of differences in industrial structure between cities hinders the agglomeration of similar industries, which is not conducive to intercity communication and cooperation, thus failing to significantly impact the formation of spatial correlation relationships.

(7) The regression coefficient of the government intervention degree difference is not significant in both the YREB and the YRB, indicating that the government intervention degree difference does not affect the formation of spatial correlations of HQED. The reason is that local governments distort factor markets, change factor prices, and adjust the optimal behavior of micro-subjects to achieve their own HQD through financial intervention. However, in cities where government intervention is excessive due to the distortion of their factor markets, it will trigger local protectionist thinking and market segmentation phenomena, which only stay within the local area, making it difficult for the impact of government intervention to penetrate further into the spatial relations of the city, leading to the insignificant regression coefficient of the government intervention degree differences.

## Discussion

This study took the relational data as a starting point to cover the HQED of the YREB and the YRB Economic Belt in the same framework for the first time. This expands the research content of the HQED of river basin economies and introduces a novel perspective in spatial analysis of urban HQED. Through the findings mentioned above, it has been discovered that there is a spatial correlation network, which demonstrates both similarities and specific heterogeneity, between the HQED of the YREB and the YRB. From the overall network perspective, the networks of the YREB and the YRB are relatively stable. However, the network density for both is relatively low, which indicates that the degree of spatial correlation between cities for HQED is low (Wang et al. 2022). The network structure exhibits a certain degree of flexibility, providing opportunities to strengthen spatial cooperation and interaction among cities. It is worth noting that a higher network density is not always better. A higher network density can lead to excess connections, and if the number of these excess connections reaches the maximum network carrying capacity, it will reduce the efficiency of factor flow, resulting in an inefficient network. Therefore, when promoting collaborative cooperation between cities, it is important to maintain the network density at a reasonable level to achieve the optimal spatial configuration results. From the individual network perspective, the YREB and the YRB exert substantial differences. In the YREB, cities with higher centrality are distributed in provincial capitals or the YRD urban agglomeration. These cities play a role as central actors and bonds, forming a development model

in which the central city drives the development of other cities. This virtuous development model contributes to the relatively high level of HQED in the YREB. In contrast, cities with higher centrality in the YRB, except for Zhengzhou and Xi'an, are distributed in non-provincial capital areas in the middle reaches of the YRB. However, cities such as Qingdao, Weihai, Yantai, Dongying, Zibo, and Weifang in the Shandong Peninsula urban cluster (ranked third, 6th, 7th, 10th, 11th, and 14th in terms of HQED in 2021), and provincial capital cities like Lanzhou, Hohhot, and Xining (ranked the 8th, 9th, and 15th in terms of HQED in 2021) have high levels of HQED. However, their centrality is relatively low, positioning them at the outer edges of the spatial network in the YRB. This finding suggests that cities with high levels of HQED in the YRB region have limited spatial spillover effects on neighboring cities. Therefore, there is a need to enhance their capacity for driving the development of other cities in the region. Compared to the spatial linkage effects in the YREB, the YRB still needs to form a positive development pattern, resulting in a lower level of HQED as a whole than the YREB. From the spatial clustering perspective, both the YREB and the YRB exhibit distinct spatial clustering phenomena. However, the leading associations and communication occur between cities within each plate, and there are still barriers to communication between the two plates (Zhang and Weng, 2022). The synergistic effect of “A game of chess for the entire river basin” has not yet been formed.

Given the above research, this article still has some limitations. Firstly, due to data limitations, this study only focused on HQED from 2010 to 2021, and thus cannot comprehensively demonstrate the temporal changes in HQED. In the future, further exploration of data and extension of the study period are needed to understand the temporal evolution of HQED comprehensively. Secondly, the network of HQED is subject to a multitude of factors. The examination in the article only includes seven factors, which is somewhat one-sided. Other influencing factors, such as topography and technological progress, need to be further explored by future scholars.

## Conclusions and recommendations

### Conclusion

The study is based on panel data from 189 cities in the YREB and YRB from 2010 to 2021, using the objective weighting method to measure HQED. And an improved gravity model is employed to construct the spatial correlation matrix. Then,

SNA was employed to investigate the overall network characteristics and individual network properties and spatial clustering patterns. Based on this, the QAP model is utilized to explore the spatial correlation networks' formation mechanism. The conclusions are as follows:

Firstly, throughout the duration of the study, there has been a consistent upward trajectory in the advancement of HQED within both the YREB and the YRB. The level of HQED in the YREB has consistently been higher than in the YRB. The YREB exhibits a distribution pattern of “higher in the east and lower in the west.” However, the YRB exhibits a distribution pattern of “lower in the central region and higher on both sides.”

Secondly, the HQED in the YREB and the YRB has surpassed geographical adjacency, demonstrating a complex and multithreaded network structure. From the overall network perspective, the YREB and the YRB exhibit a network connectedness value of 1 and a network hierarchy value of 0, indicating spatial solid connectivity and the absence of hierarchical order. The network efficiency is relatively high, with multiple overlapping phenomena, but the degree of correlation needs to be enhanced, and a substantial degree of stability was observed in various network indicators over the course of the study.

Thirdly, from individual network perspective, the provincial capital cities such as Chongqing, Wuhan, Hefei, Nanjing, Hangzhou, Shanghai, and Changsha in the YREB, as well as the midstream cities in the YRB such as Zhengzhou, Xi'an, Luoyang, Yulin, Hulunbuir, Ordos, and Nanyang, are located at the networks' central position and play the roles of central actors and “bridges.” However, most cities located in the upper reaches of the YREB and middle reaches of the YRB are in peripheral positions within the network.

Fourthly, from spatial clustering perspective, the networks of YREB and the YRB can be categorized into four distinct functional plates: agent plate, main outflow plate, bidirectional spillover plate, and main inflow plate. However, there are fewer inter-plate linkage effects. Cities located at the networks' center mostly belong to the main inflow plate, whereas cities in the middle reaches of the YREB and the YRB are predominantly part of the agent plate, serving as important connectors or intermediaries.

Fifthly, from the regression results, it is apparent that the reverse geographical distance has a notable positive impact on the networks' formation in the YREB and the YRB. The digital economic difference has a significant negative influence on the networks' formation in the YREB and the YRB. However, the difference in urbanization level only has a significant positive influence on the networks' formation in

the YREB. The difference in environmental regulation and material capital accumulation only significantly positively influences the networks' formation in the YRB. The regression coefficients for the remaining explanatory factors did not demonstrate statistical significance, and their influencing mechanisms require further reinforcement.

## Recommendations

Based on the aforementioned research conclusions, this study proposes the following recommendations:

Firstly, the urban HQED of the YREB and the YRB, although still at a relatively low level overall, has already shown a spatial correlation network pattern. It indicates that the improvement of HQED depends not only on the development planning and policies within the cities themselves but also is closely related to the HQD policies and planning implementation of other cities in the basin. Therefore, the government should further enhance the closeness of the spatial correlation network of HQD of cities in the YREB and YRB. The central government should coordinate the overall planning of the entire basin's population, resources, environment, and economic and social development; establish a commission under the State Council; and promote the coordinated ecological protection and HQD of the two major basins. Provincial, municipal, and district governments should also break away from the traditional "point-to-point" thinking, eliminate local protectionism and market segmentation behavior between cities, and create more spatial overflow "pathways" from the perspective of "A game of chess for the entire river basin."

Secondly, developing differentiated development strategies based on the individual network structure features. For the YREB, according to the positioning of various cities in the network, the government should give full play to the core radiation role of Shanghai, Nanjing, Hangzhou, Suzhou, Changzhou, Hefei, and other cities in the Yangtze River Delta, as well as Chongqing, Wuhan, Nanchang, Changsha, Chengdu, and other provincial capital cities, to forcefully drive the HQD of the surrounding areas and even the entire basin. For the YRB, the government should actively guide coastal cities such as Qingdao, Weihai, Yantai, Dongying, Zibo, and Weifang to lead the inland cities and re-establish the central position of the Shandong Peninsula urban cluster and provincial capital cities like Lanzhou, Hohhot, and Xining in the network, fully leveraging their radiation and driving role.

Thirdly, to address the functions of different spatially related plates, the government should break free from the traditional linear thinking of "upstream, midstream, downstream" and tailor its policies to each related plate's specific positions and functions, implementing policies based on local conditions. Focusing on strengthening the bonding effect between the agent plate and the bidirectional spillover plate further expands the scope of the spillover of resources and elements from the main outflow plate, maximizing the spatial spillover effects between plates. Additionally, the government should actively promote communication between plates, using urban agglomeration construction as the pivot and transportation infrastructure construction as the starting point, accelerating the process of HQED from "point" to "axis" to "surface" in river basins.

Fourthly, the YREB and the YRB should break through the constraints of geographical distance and the gap in the digital economy and choose different focuses. The YREB should fully consider the impact of the difference in urbanization levels on the formation of spatial correlation networks. In the process of the new-type urbanization construction, the YREB should take urban agglomerations as the primary spatial carriers of the new urbanization, play a leading role in the development of new urbanization in the Yangtze River Delta urban agglomeration, promote the integrated development of industries in the urban agglomeration in the middle reaches of the Yangtze River (Sun and Huang 2020), strengthen the ecological environment protection efforts of the urban agglomeration in the upper reaches of the Yangtze River, and narrow the urbanization gap in the construction of the YREB in the upper, middle and lower reaches. The YRB should fully consider the driving factors that affect the formation of the spatial correlation network structure, such as differences in environmental regulations and material capital accumulation. The core issue in the YRB is still ecological fragility. The government should change the economic development model and implement the concept of "green waters and lush mountains are invaluable assets" from the overall perspective of the Yellow River ecosystem, promote ecological environment protection and restoration in a classified manner, and protect water sources in the upper reaches, soil and water in the middle reaches, and wetlands in the lower reaches. In addition, the government should also promote economic integration and development, the construction of new infrastructure, and a comprehensive transportation system based on local conditions; increase fixed asset investment; and accelerate the effective accumulation of material capital.



## Appendix 1

**Table 7** Abbreviations of 189 cities

City	Abbreviation	City	Abbreviation	City	Abbreviation	City	Abbreviation
Anqing	AQ	Luzhou	LZ	Yuxi	YX	Nanyang	NY
Anshun	AS	Ma'anshan	MAS	Yueyang	YY1	Pingdingshan	PDS
Bazhong	BZ	Meishan	MS	Zhangjiajie	ZJJ	Pingliang	PL
Bengbu	BB	Mianyang	MY	Changsha	CS	Puyang	PY
Baoshan	BS	Nanchang	NC	Zhaotong	ZT	Qingdao	QD
Bozhou	BZ1	Nanchong	NC1	Zhenjiang	ZJ	Qingyang	QY
Guang'an	GA	Nanjing	NJ	Chongqing	CQ	Rizhao	RZ
Changde	CD	Nantong	NT	Zhoushan	ZS	Sanmenxia	SMX
Changzhou	CZ	Neijiang	NJ1	Zhuzhou	ZZ	Shangluo	SL
Ganzhou	GZ	Ningbo	NB	Ziyang	ZY	Shangqiu	SQ1
Chenzhou	CZ1	Panzhuhua	PZH	Zigong	ZG	Shizuishan	SZS
Chengdu	CD1	Pingxiang	PX	Zunyi	ZY1	Shuozhou	SZ3
Fuyang	FY	Pu'er	PE	Ankang	AK	Taiyuan	TY
Guangyuan	GY	Qujing	QJ	Anyang	AY	Tai'an	TA
Chizhou	CZ2	Quzhou	QZ	Bayannur	BYN	Tianshui	TS
Chuzhou	CZ3	Shanghai	SH	Baiyin	BY	Tongliao	TL1
Dazhou	DZ	Shangrao	SR	Baotou	BT	Tongchuan	TC
Fuzhou	FZ	Shaoyang	SY	Baoji	BJ	Weihai	WH2
Deyang	DY	Shaoxing	SX	Binzhou	BZ2	Weifang	WF
Ezhou	EZ	Shiyan	SY1	Chifeng	CF	Weinan	WN
Guiyang	GY1	Suzhou	SZ	Datong	DT	Wuhai	WH3
Hangzhou	HZ	Suqian	SQ	Dezhou	DZ1	Wulanchabu	WLC
Hefei	HF	Suzhou	SZ1	Dingxi	DX	Wuzhong	WZ1
Hengyang	HY	Suizhou	SZ2	Dongying	DY1	Wuwei	WW
Huzhou	HZ1	Suining	SN	Ordos	OD	Xi'an	XA
Taizhou	TZ	Guyuan	GY2	Xining	XN	Huai'an	HA
Taizhou	TZ1	Hanzhong	HZ2	Xianyang	XY2	Yantai	YT1
Tongling	TL	Heze	HZ3	Xinzhou	XZ1	Yan'an	YA1
Wenzhou	WZ	Hebi	HB1	Xinxiang	XX	Yangquan	YQ
Wuxi	WX	Hohhot	HHT	Xinyang	XY3	Yinchuan	YC3
Wuhu	WH	Hulunbuir	HLB	Xuchang	XC1	Yulin	YL
Wuhan	WH1	Huaihua	HH	Jinan	JN	Yuncheng	YC4
Ji'an	JA	Xianning	XN	Jining	JN1	Zaozhuang	ZZ1
Jiaxing	JX	Xiangtan	XT	Jiayuguan	JYG	Zhangye	ZY2
Jinhua	JH	Xiangyang	XY	Jiaozuo	JZ1	Changzhi	CZ4
Jingmen	JM	Xiaogan	XG	Jinchang	JC	Zhengzhou	ZZ2
Jingzhou	JZ	Xinyu	XY1	Jincheng	JC1	Huanggang	HG
Jingdezhen	JDZ	Xuzhou	XZ	Jinzhong	JZ2	Yancheng	YC
Jiujiang	JJ	Xuancheng	XC	Jiuquan	JQ	Yangzhou	YZ
Kunming	KM	Ya'an	YA	Kaifeng	KF	Yibin	YB
Leshan	LS	Huangshi	HS1	Lanzhou	LZ1	Huaibei	HB
Lijiang	LJ	Lincang	LC	Liaocheng	LC1	Zhongwei	ZW
Lishui	LS1	Huangshan	HS	Linfen	LF	Zhoukou	ZK
Lianyungang	LYG	Yichang	YC1	Linyi	LY	Zhumadian	ZMD
Huainan	HN	Yichun	YC2	Longnan	LN	Zibo	ZB
Lu'an	LA	Yiyang	YY	Luoyang	LY1		
Liupanshui	LPS	Yingtian	YT	Luohe	LH		
Loudi	LD	Yongzhou	YZ1	Lvliang	LL		

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**Data availability** Data will be made available on request.

## Declarations

**Ethics approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Consent to participate** Informed consent was obtained from all the individual participants included in the study.

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