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Analysis of the spatiotemporal coupling coordination relationship between industrial development and water resource security in China

Fuchun Sun[a], Zenan Wang[b,*] and Zhida Ma[c]
[a] School of Applied Economics, University of Chinese Academy of Social Sciences, Beijing 102401, China
[b] College of Music, Shandong Normal University, Shandong, China
[c] School of Government, University of Chinese Academy of Social Sciences, Beijing, China
*Corresponding author. E-mail: 624021@sdnu.edu.cn

ZM, 0000-0002-9762-1879

ABSTRACT

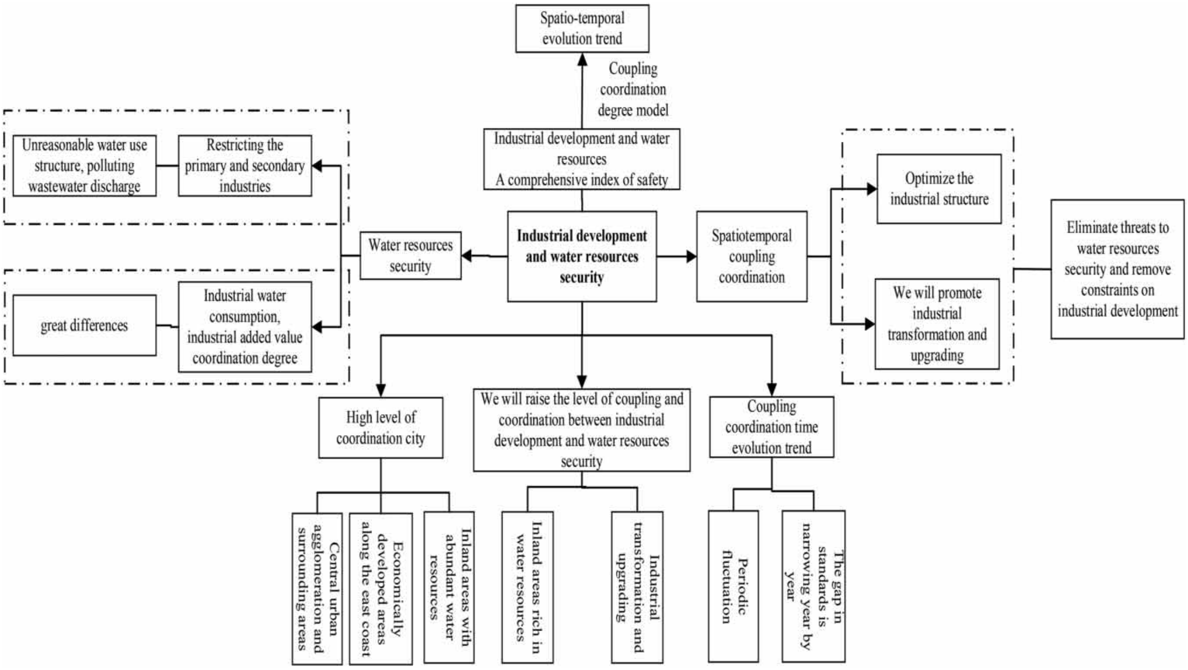
Industrial development is an important part of economic and social development, and a stable pattern of water resource security can meet the needs of economic and social development. Therefore, correctly handling the relationship between industrial development and water resource security in China is the key to achieving high-quality development. This paper takes 287 prefecture-level cities in China from 2010 to 2019 as the research object, establishes the evaluation index system of industrial development and water resource security, calculates the comprehensive index of industrial development and water resource security by the entropy weight method, and analyzes the spatiotemporal evolution trend of the two by using the coupling coordination degree model. The results show that the degree of coupling coordination between industrial development and water resource security in China shows an overall upward trend from 2010 to 2019. Optimizing the industrial structure and promoting industrial transformation and upgrading can effectively improve the coupling coordination level between industrial development and water resource security, and the degree of industrial development threatening water resource security is stronger than the degree of water resource security restricting industrial development. The research conclusion has important practical significance for optimizing industrial structure and implementing regional differentiation policy.

Key words: Coupling coordination, Industrial development, Spatiotemporal analysis, Water resource security

HIGHLIGHT

- This exploration investigates the spatiotemporal variations between industrial development and water resource security at the prefecture-level city level in China, providing reference for promoting industrial development and maintaining stable water resource security.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water resources, essential for human survival, are crucial for maintaining ecological balance and ensuring sustainable socio-economic development (Liping *et al.*, 2009). The rapid population increase has led to rising water consumption. Additionally, water pollution, environmental degradation, and frequent water-related disasters have made scarce water resources a bottleneck for global development, posing significant challenges to water resource security systems. Water resource security issues refer to the conflicts between water supply and demand that harm human living conditions and socio-economic development (Zhong *et al.*, 2022). Industrial development, a critical part of socio-economic growth, has a significant supply–demand conflict with water resources. During industrial development, many regions have pursued economic benefits at the expense of ecological health, leading to water resource overuse and severe threats to water resource security. Therefore, understanding the relationship between industrial development and water resource security in China, mitigating threats from industry to water resource security, and addressing the constraints of water resource security on the industry are crucial.

In 2010, the State Council approved the 'National Comprehensive Water Resources Plan (2010–2030)' (hereinafter referred to as the 'Plan'), which called for 'effectively changing water usage practices and continuously improving the efficiency and benefits of water resource utilization'. Now that the Plan is more than halfway complete, China's water resource security system exhibits the following characteristics: From 2010 to 2019, the water consumption per unit of gross domestic product (GDP) decreased from 146.13 m^3/10,000 yuan to 61.04 m^3/10,000 yuan, improving water use efficiency by 58.23%. On the other hand, in 2019, Shenzhen had the highest water use efficiency with only 7.8 m^3/10,000 yuan per unit of GDP, while Jiamusi had the lowest at 861.5 m^3/10,000 yuan, a difference of over 100 times. Overall, although the management results over the past decade have been significant, differences in the temporal and spatial distribution of water resources directly affect the coordination between regional industrial development and water resource security. In 2021, President Xi Jinping proposed the ‘Four Water Principles’: ‘determining the city, land, population, and industry by water’. The aim is to improve water use efficiency and reduce water resource damage by optimizing industrial structure and promoting industrial transformation and upgrading, thereby achieving water resource security goals and ultimately meeting the water needs of industrial development.

In summary, to understand the ‘Four Waters Four Determinations’ principle scientifically, this study examines the 10 years from 2010 to 2019 following the Plan’s approval, analyzing the coordination between industrial development and water resource security. The ‘industrial development–water resource security’ relationship is a complex system involving multiple factors, including the economy, society, and the environment (Hao & Jianhua, 2012). This paper constructs a comprehensive evaluation index system for industrial development and water resource security, calculates the coupling coordination degree between the two systems, and accurately reflects their overall levels and relationship, providing a basis for achieving spatial and temporal coordination between industrial development and water resource security in China.

The innovation of this paper is to use the comprehensive analysis framework to discuss and solve the coordination of industrial development and water resource security at the national level. By constructing the comprehensive evaluation index system of ‘industrial development–water resource security’, the paper systematically quantifies and analyzes the impact of multiple factors, such as national economic and social development and ecological environment, on water resource security. This framework not only shows the complex relationship between industrial development and water resources but also reveals the dynamics of this relationship across regions and industries. By analyzing water use efficiency and industrial development in different regions across the country, this study identifies the differences in water use and imbalance in resource allocation in different regions of China. The research results provide a scientific basis for optimizing water resources and industrial layout, and support the implementation of the principle of ‘determining city, land, people, and production by water’. This study not only deepens the understanding of the coordination relationship between industrial development and water resource security in theory but also provides strong support for achieving sustainable development goals in practice.

2. THEORETICAL ANALYSIS

‘Industrial development–water resource security’ is a complex system that includes many factors such as economy, society, and ecological environment. Water resource security is the source of vitality to promote high-quality industrial development, and a stable water resource security pattern is the cornerstone of sustainable industrial transformation and upgrading (Jun & Yizhong, 2002). At the same time, the healthy and orderly development of industry is also a key part of water resource security, efficient and reasonable industrial development is conducive to the development and utilization of water resources and provides a strong guarantee for the construction of water resource security (Yonghui *et al.*, 2017). Thus, they constitute an interdependent and interrelated coupling system. Therefore, we should fully recognize the close connection between China’s industrial development and water resource security and put the coordination analysis between industrial development and water resource security into the context of the new era of high-quality development and ecological protection.

The uneven spatial and temporal distribution of water resources in China is the main reason that water resource security restricts industrial development: on the one hand, it has the distribution characteristics of ‘more summer and autumn, less winter and spring’ in time. Different rainfall periods directly lead to uneven distribution of inter-annual and intra-year water resources and frequent land drought and flood disasters (Xinrui *et al.*, 2021). On the other hand, it forms a spatial distribution law of ‘abundant south and lacking north, abundant east and few west'. Some rivers and lakes in the north, central, and western regions with scarce water resources are intermittently cut off, and they cannot even maintain water for basic living and ecological environment. Unreasonable water resources planning and development in water-rich areas such as the south and the east have resulted in differences in industrial development levels among regions (Aijun & Zhiming, 2010). In addition, after water resources are damaged by pollution, they cannot repair and regenerate through their own circulation system, which is also the key to restricting industrial development (Jun & Yizhong, 2002; Zhiming *et al.*, 2014). Therefore, the water resource security constraint of industrial development is caused by the unreasonable development of the industry itself threatening water resource security.

Through the above analysis, it can be seen that water resource security mainly restricts the development of the primary industry and the secondary industry, and the problems caused by the unreasonable structure of agricultural and industrial water use and the discharge of polluted wastewater are in turn threatening the security of water resources. In 2019, China's agricultural water consumption accounted for 61.16% of the country's total water consumption, but the added value of the primary industry only accounted for 7.11% of the GDP, and the discharge of agricultural wastewater pollutants is increasing year by year, so that the water efficiency of many water-rich regions in China is not rising. The scale expansion of agricultural production has not only failed to improve the production efficiency of agricultural technology but also reduced the utilization efficiency of water resources, thus threatening the security of water resources (Lian *et al.*, 2013; Qian & Huajun, 2015). In 2019, China's industrial water consumption accounted for 20.22% of the country's total water consumption, and the added value of the secondary industry accounted for 38.97% of GDP. Although industrial water efficiency is relatively high, there is a large gap in industrial water technology among regions. In areas with relatively backward industrial development, the security and stability of water resources have been neglected in the process of accelerating industrial development, resulting in a decline in the efficiency of water resource pollution emission control. Moreover, these cities are mainly located in the middle and upper reaches of several major river systems in China. As water pollution in these regions continues to worsen, China's overall water resource security will face a dilemma of overall deterioration (Manhong & Yongyi, 2015).

In general, the coupling and coordination between China's industrial development and water resource security are closely related, and the two complement each other (Liping *et al.*, 2009). However, at present, there is still a big difference between the coordination degree of water consumption and the added value of various industries. While the water consumption of industry and agriculture is large, the added value of industry is not high (Jiahang *et al.*, 2021). In China, the tertiary industry accounted for only 6.23% of the total water consumption in 2019, and the added value of the tertiary industry accounted for 53.91% of the GDP, indicating that the tertiary industry has the characteristics of high output value and low water demand. Therefore, actively promoting agricultural water-saving, vigorously promoting industrial water-saving transformation, and accelerating the development of the tertiary industry are important paths to achieve high-quality industrial development and water resource security and stability (Xiaojun *et al.*, 2010; Dan, 2018). Water resource security, as the core part of China's ecological environment security, is also the fundamental reason that restricts China's industrial development. Optimizing the industrial structure and promoting industrial transformation and upgrading is the key to eliminating the threat of water resource security and resolving the constraints of industrial development. Therefore, it is of great theoretical significance and practical value to study the spatiotemporal coupling and coordination relationship between industrial development and water resource security in China.

3. INDICATOR SYSTEM AND RESEARCH METHODS

After analyzing the coupling and coordination effect of industrial development and water resource security, this section constructs an index system for the comprehensive evaluation of China's industrial development and water resource security under the rigid constraints of water resources and adopts the subjective valuation method and entropy method to calculate and analyze the weights of each index in the system. Based on 23 indexes of 287 prefecture-level cities under the jurisdiction of 29 provinces and cities in China from 2010 to 2019, the coupling coordination model is used to analyze the coupling coordination relationship between industrial development and water resource security in prefecture-level cities in China.

3.1. Construction of an indicator system for China's industrial development and water resource security

3.1.1. Industrial development indicator system

The 18th Fifth Plenary Session of the Communist Party of China introduced the new development concept of 'innovation, coordination, green, openness, and shared development'. It established an industrial development index system based on the 'Five Major Development Concepts', capable of revealing both current industrial development status and future trends. This includes five aspects: industrial innovative development, industrial coordination development, industrial green development, industrial openness development, and industrial shared development (Yinliang & Huiyan, 2020).

Industrial innovation development is assessed by the proportion of education expenditure and scientific and technological innovation expenditure. The proportion of education expenditure calculates the share of such expenditure in local fiscal outlays. Education, as the foundation and cornerstone of a nation, reflects the future strength of innovation based on its long-term investment. The proportion of scientific and technological innovation calculates the share of such expenditure in local fiscal outlays. Innovation serves as the primary driving force for development, providing effective support for industrial transformation and upgrading.

Industrial coordination development is assessed through the degree of economic service, the proportion of the tertiary industry, and the gap in nonagricultural labor productivity. The degree of economic service calculates the ratio of value added in the tertiary industry to that in the secondary industry, reflecting the transition from the secondary industry to the tertiary industry after significant development in the former. The proportion of the tertiary industry calculates the share of its value added in GDP. The higher this proportion, the more developed the regional economy. The gap in nonagricultural labor productivity calculates the ratio of value added in the secondary and tertiary industries to the number of employed persons in these industries. China exhibits a small gap in agricultural labor productivity but a significant gap in nonagricultural labor productivity. This difference provides room for labor transfer between industries, thereby promoting industrial development through labor mobility.

Industrial green development is assessed through emissions of smoke, sulfur, carbon, and wastewater, with the measurement method being the ratio of pollutant emissions to industrial value added. Greenness is essential for sustainable development and reflects people's pursuit of a better life. The intensity of pollutant emissions per unit of industrial value added serves as a criterion for assessing whether industries engage in green development. The magnitude of emissions correlates positively with industrial scale and energy consumption intensity but negatively with pollution control and environmental governance.

Industrial openness development is assessed through the proportion of total import and export trade volume and the proportion of actual use of foreign capital in the current year. The proportion of total import and export trade volume calculates the proportion of total import and export trade volume to GDP, while the proportion of actual use of foreign capital in the current year calculates the proportion of actual use of foreign capital to GDP. Together, they reflect the region's position in international trade scale and investment influence.

Industrial shared development is evaluated through the disparity in the level of industrial shared development, residents' income level, and quality of life. The level of industrial shared development is measured using the Engel coefficient, which calculates the proportion of household food expenditure to total consumption expenditure.

A lower value indicates higher income and greater prosperity in the region. The disparity in residents' income level and quality of life is calculated as the ratio of the growth rate of per capita disposable income to the GDP growth rate. If the growth rates remain consistent or if the growth rate of per capita disposable income exceeds that of GDP, it indicates that the achievements of industrial development are benefiting the people more.

3.1.2. Water resource security indicator system

To address China's water resource security issues, promote sustainable water use, and drive efficient economic and social development, a comprehensive water resource security indicator system is established. It encompasses five dimensions: water resource main body security, water resource yield security, water resource social security, water resource economic security, and water resource ecological security (Shaofeng *et al.*, 2002; Jianqiang *et al.*, 2011; Weng *et al.*, 2013).

Water resource main body security is assessed based on per capita water availability and precipitation capacity. Per capita water availability measures the average water quantity per person in a region during a specific period, while precipitation capacity indicates the amount of precipitation in a region over a year. The global average per capita water availability is 9,000 m^3, whereas China's is only 2,200 m^3. Despite being the world's most populous country, China has the lowest per capita water resources, making it extremely challenging to sustain its large population with scarce water resources. Therefore, using the aforementioned indicators to assess water resource main body security is quite reasonable.

Water resource yield security is assessed through the water yield coefficient and water yield modulus: the water yield coefficient describes the proportion of total water resources in a region to precipitation, reflecting the conversion of precipitation into water resource yield; the water yield modulus describes the quantity of water resources per unit area in a region, reflecting the ability of a certain area or basin to produce water.

Water resource social security is assessed through per capita water usage and water consumption per unit gross regional product (GRP): per capita water usage measures the average water consumption per person in a region during a specific period, where water consumption refers to the volume of water used by households. Water consumption reflects the balance between demand and supply of water resources in an area, reflecting the level of social equity in water resource allocation (Jiayuan *et al.*, 2016). Water consumption per unit GRP refers to the amount of water resources used per unit GRP, serving as the primary safety indicator reflecting the level of water consumption and efficiency in water conservation.

Water resource economic security is assessed through agricultural and industrial water use efficiency: Agricultural and industrial water use efficiency is measured by the amount of water used per unit of agricultural and industrial value added, respectively. A higher industrial water usage indicates greater demand for water resources in the area, deeper pressure of water resources on the industry, and greater difficulty in ensuring water supply–demand balance. Therefore, addressing water scarcity primarily involves improving agricultural and industrial water use efficiency.

Water resource ecological security is assessed through ecological water usage and centralized treatment rate of wastewater treatment plants. Ecological water usage refers to the minimum water requirement for ecological environment construction, restoration, and maintenance of existing ecological environment quality without deterioration. The ecological environment improves with an increase in ecological water usage. The centralized treatment rate of wastewater treatment plants refers to the ratio of total wastewater treated by wastewater treatment plants to total wastewater discharged. A higher indicator value indicates greater safety, higher sewage treatment and recycling efficiency, and reduced human pressure on water and water-related ecosystems.

Based on the previous research results on industrial development and water resource security (Peng & Zhenyu, 2019), the core issues of industrial development and water resource security are reflected as comprehensively as possible by following the principles of scientificity, accuracy, and authenticity. Based on existing research on the evaluation of the indicator system (Shaofeng *et al.*, 2002; Jianqiang *et al.*, 2011; Yinliang & Huiyan, 2020), 10 primary indicators are established: industrial innovation development, industrial coordinated development, industrial green development, industrial open development, industrial shared development, water resource main body security, water resource yield security, water resource social security, water resource economic security, and water resource ecological security. Under each primary indicator, 2–3 secondary indicators are further defined, with each secondary indicator corresponding to 1–3 tertiary indicators, resulting in a total of 23 tertiary indicators. Using the subjective assignment method and entropy method and adhering to the principles of indicator system construction, the indicators at each conceptual level are aggregated to obtain a comprehensive and relatively independent assessment indicator system coupling industrial development with water resource security (Table 1).

3.2. Data sources

The data for the industrial development index system constructed in this study are derived from the annual statistical yearbooks of Chinese cities, as well as the statistical yearbooks of provinces, autonomous regions, municipalities directly under the central government, and prefecture-level cities. The data for the water resource security index system are obtained from the water resource bulletins of provinces, autonomous regions, municipalities directly under the central government, and prefecture-level cities. Additionally, historical data from prefecture-level government work reports and government information disclosures from water conservancy bureaus were manually collected and compiled to supplement any missing data. The sample period covers 2010–2019, excluding Tibet, Hainan, and the Hong Kong, Macao, and Taiwan regions, comprising 29 provinces and 287 prefecture-level cities in China, ensuring the survey sample's national representativeness. Foreign exchange-related data, such as total import and export trade volume and total actual use of foreign capital for the current year, were converted to Renminbi using the average exchange rate for that year to eliminate the impact of exchange rate fluctuations.

3.3. Calculation method

3.3.1. Construct indicator matrix

For each of the 287 prefecture-level cities, an initial matrix is constructed consisting of 23 evaluation indicators, $X = \{x_{ij}\}_{m\times n}$, x_{ij} representing the value of the jth indicator for region i.

3.3.2. Data standardization

To eliminate the influence of different units of measurement and ensure the additivity of each indicator layer, it is necessary to standardize each indicator value. Following previous research (Mingxing *et al.*, 2009), the range standardization method is employed for dimensionless processing. However, as zero values may arise after standardization, which would affect the calculation of information entropy in subsequent sections, the standardized data are shifted by 0.000001 to mitigate this issue.

3.3.3. Determining indicator weights

First, subjective valuation is adopted for the destination layer of the industrial development and water resource security indicator systems in China, setting the mutual importance of 10 indicators within the destination layer. Both the industrial development and water resource security conceptual layers are assigned a weight value of 1/5, thereby obtaining the final comprehensive indicators for the two indicator systems.

Second, to ensure the objectivity of the weight results, objective valuation is employed for each indicator layer within the conceptual layer to prevent the subjectivity bias introduced by subjective weighting at different layers

Table 1 | Coupled evaluation indicator system for industrial development and water resource security.

	Conceptual layer	Destination layer	Indicator layer	Weight	Pointer type
Industrial development (I)	Industrial innovation development	Ratio of education expenditure	Education expenditure as a percentage of local fiscal expenditure	0.1851	$+(i_1)$
		Ratio of expenditure on scientific and technological innovation	Expenditure on scientific and technological innovation as a percentage of local fiscal expenditure	0.0149	$+(i_2)$
	Industrial coordination development	Degree of economic serviceization	Value added of the tertiary industry divided by value added of the secondary industry	0.1421	$+(i_3)$
		Proportion of the tertiary industry	Tertiary industry added value divided by GDP	0.0512	$+(i_4)$
		Discrepancy in labor productivity between nonagricultural industries	Added value of the secondary and tertiary industries divided by the number of employees in the secondary and tertiary industries	0.0067	$-(i_5)$
	Industrial green development	Industrial exhaust emissions	Unit industrial value-added dust emission (10,000 tons/10,000 yuan)	0.0741	$-(i_6)$
			Unit industrial value-added sulfur dioxide emission (10,000 tons/ 10,000 yuan)	0.0522	$-(i_7)$
			Unit industrial value-added carbon dioxide emission (10,000 tons/ 10,000 yuan)	0.0328	$-(i_8)$
		Industrial wastewater discharge	Unit industrial value-added industrial wastewater discharge (10,000 tons/ 10,000 yuan)	0.0409	$-(i_9)$
	Industrial openness development	Proportion of total import and export trade	Import and export trade total/GDP	0.1278	$+(i_{10})$
		Proportion of total foreign investment	Total foreign investment for the year/ GDP	0.0722	$+(i_{11})$
	Industrial openness development	Level of shared development in industries	Engel coefficient (family food expenditure/total consumption expenditure)	0.1644	$-(i_{12})$
		Discrepancy in residents' income level and quality of life	Per capita disposable income growth rate/GDP growth rate	0.0336	$+(i_{13})$
Water resource security (W)	Water resource main body security	Per capita water resources	Total water resources divided by the total population of the region (m^3/person)	0.1464	$+(w_1)$
		Precipitation capacity	Amount of precipitation (in 10,000 m^3)	0.0536	$+(w_2)$
	Water resource yield security	Water resource yield coefficient	Water yield coefficient: Total water resources divided by the equivalent rainfall water volume	0.1178	$+(w_3)$

(*Continued.*)

Table 1 | Continued

Conceptual layer	Destination layer	Indicator layer	Weight	Pointer type
	Per unit area water production capacity	Water yield modulus: Total water resources divided by the ratio of the region's area (in 10,000 m³/km²)	0.0822	$+(w_4)$
Water resource social security	Per capita water usage	Total water usage divided by the total population (m³/person)	0.1302	$-(w_5)$
	Water usage per unit of regional GDP	Total water usage divided by GDP (in m³/10,000 yuan)	0.0698	$-(w_6)$
Water resource economic security	Agricultural water use efficiency	Water usage per unit of agricultural added value: Agricultural water usage divided by agricultural added value (in m³/10,000 yuan)	0.1838	$-(w_7)$
	Industrial water use efficiency	Water usage per unit of industrial added value: Industrial water usage divided by industrial added value (in m³/10,000 yuan)	0.0162	$-(w_8)$
Water resource ecological security	Ecological water usage rate	Ecological water usage divided by total water usage	0.1944	$+(w_9)$
	Concentration rate of sewage treatment plants	Sewage treatment volume divided by sewage discharge volume	0.0056	$+(w_{10})$

of the indicator system. Hence, the entropy method is utilized, assigning objective values to the indicators based on the magnitude of their inherent information entropy. Lower information entropy values indicate higher dispersion of the indicator, implying greater information content covered and thus higher weights assigned; conversely, higher information entropy values suggest a more balanced structure for the indicator, resulting in lower weights assigned.

Applying the entropy method (Yang *et al.*, 2012), calculations were conducted for the original data of 66,010 entries comprising 23 indicators across 287 prefecture-level cities in China from 2010 to 2019, resulting in the determination of weights for each indicator (Table 1). Based on the weight results, the industrial development system and the water resource security system exhibit distinct characteristics as follows.

In terms of industrial innovation development, education expenditure accounts for a weight as high as 0.1851. This indicates that currently, across China, the support for education is much higher than that for technological innovation. Moreover, there remains a significant disparity between regions with advanced education and those with lagging education. In terms of industrial coordination development, the degree of economic serviceization plays a dominant role, with a weight of 0.1421. This indicates that the transition and upgrade from the secondary industry to the tertiary industry will directly promote overall industrial development progress. On the other hand, the proportion of the gap in labor productivity in nonagricultural industries is relatively low, highlighting the urgent need to improve the transfer of labor from the primary industry to the secondary and tertiary industries. From the perspective of industrial green development, the proportion of industrial carbon dioxide emissions and industrial wastewater discharge is low. This indicates that the effective implementation of low-carbon environmental protection and measures to prevent water pollution in recent years has played a crucial role. In terms of industrial openness development, the proportion of total import and export trade volume between regions more accurately reflects the degree of openness development, highlighting the importance of strengthening trade exchange and cooperation. Additionally, the proportion of actual use of foreign capital in the current year also holds a certain weight, indicating the need to continue expanding the scope of investment attraction and increasing the use of foreign investment. In terms of industrial shared development, there is a significant disparity in the level of industrial shared development between cities, indicating that many regions have not yet widely benefited from the achievements of industrial development.

In terms of water resource security, the per capita water resource availability essentially reflects the condition of water resources itself, with a relatively high weight of 0.1464. This indicates the uneven spatial distribution of water resources in China, with the difference in precipitation being relatively reduced. It suggests that the objective influence of river and lake systems on spatial distribution can hardly be changed solely by adjusting precipitation. In terms of water resource production safety, there is little difference in the weights of the water yield coefficient and water yield modulus, indicating that the differences in water production and water capacity between regions have been roughly equivalent in recent years. Water usage is a direct cause affecting the economy. In terms of social water resource security, the weight of per capita water usage accounts for 0.1302, indicating that economic development can only proceed further when water resources ensure the basic water needs of the people. In terms of water resource economic security, the weight of agricultural water use efficiency is as high as 0.1838, indicating that the upgrading of agricultural water use has far exceeded that of industrial water use, confirming the pressure of industrial development on water resource security. In terms of water resource ecological security, the weight of the ecological environment water usage rate is as high as 0.1944, which basically depicts the degree of water resource ecological security. Additionally, it has been observed that sewage treatment efficiency has greatly improved in recent years.

3.4. Coupling coordination model

Coupling degree was originally used in the research of physics, and now extends to the research fields of other disciplines, mainly as a method to describe the degree of interaction between various systems or elements. Referring to previous research (Liang *et al.*, 2019), the coupling coefficient model is employed to assess the coupling degree between industrial development and water resource security in China. The calculation formula is as follows:

$$C = 2 \times \sqrt{\frac{\text{Industrial development} \times \text{Water resource security}}{(\text{Industrial development} + \text{Water resource security})^2}} \tag{1}$$

where Industrial development represents the comprehensive index of industrial development, Water resource security represents the comprehensive index of water resource security, and C denotes the system coupling degree, where $C \in [0,1]$.

Furthermore, coupling coordination primarily serves as a descriptive method for assessing the degree of coordinated development between systems or elements, reflecting the magnitude of interdependence and illustrating the quality of coordination between systems. A higher coupling coordination indicates a better coordination relationship between two systems, and its calculation formula is:

$$D = \sqrt{C \times T} \tag{2}$$

$$T = a \times \text{Industrial development} + \beta \times \text{Water resource security} \tag{3}$$

In the equation, D represents the coupling coordination, T denotes the coordination index, α and β are undetermined coefficients used in the formula. As industrial development and water resource security are equally important in this study, $\alpha = \beta = 0.5$ is adopted. To identify which has a deeper impact, the pressure of industrial development on water resource security or the constraint of water resource security on industrial development, a sub-level of coupling coordination is introduced based on the division of coupling coordination sub-levels. I represents the level of industrial development, and W represents the level of water resource security. The division is based on the following criteria: within the same sub-level range of coupling coordination, when the level of industrial development surpasses that of water resource security by more than 0.1, it indicates that the water resource security system lags behind, hindering industrial development; similarly, when the level of water resource security surpasses that of industrial development by more than 0.1, it suggests that the industrial development system lags behind, affecting water resource security stability. Moreover, when the level of industrial development is superior to that of water resource security or vice versa, and the absolute value of their difference is less than or equal to 0.1 and greater than or equal to 0, it indicates that at this sub-level of coupling coordination, the level of industrial development and water resource security remains relatively consistent. Drawing on previous research findings and combining the obtained data for analysis, the coupling coordination (Table 2) is categorized and graded.

4. EMPIRICAL ANALYSIS AND DISCUSSION

After establishing the index system and determining the research method, this section divides the level of China's industrial development and water resource security under the rigid constraints of water resources and the coupling coordination degree between them. The research results show that the degree of China's industrial development threatening water resource security is stronger than the degree of water resource security constraining industrial development, but the level gap between the two is narrowing. In the past decade, China's industrial development level, water resource security level, and the degree of their coupling and coordination have been on

Table 2 | Classification of coupling coordination degree levels for China's industrial development and water resource security.

Coupling coordination interval	Coupling coordination sub-level	Coupling coordination sub-sub-level	Coupling coordination type
$0 < D \leq 0.3$	Severe discoordination	$I–W > 0.1$	Severe discoordination–water resource lag
		$W–I > 0.1$	Severe discoordination–industrial development lag
		$0 \leq \lvert I–W \rvert \leq 0.1$	Severe discoordination
$0.3 < D \leq 0.5$	Basic discoordination	$I–W > 0.1$	Basic discoordination–water resource lag
		$W–I > 0.1$	Basic discoordination–industrial development lag
		$0 \leq \lvert I–W \rvert \leq 0.1$	Basic discoordination
$0.5 < D \leq 0.7$	Basic coordination	$I–W > 0.1$	Basic coordination–water resource lag
		$W–I > 0.1$	Basic coordination–industrial development lag
		$0 \leq \lvert I–W \rvert \leq 0.1$	Basic coordination
$0.7 < D \leq 1$	Advanced coordination	$I–W > 0.1$	Advanced coordination–water resource lag
		$W - I > 0.1$	Advanced coordination–industrial development lag
		$0 \leq \lvert I–W \rvert \leq 0.1$	Advanced coordination

the rise. The cities with high coupling coordination degree are mainly distributed in the central urban agglomeration, the surrounding areas, the eastern coastal areas with developed economy, and abundant water resources. The coordination level of industrial development and water resource security in the Yellow River Basin has a more prominent impact on the construction of the overall pattern in China.

4.1. Patterns of industrial development and water resource security in China

Based on existing research (Liang *et al.*, 2019), we used the standard deviation truncation method to classify the levels of industrial development and water resource security in various prefecture-level cities in China for 2010 and 2019. We divided them into four categories: low-level areas, moderate-level areas, relatively high-level areas, and high-level areas to explore the spatial pattern evolution of China's industrial development and water resource security levels.

4.1.1. Evolution of China's industrial development pattern

From 2010 to 2019, China's industrial development significantly improved. The average industrial development levels in 2010 and 2019 were 0.4059 and 0.4291, respectively, indicating a 5.7% increase. The standard deviations in 2010 and 2019 were 0.0512 and 0.0436, respectively, showing a 14.9% reduction in absolute disparity. The coefficients of variation were 0.1262 and 0.1016, indicating a 19.5% reduction in relative disparity. These results demonstrate that, with the continuous upgrading of industrial structure, both the absolute and relative gaps in industrial development levels among cities are narrowing, optimizing spatial differences and moving toward a more balanced overall development. In 2010, 17 cities, including Beijing, Shanghai, Guangzhou, and Shenzhen, were high-level industrial development areas, mainly concentrated in the developed eastern coastal regions, with more than half in the Pearl River Delta. Sixty-nine cities were low-level areas, primarily in the central and western regions, accounting for one-quarter of all cities. By 2019, the number of high-level cities increased to 60, encompassing provincial capitals, sub-provincial cities, first-tier cities, and new first-tier cities, with significant improvements in the number and spatial distribution of industrial development levels. High-level industrial clusters in regions such as Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Shandong Peninsula, Lanzhou-Xining, and Harbin-Changchun, while less developed clusters need policy improvements. Only 13 low-level cities remained, with 84 medium-level cities scattered across the central, western, and northeastern regions. The industrial development level of Beijing, the highest, and Jiayuguan, Gansu, the lowest, differed by less than twice, further confirming the narrowing gap and the 'east-middle-west' stepped distribution pattern of China's industrial development.

4.1.2. Evolution of China's water resource security pattern

From 2010 to 2019, China's water resource security gradually stabilized, showing significant improvement. The average water resource security levels in 2010 and 2019 were 0.3820 and 0.4149, respectively, marking an 8.6% increase. The standard deviations were 0.0367 in 2010 and 0.0392 in 2019. The coefficients of variation were 0.0960 and 0.0946, respectively, indicating a 7% increase in absolute disparity and a 1.4% decrease in relative disparity. These results suggest that despite various water resource security measures, absolute disparities between cities are widening. However, the reduction in relative disparities indicates an overall improvement in China's water resource security. In 2010, only 12 cities had high levels of water resource security. Apart from Baishan in Jilin, with an 84.5% forest coverage, and Hailar in Inner Mongolia, known as the 'water town', other cities were in Zhejiang, Fujian, Anhui, and Sichuan. These cities are generally located at the intersections of river and lake systems and regions with abundant rainfall. Thirty-three cities had low levels of water resource security. A few of these cities are in southern provinces, but most are in the north, where water resources are scarce, or conservation efforts are insufficient. These cities are mainly concentrated in the northwest and northeast of China, creating a spatial distribution where water resource security weakens from south to north. In 2019, the number of cities with high water resource security significantly increased to 44, mostly located in the Yangtze River Basin and southern regions. However, there were almost no high-security cities in the Yellow River Basin and northern regions, indicating better improvement in the Yangtze River Basin over the past decade. Additionally, 17 cities remained at low levels of water resource security, all in the north. Ya'an in Sichuan, known as the 'rain city of China', had a water resource security level of 0.5997, while drought-stricken Bayannur in Inner Mongolia had a level of 0.2254, showing a nearly threefold difference. This indicates that while overall water resource security in China is improving, the disparity between the north and south is widening, with significant polarization. This north-south disparity is especially evident along the Yangtze and Yellow River Basins.

4.2. Spatial distribution characteristics of the coupling coordination between China's industrial development and water resource security

The complex coupling relationship between industrial development and water resource security systems is reflected in the interactions among various indicators and the temporal and spatial changes. To explain the spatial variation characteristics of the coupling between industrial development and water resource security systems, the coupling coordination degree from 2010 to 2019 was calculated using a coupling coordination model. Referring to the classification of the coupling coordination degree (Table 2), the coupling coordination degree was divided into four levels using the standard deviation truncation method: high, good, moderate, and low coordination. This method provided the annual spatial distribution of the coupling coordination.

Observing the spatial evolution trend of coupling coordination in 2010 and 2019, it was found that in 2010, the overall coupling coordination level was low, with 177 cities classified as low to moderate coupling coordination. Only 21 cities had high coupling coordination, mainly distributed in the economically developed eastern coastal regions and areas with abundant inland water resources, consistent with the spatial distribution of industrial development and water resource security levels. This indicates that the coupling coordination level between industrial development and water resource security is closely related to their fundamental levels. Changes in the basic level within the system will directly affect their coupling coordination. Additionally, there are still differences in the sub-level classification of coupling coordination types. In low coupling coordination cities, the majority are 'low coordination–water resource security lagging' types. Shortly after the 2010 plan was issued, the water resource security levels in lagging cities could not keep pace with industrial development, resulting in an overall low degree of coupling coordination, reflecting the constraint effect of water resource security on industrial development. In moderate and good coordination cities, most are of the type where industrial development lags behind, indicating spatial distribution differences in the coupling coordination degree between industrial development and water resource security. This is related to factors such as the economic and social development levels, location conditions, resource endowments, and natural geographical conditions of each city. The staged characteristics reflect the stress effect of industrial development on water resource security. Mismatched development speeds will limit the coupling coordination level between industrial development and water resource security. When water resource security is good, it provides favorable development conditions for the industry. It is also essential to maintain the harmony and stability of water resource security.

By 2019, the overall coupling coordination level between industrial development and water resource security had significantly improved. Good coupling coordination types dominated, low to moderate types were fewer, and high coupling coordination types increased significantly, comprising one-third of the cities. The overall spatial distribution pattern was roughly similar to 2010. However, in the high coupling coordination sub-level classification, most cities were of the 'high coordination–industrial development lagging' type, which will be further discussed later. It was also found that, apart from the Lansi urban agglomeration, which is severely constrained by water resources, the spatial evolution trend of coupling coordination is more similar to the spatial distribution of industrial development levels than to the water resource security pattern. This suggests that industrial development has a greater impact on the overall coupling coordination degree and exerts more pressure on water resource security. Therefore, in the process of consolidating water resource security, insufficient motivation for industrial transformation and upgrading will intensify the pressure of industrial development on water resource security, severely hindering the coordinated and synchronized development of the two systems. This situation poses potential risks to future urban water resource security.

4.3. Spatial distribution characteristics of the coupling coordination between industrial development and water resource security in China

Analyzing the temporal changes in coupling coordination degree can more specifically reflect the temporal characteristics of the coupling between China's industrial development and water resource security systems. Referencing existing studies on the temporal distribution of coupling coordination (Shengwu *et al.*, 2012) and using the classification method mentioned above, the number of cities with different levels of coupling coordination for each year was calculated. The temporal evolution trend of the number of cities at each sub-level of coupling coordination was then plotted (Figure 1). The following characteristics of changes in the coupling between China's industrial development and water resource security were observed: The number of cities with high coupling coordination showed an overall increasing trend but with fluctuations. Inflection points appeared around 2011 and 2017. The decrease in the number of highly coupled cities in 2011 may be due to the recent issuance of the plan, with many cities yet to implement the policies. The industrial development and water resource security levels in most cities remained unstable. After six consecutive years of increase, the number of highly coupled cities slightly decreased in 2017 but maintained an overall upward trend. This was due to increased efforts in ecological environment governance following the 19th National Congress of the Communist

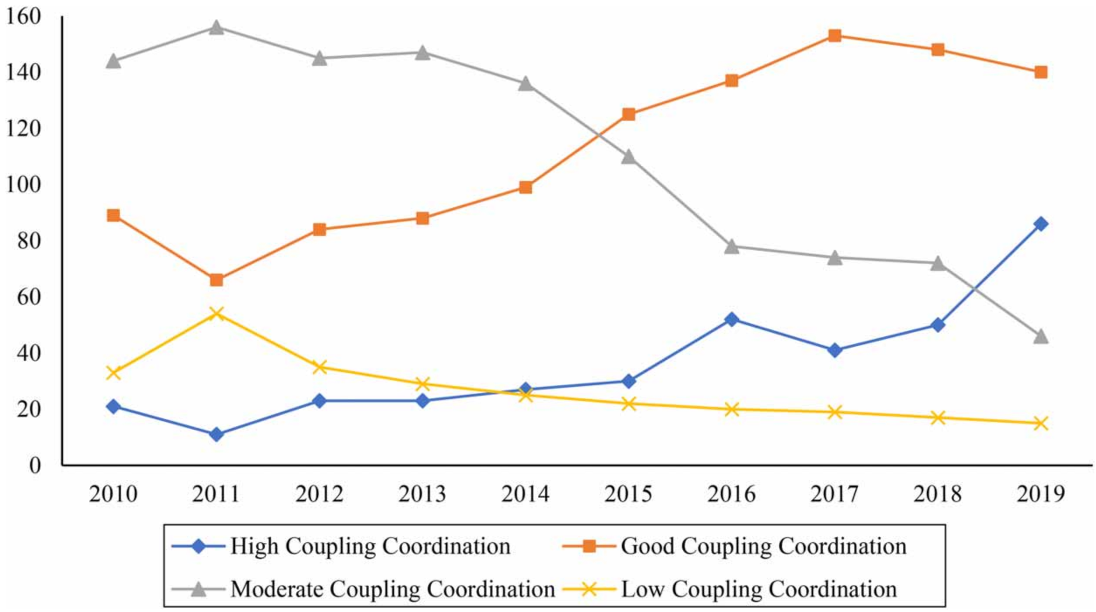


Fig. 1 | Temporal evolution trend of the number of paraisopolar cities with coupling coordination degree.

Party of China. The government enforced mandatory transformation and even shutdown of highly polluting and energy-intensive enterprises, curbing ecological degradation. This improved water resource security levels while reducing industrial development levels, resulting in fewer highly coupled cities. Although some immediate economic benefits might be sacrificed in the short term, leading to higher investment costs and temporary declines in production capacity, it injects new vitality into industrial development in the long run. The number of cities with good coupling coordination also fluctuated in 2011 before rising but began to decline from 2017. This decline is because, after industrial transformation and upgrading, both industrial development and water resource security levels improved, shifting the good coupling coordination degree to a higher level each year. The number of cities with moderate coupling coordination showed a clear overall decline, with the speed of decline occurring in three stages: initially stable, then accelerating, and finally slowing down. This indicates that when the carrying capacity level of water resource security reaches a certain point, it becomes saturated and no longer changes. Cities with relatively backward industrial development gradually transitioned to a good coupling coordination degree during this period. Simultaneously, the development status of cities with low coupling coordination also gradually improved, with their numbers consistently decreasing except for an increase in 2011. In recent years, the coupling coordination relationship between China's industrial development and water resource security has gradually evolved toward a good to high level. Based on this trend, the continuous improvement of the water resource security system will continue to drive industrial development. Therefore, comprehensive management of China's water resource security must continue to ensure the sustainable development of high-quality industry.

The trend in the number of cities at sub-levels of coupling coordination alone cannot fully express the extent to which industrial development pressures water resource security or vice versa. Therefore, by observing the trend in the number of cities at sub-levels, we further analyze the degree of coupling coordination between the two. We calculated the number of cities lagging in water resource security and industrial development and plotted the trend of city numbers at sub-levels over time (Figure 2). The number of cities lagging in water resource security has generally declined, except for fluctuations in 2017. Overall, more cities have better water resource security than industrial development. This indicates that water resource security levels are generally better than industrial development levels, with the pressure from industrial development on water resource security being greater than the constraint of water resource security on industrial development. This result aligns with the spatial distribution patterns. However, examining the trend reveals that since 2012, the constraint of water resource security on industrial development has increased, while the pressure of industrial development on water resource security has lessened. This suggests that the gap between the two levels is narrowing, with increasing demands for water resource security from industrial development. As the pace of industrial optimization and upgrading accelerates, a higher level of water resource security is needed to support this transformation.

Although the complex interaction between industrial development and the internal indicators of the water resource security system has been identified, how to better interact and optimize in the future at the specific operational level still needs to be further explored. Existing governance measures are effective, but continued attention needs to be paid to the key role of educational innovation and industrial structure optimization in ensuring long-term water security. The eastern coastal and inland water-rich regions exhibit a high degree of coupling and coordination, making these regions the focus of policy optimization and resource allocation. This reflects the important impact of economic activity concentration and the accessibility of natural resources on regional industrial development. Since 2010, the variation of the coupling coordination degree of each city is quite different, and the level has changed from low to good. Highly coupled coordinated cities are basically distributed in the eastern coastal areas with developed economies and abundant water resources, which are related to the social, economic, and cultural level of the cities and natural location factors, forming the distribution characteristics centered on several major urban agglomerations in China.

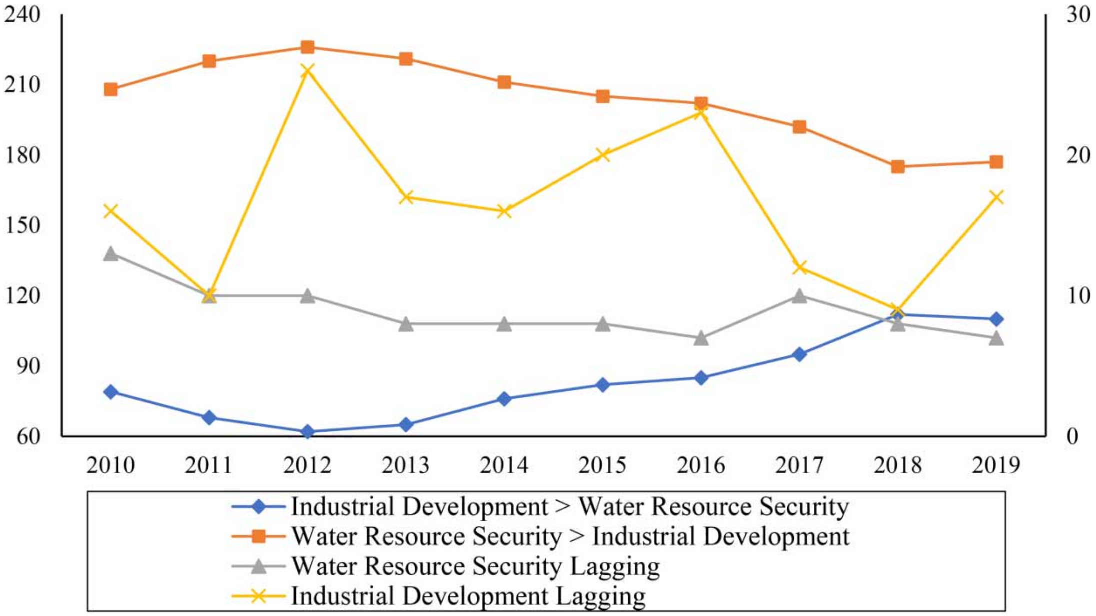


Fig. 2 | Temporal evolution trend of the number of cities at the sub-level of coupling coordination degree.

5. CONCLUSION

Based on the construction of the index system and the application of the coupling coordination method, the main factors of China's industrial development and water resource security and the spatiotemporal evolution of the coupling coordination degree are analyzed, and the following conclusions are drawn:

(1) The interaction and coupling between industrial development and the internal indicators of the water resource security system are complex, and the overall table shows the stress effect of industrial development on the water resource security system and the restraint effect of water resource security on the industrial development system. The level of industrial development has increased by 5.7%, the level of water resource security has increased by 8.6%, and the management effect of water resources is obvious. It is found that insufficient investment in education innovation, unreasonable industrial structure, and gaps in industrial pollutant discharge and treatment are the main factors that stress water resource security. The uneven distribution of water resources in time and space, low water use efficiency, and insufficient ecological water input are the main reasons restricting the development of the industry.

(2) The spatial analysis results of the coupling coordination degree of industrial development and water resource security show that since 2010, the coupling coordination degree of each city has a large variation, and the level has changed from low to good to high. The highly coupled coordinated cities are basically distributed in the economically developed areas along the eastern coast and the inland areas with abundant water resources, which are related to the social, economic, and cultural level of the cities and the natural location factors, forming the distribution characteristics centered on several major urban agglomerations in China. The spatial evolution trend of coupling coordination is more similar to the distribution characteristics of the evolution trend of industrial development level, indicating that industrial development has a greater impact on the overall

coupling coordination degree. Optimizing industrial structure and promoting industrial transformation and upgrading can effectively improve the coupling coordination level of industrial development and water resource security.

(3) The time analysis results of the coupling coordination degree of industrial development and water resource security show that after the promulgation of the Plan and the implementation of relevant measures formulated by the 19th National Congress, the sequential changes of the coupling coordination degree of industrial development and water resource security system show significant characteristics of stages and fluctuations. This paper finds that the stress effect of industrial development on the water resource security system is deeper than the constraint effect of water resource security on industrial development in general. Fortunately, the level gap between the two is narrowing year by year, and from the long-term trend, the instability of water resource security will restrict the high-quality development of future industries. After the implementation of the policy, the periodic changes and fluctuations of the coupling coordination degree in time reveal the delayed effect of the policy response and the dynamic adjustment needs. This phased feature provides the basis for policy optimization and adjustment direction, so as to enhance the synchronization and consistency of water resources management and industrial development.

(4) Water resource security has gradually become an important carrier of industrial development, and the macro-strategy of constantly adjusting and optimizing industrial structure on the basis of maintaining water resource security and stability has formed a long-term mechanism. While continuously improving the growth pole of the coordination degree between industrial development and water resource security, the improvement work of the middle and low coupling coordination city also needs to be solved. The cities in China are mainly concentrated in economically backward areas and water-scarce areas in the central and western parts of the country and northeast of the country. Therefore, the promotion of high-quality industrial development should be carried out simultaneously with the consolidation and stability of water resource security rural revitalization and common prosperity. These cities lack natural basic conditions for development. First of all, solving the problem of resource imbalance between cities and within urban and rural areas is the key to solving the low level of coordination and realizing the policy of common prosperity, and it will have a far-reaching impact on the coordinated development of regions in China. In addition, the Outline of Ecological Protection and High-quality Development Planning for the Yellow River Basin, as a programmatic document guiding industrial development and water resource security in the Yellow River Basin, also provides the direction of thinking and theoretical basis for the overall pattern construction planning.

(5) This paper discusses the spatial and temporal distribution characteristics of the coupling coordination between industrial development and water resource security in China, and expounds on the influencing factors of the coupling coordination between systems, providing a detailed and comprehensive understanding of how to optimize and adjust the industrial structure and consolidate the water resource security in China. The research based on the coupled coordination model provides a new paradigm for the research of industrial development and water resource security, but due to the availability of data, only the data from 2010 to 2019 is selected for analysis. Whether these 10 years can reflect the trend of coupling coordination in longer time series needs to be investigated by follow-up studies.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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