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Study on Spatial and Temporal Differences of Water Resource Sustainable Development and Its Influencing Factors in the Yellow River Basin, China

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Abstract: This study conducted a comprehensive analysis of the spatial and temporal variations of water resource carrying capacity (WRCC) and its influencing factors in the significant Yellow River Basin in China. Combining the composite weighting TOPSIS method with geographic detector analysis, the water resource carrying capacity index for nine provinces within the Yellow River Basin was evaluated from 2005 to 2021. The results reveal a continuous upward trend in water resource carrying capacity in the Yellow River Basin, with significant improvements attributed to increased investment in scientific research, enhanced water use efficiency, proactive water resource management, and environmental protection measures. The study also identified differences in water resource carrying capacity among provinces, highlighting the significant impact of factors such as economic development, population density, industrial wastewater discharge, and precipitation. The findings underscore the importance of balancing economic growth with environmental protection. Specifically, Inner Mongolia and Ningxia provinces showed remarkable progress, while Qinghai and Sichuan provinces exhibited slower growth, primarily due to geographical location and industrial development status. Based on these findings, it is recommended that research investment be strengthened, economic structures be optimized, water resource management be improved, and environmental protection measures be enhanced.

Keywords: Yellow River Basin; water resource carrying capacity; temporal and spatial analysis; economic and environmental protection; sustainable development

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1. Introduction

The Yellow River, the second longest river in China, provides valuable water resources for agricultural irrigation, industrial use, and residential water supply within the basin, promoting economic and social coordination among different areas [1,2]. The river plays a significant role in advancing regional integration, optimizing resource allocation, and facilitating industrial upgrading, thus contributing to the sustainable development of water resources in the Yellow River Basin [3,4]. Despite accounting for only 7% of China's total water resources, the Yellow River Basin supplies water to 12% of the country's population, 17% of its arable land, and over 50 large and medium-sized cities. With a water utilization rate of 80%, the per capita water resources availability in the basin is only 27% of the national average, indicating significant pressure on the water resources environment. The protection and high-quality development of the Yellow River Basin, along with coordinated development in the Beijing–Tianjin–Hebei region, the Yangtze River Economic Belt, the Guangdong–Hong Kong–Macao Greater Bay Area, and the integrated development of the Yangtze River Delta, have become major national strategies in China [5]. In recent years, the Chinese government has placed significant emphasis on the conservation of the ecological environment and the effective management of water resources in the Yellow River Basin. This commitment has been demonstrated through implementing a series of policies and strategic initiatives. It is anticipated that safeguarding and fostering the sustainable development of the Yellow River Basin will continue to be a primary focus of the government's agenda in the foreseeable future [5]. The water resources carrying capacity (WRCC) in various provinces within the Yellow River Basin is subject to a range of influencing factors, including economic conditions, environmental pressures, industrial dynamics, infrastructure quality, and shifts in governmental policies. Conducting a systematic assessment of WRCC's sustainable development and an analysis of the evolving driving forces holds substantial value as a guiding framework for governmental decision-making concerning water resource development.

WRCC refers to the maximum capacity of the water environment in a region to supply water for industrial, agricultural, population, and ecological needs. Research on WRCC can be traced back to the 1960s when people began to focus on managing and utilizing water resources. The emphasis was primarily on water supply and usage, with the main goal of meeting basic human water needs and ensuring the sustainable supply of water resources [6]. In the 1980s, as awareness of sustainable water resource utilization increased, scholars such as Young, R. (1985) [7] realized that simply focusing on the quantity of water resources was not enough. It was necessary to consider the quality and sustainability of water resources, which led to the gradual formation of the concept of WRCC. In the 1990s, researchers such as Pimentel, D. (1997) [8] and Kundzewicz, Z. (1997) [9] began to propose definitions of WRCC and attempted to develop corresponding indicators for measurement and assessment. Water resources carrying capacity was defined as the ability of a region or basin to sustainably utilize water resources over a certain period. Starting in the 21st century, researchers such as Xu, Z. (2004) [10] developed various methods and models to better understand and evaluate WRCC. Tools such as system dynamics, water resources system models, and watershed models were applied in the study of WRCC, considering the interactions among factors such as human activities, water cycle processes, and environmental factors [11]. Since 2010, WRCC research has entered a phase of integration and sustainable development. The study of WRCC has gradually merged with the concepts of ecological and environmental protection and sustainable development. Scholars such as Deng, L. (2021) [12] focused on the relationship between WRCC and ecosystem health and biodiversity conservation, emphasizing the coordinated development of sustainable utilization of water resources and environmental protection.

In recent years, research on WRCC has been closely linked to the goals of sustainable development. Scholars such as Zare, F. (2019) [13] and Dost, R. (2023) [14] made efforts to explore the balance between WRCC and economic growth, social development, and environmental protection, aiming to achieve sustainable development of the economy, society, and environment. The main aspects covered in the study of WRCC are as follows: Firstly, sustainable management and governance of water resources. With increasing global water resource pressures, researchers such as Li, P. (2018) [15], Xiang, X. (2021) [16], Nie, S. (2021) [17], and Yang, J. (2023) [18] focused on achieving sustainable management and governance of water resources. Key issues include improving water supply systems, promoting water-saving measures, optimizing water resource allocation and distribution mechanisms, and addressing water pollution. Secondly, assessment and prediction of WRCC. Researchers have been committed to developing more accurate and reliable methods for assessing WRCC. Scholars such as Liu, T. (2020) [19], He, L. (2021) [20], and Wei, Y. (2021) [21] utilized remote sensing technology, geographic information systems, and modeling simulations to explore the spatial distribution characteristics and trends of WRCC, providing scientific evidence for decision-making. Thirdly, the relationship between water resources and climate change. The impact of climate change on water resources has become an important research direction. Researchers such as Mall, R. K.

(2006) [22], Ostad-Ali-Askar (2018) [23], Yu, Y. (2019) [24], and Araza, A. (2021) [25] focused on the effects of climate change on precipitation distribution, evaporation–transpiration, and snow and ice melting, studying their potential impacts on WRCC and exploring corresponding adaptation measures. Fourth is the interaction between water resources and the ecological environment. Recent studies have emphasized the interaction between WRCC and the ecological environment. Researchers such as Wang, X. (2019) [26], Haro-Monteagudo (2020) [27], and An, Z. (2021) [28] have explored the impact of water resource utilization on aquatic ecosystems, with particular attention to the health status of rivers, lakes, wetlands, and urban ecosystems, aiming to achieve sustainable utilization of water resources and protection of the ecological environment. Fifth is the relationship between WRCC and socio-economic development. In the study conducted by Ebrahimi Sarindizaj, E. (2022) [29], Li, Y. (2019) [30], Li, J. (2019) [31], Zhang, X. (2020) [32], Li, L. (2022) [33], and Shi, C. (2022) [34], the research directions encompass exploring the interplay between water resource utilization and various domains, including agriculture, industrial development, and urbanization. Furthermore, the investigation examines the correlation between water resource utilization and broader societal concerns, such as social equity, food security, and energy security. Lastly, transboundary water resources cooperation and management. With the increasing demand for cross-border allocation and cooperation of global water resources, researchers such as Zhou, R (2022) [35], Arain, H. (2019) [36], Upadhyay, M. (2020) [37], Yin, Y. (2021) [38], and Mohtar, W. (2021) [39] focused on transboundary water resources management and cooperation mechanisms. Key research areas include international river basin water resources cooperation, resolution of transboundary water resource conflicts and international legal and policy frameworks for water resource governance.

In summary, the exploration of WRCC has evolved significantly over time. Initially rooted in resource economics, it has subsequently expanded into environmental economics, regional development, and sustainable development [40,41]. Scholars have progressively realized that WRCC encompasses not only resource utilization and environmental capacity but also broader objectives, including economic growth, social equity, and environmental protection [42,43]. Consequently, WRCC research has transitioned from its origins as a single-disciplinary study to encompass multidimensional and comprehensive research directions. Furthermore, WRCC research has witnessed significant growth and depth in its methodologies and applications. In terms of assessment methods, researchers have advanced from initial single-indicator evaluations to the development of comprehensive indicator systems and multidimensional evaluation approaches. These advancements aim to provide a more holistic understanding of various facets of sustainable industrial development. This integration has offered valuable references and guidance to governments and decision-makers alike.

Prior research efforts have undeniably made substantial contributions to the field of WRCC, driving progress in sustainable water environment development. Nonetheless, certain limitations are evident within the existing body of literature. A predominant focus of these studies has been directed toward individual provinces or countries, thereby neglecting comprehensive inquiries into WRCC within the Yellow River Basin. Moreover, many research efforts have solely examined WRCC from a temporal or spatial standpoint without comprehensively analyzing the spatiotemporal variations within the basin. Additionally, while some scholars have explored spatial changes related to WRCC, a comprehensive understanding of the influencing factors responsible for spatial variations in the Yellow River Basin remains lacking.

This paper contributes and innovates in the following aspects: First, it establishes an evaluation indicator system for WRCC in the Yellow River Basin, enriching the theory and practice of sustainable water resources development. Second, it conducts a comprehensive assessment of WRCC in the nine provinces of the Yellow River Basin and analyzes their spatial characteristics. Third, by utilizing the geographic detector, it investigates the influencing factors of WRCC in the Yellow River Basin and explores the interactive relationships among these driving factors, providing a basis for improving the water resources environment.

2. Model Construction and Research Methods

2.1. Evaluation Index Selection

WRCC is a complex system encompassing multiple elements, including the environment, economy, and society. Assessing its level of sustainable development requires establishing a comprehensive indicator system. This model offers a structured approach to analyze the relationship among various factors, reducing redundancy and enhancing efficiency. As such, the DPSIR model serves as a valuable framework for evaluating water resources carrying capacity.

The DPSIR model is a thinking model that describes complex systems [44]. Based on DPSIR, the WRCC model can comprehensively depict the evolutionary feedback mechanism of the "water–environment–economy–policy" system: potential driving forces → pressures on the water system → state of the water environment → impacts generated → responses made by humans. In the model, driving forces (D) encompass social development, economic construction, and human demands; pressures (P) include pollutant emissions and resource consumption; state (S) includes water supply volume, per capita water resources, and so on; impacts (I) encompass indicators related to water environment, such as water supply coverage and natural reserve area; responses (R) refer to the actions taken by decision-makers in response to undesired impacts.

The WRCC evaluation based on the DPSIR model offers a comprehensive and well-structured approach, providing a holistic evaluation framework and decision support. However, its limitations lie in the substantial requirement of panel data support and the potential subjectivity in determining evaluation criteria. To address these issues, this study aims to construct a scientifically reasonable evaluation indicator system and utilize the entropy weight and coefficient of variation method to enhance the objectivity and accuracy of the results.

In order to conduct an objective and scientific evaluation of WRCC in the nine provinces of the Yellow River Basin, this study, based on the DRSIR model and referring to the works of Wang, Y. (2018) [45] and Zuo, Q. (2021) [46], establishes a WRCC evaluation indicator system consisting of 25 indicators. The selection of these indicators considers the characteristics of water resources and data availability (Table 1). In the indicator system, the attribute "+" indicates a higher value that is more favorable, while the attribute "-" indicates a lower value that is more favorable.

Table 1. Evaluation indicator system for WRCC in the Yellow River Basin.

Standard Layer	Index Layer	Unit	Indicator Property
Driving (D)	X1: GDP per capita	CNY 10,000	+
	X2: Urbanization rate	%	+
	X3: Population density	People per square kilometer	+
	X4: Proportion of tertiary industry	%	+
Pressure (P)	X5: Industrial wastewater discharge	10^4 metric tons	-
	X6: Water usage per unit of cultivated land	Cubic meters per hectare	-
	X7: Water usage per CNY 10,000 of industrial-added value	Cubic meters per 10^4 yuan	-
	X8: Water usage per CNY 10,000 of GDP	Cubic meters per 10^4 yuan	-
	X9: Per capita domestic water consumption	Cubic meters per person	-
State (S)	X10: Precipitation per unit area	10^8 cubic meters per hectare	+
	X11: Water resources per unit area	Cubic meters per square kilometer	+
	X12: Per capita water resources	Cubic meters per person	+
	X13: Per capita grain production	Tons per person	+
	X14: Water resources development and utilization rate	%	-
	X15: Surface water supply	10^8 cubic meters	+
	X16: Forest coverage rate	%	+

Table 1. *Cont.*

Standard Layer	Index Layer	Unit	Indicator Property
Impact (I)	X17: Urban water supply coverage rate	%	+
	X18: Effective irrigation area	10^3 hectares	+
	X19: Proportion of nature reserve area	%	+
	X20: Green coverage rate in urban built-up areas	%	+
Response®	X21: Research and development expenditure of industrial enterprises above a certain scale	CNY 10,000	+
	X22: Investment in industrial pollution control and treatment	CNY 10,000	+
	X23: Wastewater treatment rate	Percentage	+
	X24: Wastewater treatment capacity	Ten thousand tons per day	+
	X25: Per capita environmental water consumption	Cubic meters per person	+

2.2. Calculation Methods

2.2.1. Weight Calculation

The entropy weight method is a widely recognized and objective approach for determining the weights of multiple indicators in multi-criteria decision-making [28,37]. This method, based on information entropy theory, ensures objectivity, comprehensiveness, and convenience in assessing the importance of each indicator. The specific steps of the entropy weight method involve data collection, normalization, calculation of relative entropy, weight calculation, and potential weight adjustment. By following these steps, decision-makers can obtain comprehensive and reliable weights for the indicators, facilitating a systematic and informed decision-making process.

(1) To normalize the index, the original matrix X, consisting of x_{ij} values representing the original data for the i-th province and j-th indicator are processed. Normalization is performed separately for positive and negative indicators, resulting in a standardized matrix Y, represented as $(y_{ij})_{m\times n}$.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

$$y_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} (for\ positive\ indicators) \tag{2}$$

$$y_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} (for\ negative\ indicators) \tag{3}$$

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{4}$$

(2) Calculating index weights using the entropy weight method involves initially normalizing the matrix Y to derive the matrix f_{ij}, which signifies the normalized values. This step ensures fair comparisons and reduces the influence of different measurement units. The entropy weight method then calculates the entropy value for each index based on f_{ij}, reflecting the diversity and differentiation among the indices. Higher entropy values indicate greater importance. The calculation formula is as follows.

$$f_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}} \tag{5}$$

After normalizing the matrix to obtain f_{ij}, the entropy weight method calculates the information entropy e_i for each index. This entropy value quantifies the relative importance and variability of the indices. Higher entropy values indicate greater significance. The calculation formula is as follows.

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m}\left[f_{ij} \times lnf_{ij}\right] \quad (6)$$

The entropy weight method concludes by calculating the index weights ω_j', reflecting the relative importance of each index. Decision-makers can objectively determine index weights using the entropy weight method.

$$\omega_j' = \frac{1-e_j}{\sum_{j=1}^{n}\left(1-e_j\right)} \quad (7)$$

The coefficient of variation method is an objective approach that allows determining weights unaffected by the dimensionality of indicators. It helps capture the spatial differences in WRCC levels among provinces in the Yellow River Basin. By considering the coefficient of variation, decision-makers can assess the relative variations in WRCC and identify provinces with higher variability. This method provides a quantitative means to compare WRCC variations based on indicators' mean and standard deviation, facilitating a comprehensive evaluation. Through utilizing the coefficient of the variation method, decision-makers gain insights into the heterogeneity of WRCC across the basin, supporting targeted strategies and interventions for promoting sustainable development.

$$C = \frac{1}{R_0}\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(R_I - R_0\right)^2} \quad (8)$$

$$\omega_j'' = \frac{C}{\sum_{j=1}^{n} C} \quad (9)$$

The coefficient of variation (C) formula incorporates components such as the average value (R_0), original value (R_i), and weight (ω_j') to determine the weights of each index. Equation (10) represents the calculation formula for the combined weight (A), while the resulting weight values are presented in Table 2. This approach allows decision-makers to assess the significance of each index quantitatively and identify variations among them. By considering the combined weights (A) and referring to Table 2, decision-makers can make informed evaluations and effectively utilize the weight results. This comprehensive and objective assessment enhances the accuracy and reliability of decision-making processes, leading to more effective resource allocation, planning, and policy development.

$$\omega_j = \frac{\omega_j' + \omega_j''}{2} \quad (10)$$

Table 2. Weighting of WRCC indicators in the Yellow River Basin.

User Symbol	Entropy Weighting	Coefficient of Variation Weighting	Comprehensive Weighting
X1	0.027	0.030	0.028
X2	0.024	0.017	0.020
X3	0.042	0.067	0.055
X4	0.025	0.018	0.022
X5	0.027	0.009	0.018
X6	0.026	0.008	0.017
X7	0.026	0.003	0.015
X8	0.026	0.002	0.014
X9	0.024	0.011	0.018
X10	0.025	0.023	0.024
X11	0.051	0.068	0.059

Table 2. *Cont.*

User Symbol	Entropy Weighting	Coefficient of Variation Weighting	Comprehensive Weighting
X12	0.100	0.139	0.119
X13	0.041	0.041	0.041
X14	0.028	0.007	0.017
X15	0.035	0.044	0.039
X16	0.030	0.035	0.032
X17	0.027	0.016	0.021
X18	0.035	0.050	0.042
X19	0.042	0.065	0.054
X20	0.024	0.008	0.016
X21	0.099	0.118	0.108
X22	0.057	0.056	0.057
X23	0.030	0.030	0.030
X24	0.047	0.056	0.052
X25	0.083	0.080	0.081

2.2.2. Spatial Autocorrelation Analysis

Spatial autocorrelation analysis in the Yellow River Basin's water resources carrying capacity has revealed spatial distribution patterns, assessed spatial dependence, aided in regional planning, identified hotspot areas, and improved decision support [41].

$$I = \frac{\sum_{i=1}^{n} \sum_{j}^{n} \omega_{ij} (x_i - \overline{x}) / \left(x_j - \overline{x}\right)}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} \omega_j} \tag{11}$$

2.2.3. Geodetector

A geodetector is a spatial statistical tool that is extensively employed for detecting spatial variations in phenomena and uncovering their underlying driving factors [42]. According to its fundamental theory, when an explanatory variable significantly influences the spatial variation of a dependent variable, there will be a conspicuous spatial similarity between the distribution patterns of the explanatory and dependent variables. In the context of this study, we utilized the geodetector model to explore the factors driving spatiotemporal variations in WRCC within the Yellow River Basin. The model's specific formula is as follows:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^{L} Nh\sigma_h^2 \tag{12}$$

2.3. Study Area and Data Sources

In this study, we selected nine provinces along the main stream of the Yellow River as the study area (Figure 1). A total of 25 indicators were included in this study. The data for indicators such as industrial wastewater discharge, forest coverage, and ecological water consumption were obtained from the *China Environmental Statistics Yearbook*. Data for sewage treatment capacity, investment in sewage treatment facilities, and investment in industrial pollution control were obtained from the *China Statistical Yearbook*. Data for grain production and cultivated land area were sourced from the *China Agricultural Statistics Yearbook*. Other indicators were obtained from the statistical yearbooks of respective provinces. For certain years where data were missing or not directly available, interpolation methods were employed to supplement the data.

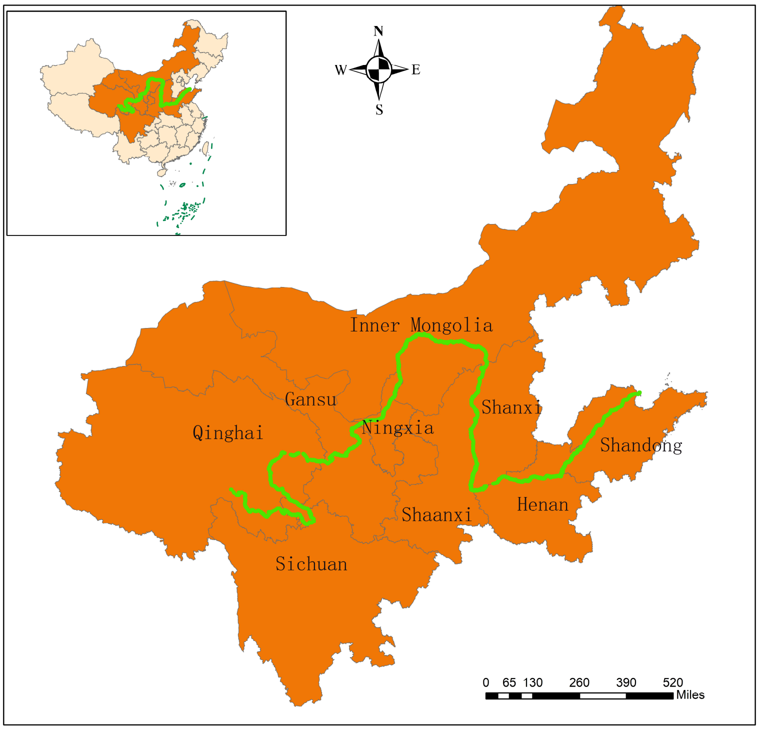

Figure 1. Location map of the study area.

3. Temporal and Spatial Variation of WRCC in the Yellow River Basin

3.1. Time Change Analysis of WRCC in the Yellow River Basin

The WRCC indices of the nine provinces in the Yellow River Basin from 2005 to 2021 were measured using the composite weighting TOPSIS method. The WRCC index trends were plotted based on the data from 2005, 2010, 2015, and 2021 (Figure 2). The WRCC index in the Yellow River Basin exhibited a persistent upward trajectory from 2005 to 2021, reaching its zenith at 3.771 in 2021. This substantial increase represents a significant expansion compared to its initial value in 2005. This indicates that significant progress has been made in improving the water resource environment in the Yellow River Basin. Analyzing the five sub-indices of WRCC, the response (R) and driving force (D) indices experienced the highest growth rate, increasing by 397.3% and 128.3%, respectively, since 2005. This suggests that the improvement in WRCC in the Yellow River Basin is attributed to increased investment in scientific research and enhanced water use efficiency, as well as proactive measures to improve water resource management and conservation.

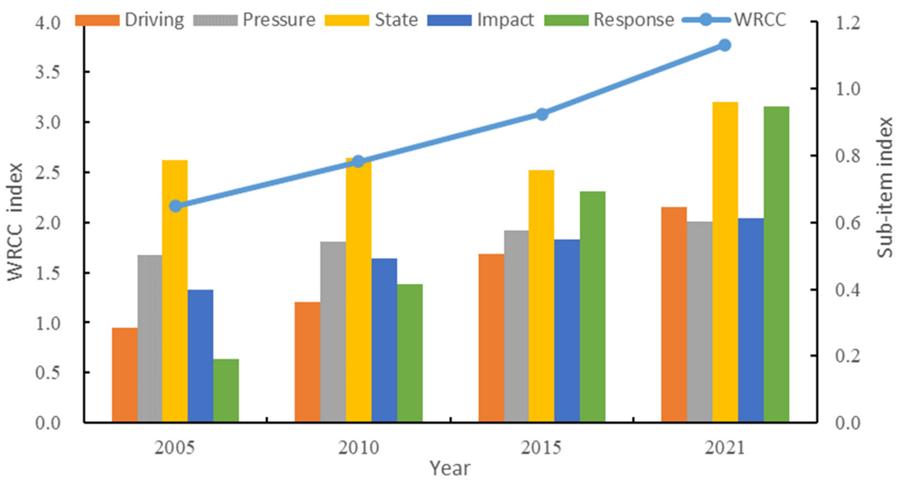

Figure 2. Temporal trends of WRCC indices in the Yellow River Basin.

Notably, the pressure (D) and state (S) indices of WRCC experienced a notable increase of 19.8% and 21.8%, respectively, from 2005 to 2021. This indicates an improvement in the water environment in the Yellow River Basin and a shift away from previous development practices that sacrificed the environment for economic growth. These findings demonstrate an enhanced level of water resource sustainability in the region.

Table 3 presents the WRCC indices for the nine provinces in the Yellow River Basin for the years 2005, 2010, 2015, and 2021. The table highlights that in 2021, Shandong, Henan, and Sichuan provinces ranked higher in terms of WRCC indices, while Ningxia, Shanxi, and Gansu provinces had relatively lower WRCC indices. Since 2005, the WRCC indices of all nine provinces in the Yellow River Basin have shown significant improvement. Inner Mongolia and Ningxia provinces witnessed a remarkable increase in their WRCC indices, with growth rates of 116.3% and 100.1%, respectively, indicating substantial efforts made to enhance the water environment. Qinghai and Sichuan provinces had relatively lower growth rates compared to other provinces, primarily due to their location in the upstream region of the Yellow River Basin, where industrial development is comparatively less advanced, and the degree of water environment degradation is relatively lower.

Table 3. WRCC index of provinces in the Yellow River Basin in 2005, 2010, 2015, and 2021.

Provinces	WRCC Index				
	2005	2010	2015	2020	2021
Qinghai	0.273	0.291	0.301	0.394	0.383
Sichuan	0.325	0.357	0.405	0.529	0.501
Gansu	0.185	0.205	0.263	0.324	0.323
Ningxia	0.138	0.199	0.240	0.279	0.275
Inner Mongolia	0.217	0.282	0.385	0.439	0.469
Shaanxi	0.223	0.280	0.314	0.355	0.389
Shanxi	0.182	0.248	0.285	0.320	0.323
Henan	0.278	0.332	0.381	0.485	0.514
Shandong	0.342	0.411	0.506	0.571	0.596

The variations in WRCC index growth rates among provinces were significant during different time periods. From 2005 to 2010, Shandong, Shanxi, and Inner Mongolia provinces demonstrated the highest growth rates. From 2010 to 2015, Inner Mongolia, Shandong, and Gansu provinces showed the highest growth rates, while from 2015 to 2021, Henan, Sichuan, and Shandong provinces exhibited the highest growth rates. Notably, provinces with better economic conditions, such as Shandong, Shanxi, and Henan, generally improved their water environment considerably. Furthermore, Inner Mongolia, located at the northernmost end of the North China Plain, actively contributed to improving water resources and protecting the ecological barrier for the North China Plain.

3.2. Spatial Analysis of WRCC Variation in the Yellow River Basin

A standard deviation classification method was employed to facilitate a comparative analysis of WRCC levels across the Yellow River Basin's nine provinces from 2005 to 2021, dividing the WRCC index into four categories: Level -IV. A higher level indicates a larger WRCC value [47]. The classification criteria are shown in Table 4.

Table 4. WRCC level classification criteria.

Grading Standards			
I	II	III	IV
(0, 0.229]	(0.229, 0.326]	(0.326, 0.423]	(0.423, 1]

Figure 3 shows that in 2005, out of the five provinces within the Yellow River Basin, five were classified as Level I, three as Level II, one as Level III, and none as Level IV. In

2010, among the nine provinces in the basin, two were Level I, four were Level II, three were Level III, and none were Level IV. In 2021, among the nine provinces, none were Level I, three were Level II, two were Level III, and four were Level IV. This indicates a significant decrease in the number of provinces classified as Level I and a notable increase in the number of provinces classified as Level IV within the Yellow River Basin.

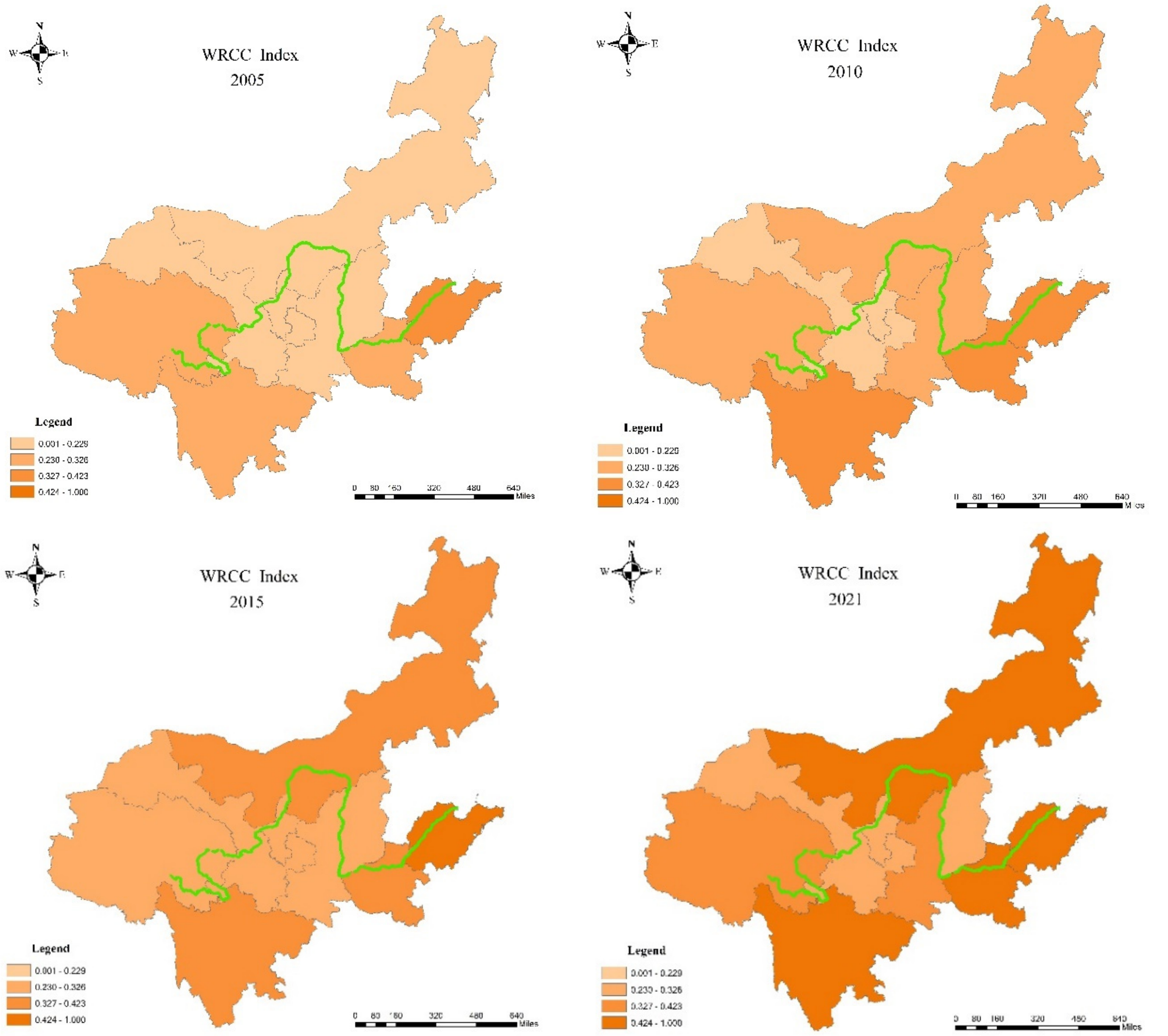

Figure 3. Spatial patterns of WRCC indices in the Yellow River Basin for 2005, 2010, 2015, and 2021.

Shandong province has consistently had a higher WRCC level compared to other provinces since 2005. This can be attributed to its advantageous coastal location, emphasis on the development of the marine economy, and high-value-added manufacturing, which have led to improved levels of economic cleanliness. Inner Mongolia, located in northern China, plays a crucial role in safeguarding China's ecological security. In this century, Inner Mongolia has actively promoted the construction of the Three-North Shelterbelt Forest Program, implemented grassland protection and restoration plans, controlled and managed desertification, and focused on soil and water conservation and wetland protection. These measures have effectively protected Inner Mongolia's abundant ecological resources, leading to continuous improvement and sustainable development of the ecological environment.

On the other hand, Shanxi province, a coal production base in China, heavily relies on coal and related industries, resulting in significant pollution. Water resource protection and management in Shanxi province need further improvement. Shaanxi, Ningxia, Gansu, and Qinghai are located in the western region, characterized by scarce precipitation and harsh natural environments, which have resulted in slower improvements in their WRCC indices. Henan and Sichuan provinces have actively adjusted their industrial structures and prioritized environmental protection, improving their water resource carrying capacity effectively.

Overall, during the study period, Shandong province in the downstream region of the Yellow River maintained its WRCC level at the first level. The second level included Henan Province in the downstream region, Sichuan Province in the upstream region, and Shaanxi, Shanxi, and Inner Mongolia in the middle reaches. The third level included Gansu, Qinghai, and Ningxia in the upstream region, mainly due to the relatively backward economic and technological equipment in these provinces, resulting in low conversion rates of production factors and, consequently, lower water resource carrying capacity.

In Figure 4, the intensity of color corresponds to the level of favorability for the WRCC sub-indicators. These sub-indicators represent various facets of WRCC within the Yellow River Basin.

The driving sub-indicator represents the demand for water resources driven by economic development and human livelihood. It is significantly correlated with the geographical location, showing an increasing trend from upstream to downstream. This correlation is attributed to population distribution and economic levels, which are positively correlated with the driving force of WRCC.

The pressure sub-indicator primarily reflects the environmental pressure caused by economic development. It is closely related to the degree of economic cleanliness. The downstream areas of the Yellow River Basin exhibit higher levels of economic development and advanced scientific and technological capabilities, reducing the pressure on the water environment.

The state sub-indicator represents the water environment's natural condition and utilization level. It is closely related to regional precipitation and the degree of water resource development. Provinces like Sichuan and Qinghai, which are the sources of the Yellow River and Yangtze River, have better water resource protection, resulting in a higher-quality water resource state. Provinces like Shandong and Shanxi have a high demand for water resources due to their economic development and agricultural irrigation, resulting in a higher degree of water resource development and limiting the improvement of the state index.

The impact sub-indicator reflects the consequences caused by changes in the water resource state. In the upstream region of the Yellow River, measures have been implemented to protect water resources in line with national policies. In the downstream regions, such as Shandong and Henan, which have relatively developed economies, efforts have been made to support water resource development and protection. Consequently, the impact index of WRCC is higher in the upstream and downstream regions.

The response sub-indicator represents the measures and policies implemented to address water resource pressures. The response index of water resource protection in the Yellow River Basin positively correlates with the degree of economic development. Provinces like Shandong and Henan actively invest in scientific research and implement strict wastewater treatment measures, leading to higher response indices.

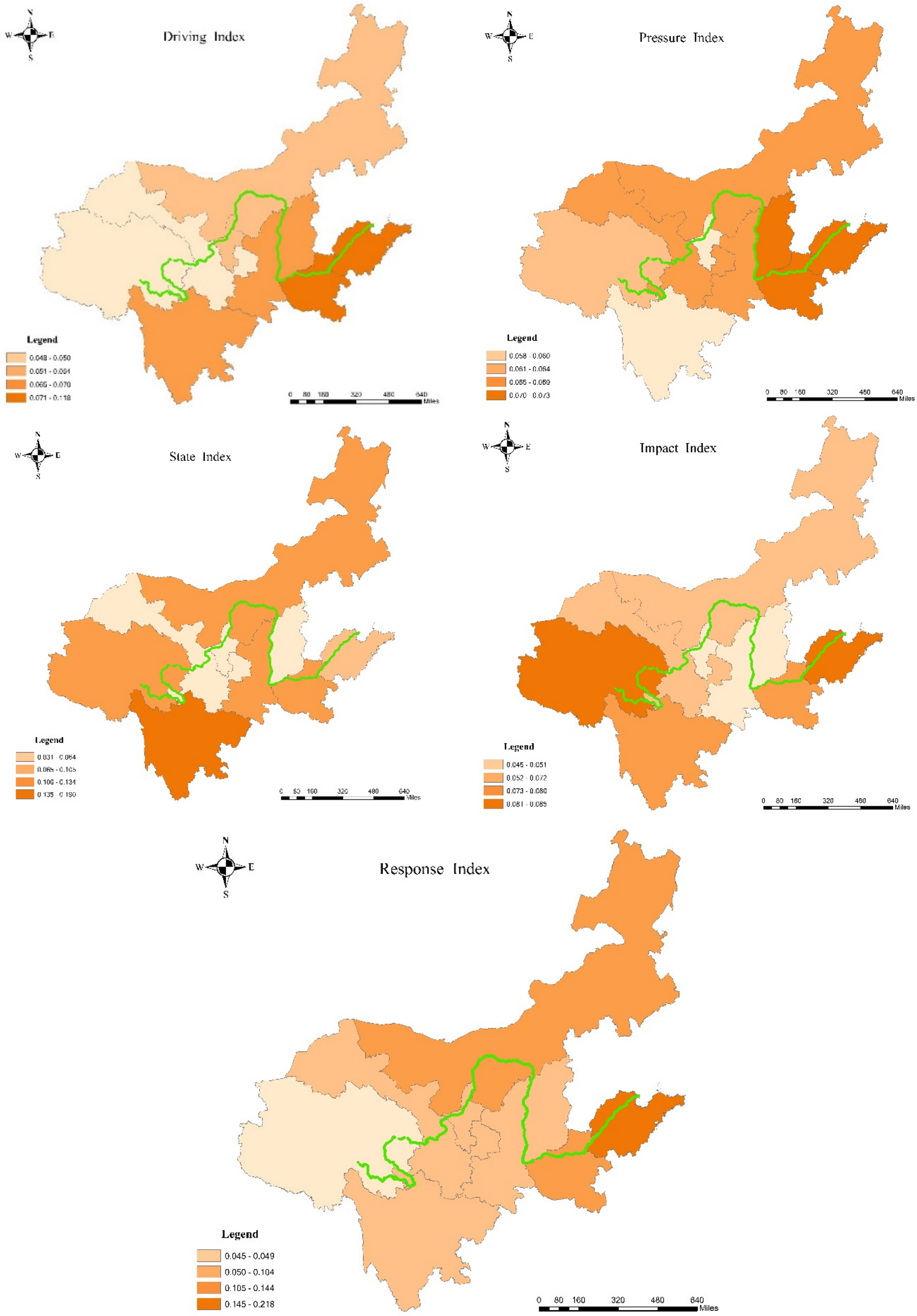

Figure 4. Spatial patterns of sub-indicators of WRCC in the Yellow River Basin for 2021.

3.3. Spatial Correlation Analysis of WRCC in the Yellow River Basin

Using Stata 17.0 software, we used a spatial weights matrix based on adjacency to compute the global Moran's I index for the time-series data from 2005 to 2021. This analysis was conducted to unveil the spatial agglomeration patterns of WRCC in the Yellow River Basin (Table 5). The global Moran's I index measures the spatial autocorrelation, indicating the degree of similarity or dissimilarity in the spatial distribution of WRCC across different provinces. From 2005 to 2010, the global Moran's I index yielded a significant result at the 10% level, with an index value greater than 0.1. This suggests a positive spatial correlation in the distribution of WRCC within the Yellow River Basin during this period. Upon further examination, we observed a decline in Moran's I index from 0.194 in 2007 to 0.125 in 2010, indicating a weakening spatial agglomeration effect of WRCC in the Yellow River Basin. Since 2011, Moran's I index exhibited a p-value greater than 0.1 and a Z-value less than 1.6, suggesting a random spatial distribution of WRCC within the basin.

Table 5. Global Moran's I index of WRCC in the Yellow River Basin (2005–2021).

Year	I Value	Z Value	p Value
2005	0.169	1.627	0.052
2006	0.148	1.550	0.061
2007	0.194	1.816	0.035
2008	0.169	1.678	0.047
2009	0.162	1.612	0.053
2010	0.125	1.419	0.078
2011	0.098	1.302	0.096
2012	0.033	0.907	0.182
2013	-0.069	0.322	0.374
2014	0.007	0.767	0.222
2015	0.004	0.748	0.227
2016	0.057	1.056	0.145
2017	0.095	1.281	0.100
2018	0.045	0.960	0.168
2019	0.037	0.912	0.181
2020	0.014	0.766	0.222
2021	0.005	0.720	0.236

These findings highlight the temporal changes in the spatial agglomeration patterns of WRCC in the Yellow River Basin. The initial positive spatial correlation between 2005 and 2010 indicates a tendency for neighboring provinces to exhibit similar WRCC levels. However, this spatial clustering effect weakened over time, eventually leading to a more random distribution of WRCC in recent years.

Continuing the examination of spatial correlation among WRCC sub-indicators within the Yellow River Basin, the findings are displayed in Table 6. Notably, the global Moran's I indices of the driving (D) and response (R) indicators for the period 2005–2021 exhibit p-values below 0.1 and Z-values surpassing the critical threshold of 1.65, signifying a robust spatial autocorrelation at a 90% confidence level. Moran's I index for the driving indicator fluctuates between 0.36 and 0.40, suggesting a persistent spatial clustering pattern in the core driving forces of WRCC in the Yellow River Basin, with generally higher WRCC values in downstream provinces compared to upstream ones. On the other hand, the I index for the response indicator has shown a decreasing trend since 2008, indicating that all provinces have actively implemented the Chinese government's strategic initiatives for ecological civilization, focusing on water pollution control and environmental protection efforts.

Table 6. Global Moran's I index for WRCC sub-indicators in the Yellow River Basin (2005–2021).

Year	Driving (D)			Pressure (P)			State (S)			Impact (I)			Response (R)		
	Moran's I	Z	p	Moran's I	Z	p	Moran's I	Z	p	Moran's I	Z	p	Moran's I	Z	p
2005	0.393	3.134	0.001	0.179	1.727	0.042	0.120	1.400	0.081	0.281	2.235	0.013	0.126	1.875	0.030
2006	0.398	3.155	0.001	0.131	1.487	0.069	0.011	0.810	0.209	0.297	2.321	0.010	0.120	1.743	0.041
2007	0.384	3.077	0.001	0.125	1.492	0.068	0.088	1.246	0.106	0.282	2.229	0.013	0.183	2.135	0.016
2008	0.381	3.090	0.001	0.075	1.229	0.110	0.044	1.009	0.156	0.248	2.047	0.020	0.248	2.564	0.005
2009	0.380	3.050	0.001	0.071	1.205	0.114	0.095	1.249	0.106	0.229	1.954	0.025	0.251	2.519	0.006
2010	0.364	2.986	0.001	−0.027	0.574	0.283	0.029	0.898	0.185	0.220	1.891	0.029	0.240	2.410	0.008
2011	0.362	2.984	0.001	0.021	0.859	0.195	0.011	0.782	0.217	0.196	1.762	0.039	0.199	2.118	0.017
2012	0.367	3.022	0.001	−0.058	0.381	0.352	0.087	1.243	0.107	0.155	1.533	0.063	0.149	1.804	0.036
2013	0.376	3.061	0.001	−0.017	0.608	0.272	−0.103	0.130	0.448	0.131	1.397	0.081	0.129	1.574	0.058
2014	0.381	3.090	0.001	0.095	1.233	0.109	0.009	0.793	0.214	0.166	1.586	0.056	0.115	1.587	0.056
2015	0.396	3.164	0.001	0.067	1.092	0.137	−0.102	0.143	0.443	0.126	1.371	0.085	0.113	1.588	0.056
2016	0.390	3.142	0.001	0.224	2.005	0.023	−0.070	0.346	0.365	0.089	1.174	0.120	0.123	1.624	0.052
2017	0.369	3.005	0.001	0.265	2.186	0.014	0.017	0.844	0.199	0.095	1.213	0.113	0.144	1.778	0.038
2018	0.384	3.031	0.001	0.231	1.972	0.024	0.063	1.102	0.135	0.085	1.152	0.125	0.132	1.599	0.055
2019	0.373	2.959	0.002	0.210	1.824	0.034	0.054	1.046	0.148	0.077	1.109	0.134	0.168	1.791	0.037
2020	0.371	2.946	0.002	0.100	1.241	0.107	0.054	1.045	0.148	0.064	1.081	0.140	0.098	1.341	0.090
2021	0.361	2.907	0.002	0.111	1.321	0.093	−0.127	−0.013	0.495	0.081	1.125	0.130	0.074	1.193	0.117

Among the five sub-indicators, the pressure (P) indicator exhibits significant fluctuations in Moran's I index *p*-values. It passed the significance test in 2005, 2017–2019, and 2021, indicating a positive spatial correlation. However, in other years, it failed to pass the significance test, suggesting a less pronounced spatial clustering phenomenon. The state (S) indicator consistently has *p*-values greater than 0.1 throughout the study period, indicating a lack of spatial correlation. Furthermore, the impact (I) indicator shows a significant positive spatial correlation with Moran's I *p*-values below 0.1 from 2005 to 2015. However, Moran's I index declined from 0.281 in 2005 to 0.126 in 2015, indicating a weakening spatial clustering effect for the impact indicator.

Overall, the WRCC index in the Yellow River Basin exhibits a positive spatial correlation, with a decreasing trend in spatial clustering since 2005. The driving indicators show evident spatial clustering effects that remain relatively stable over time. In contrast, the response indicators demonstrate a significant reduction in spatial clustering, further contributing to the weakening of the spatial clustering of the impact indicators. However, the pressure and state indicators do not exhibit clear spatial clustering patterns, likely due to their close association with the natural environment. It is evident that WRCC constitutes a complex system subject to multifaceted influences encompassing factors such as the economy, population, environment, resources, policies, and industrial structure. Consequently, a more profound and comprehensive analysis of the pivotal factors impacting WRCC is imperative.

3.4. Robustness Analysis

The selection of indicators possesses a certain degree of subjectivity. Certain indicators were replaced to verify the robustness of the results in this study. Specifically, the industrial wastewater discharge volume (X5) was substituted with per capita industrial wastewater discharge, the research and development expenditure of large-scale industrial enterprises (X21) was replaced with per capita research and development expenditure of large-scale industrial enterprises, and the investment amount in industrial pollution control (X22) was replaced with a per capita investment amount in industrial pollution control. Other indicators in the indicator system remained unchanged. This replacement aimed to assess the stability of the results.

These three replaced indicators pertain to both the pressure and response dimensions. A comparison of the deviation between the Yellow River Basin WRCC index before and after replacing the indicators is presented in Table 7. It can be observed that the changes in pressure indices are generally within 3%, changes in response indices are generally within 5%, and changes in the WRCC index are generally within 4%. Overall, the deviation in indices before and after the replacement is relatively minor, indicating the robustness of the results in this study.

Table 7. Robustness test deviation analysis.

Year	Index		
	Pressure	**Response**	**WRCC**
2005	0.2%	13.1%	−2.8%
2006	−0.3%	6.7%	−3.1%
2007	−0.3%	6.4%	−3.1%
2008	−0.5%	2.1%	−3.5%
2009	−0.5%	−0.2%	−3.8%
2010	−0.3%	0.5%	−3.7%
2011	−0.6%	0.6%	−3.6%
2012	−1.2%	−0.4%	−3.9%
2013	−1.3%	−2.5%	−4.2%
2014	−1.3%	−3.8%	−4.5%
2015	−1.3%	0.3%	−3.6%
2016	−3.5%	−2.0%	−4.5%
2017	−2.0%	3.2%	−2.9%
2018	−2.0%	0.8%	−3.6%
2019	−2.3%	0.7%	−3.6%
2020	−3.3%	0.2%	−3.9%
2021	−3.3%	−1.8%	−4.4%

4. Analysis of Influencing Factors of Spatial Differences of WRCC

Based on the previous analysis, it is evident that there are significant differences in WRCC levels across the Yellow River Basin. Therefore, in this section, we will utilize the geographic detector to assess the impact of various factors on the spatial differentiation of WRCC in the Yellow River Basin. To avoid the bias caused by a single-year random error, we first divide the study period into four groups: 2005–2008, 2009–2012, 2013–2016, and 2018–2021. We classify the indicators in each group using the natural break method in ArcGIS software. Then, considering the WRCC index of different provinces, we employ the factor detection module of the geographic detector to calculate each indicator's influence strength (q-value).

4.1. Intensity of Influencing Factors of WRCC

Figure 5 illustrates the variations in the strength of the impact of different driving factors on WRCC in the Yellow River Basin. Key changes during the study period can be observed as follows. Firstly, per capita GDP (X1) gradually increased from 0.198 to 0.471 but then declined to 0.284 in the 2018–2021 period. This indicates a weakening influence of economic development on WRCC during this time. Additionally, the urbanization rate (X2) decreased from 0.175 to 0.058, indicating a diminishing impact of the urbanization process on WRCC. Similarly, industrial wastewater discharge (X5) decreased from 0.783 to 0.482, while the unit water consumption for agricultural land (X6) increased from 0.255 to 0.376. The water consumption per 10,000 units of industrial value added (X7) increased from 0.159 to 0.332, and the water consumption per 10,000 units of GDP (X8) increased from 0.385 to 0.449. These data changes suggest a gradual weakening impact of the corresponding indicators on WRCC. However, population density (X3) remained consistently high at 0.450, and the unit area precipitation (X10) fluctuated from 0.601 to 0.534. The unit area water resources (X11) fluctuated from 0.495 to 0.387. These data variations indicate a sustained influence of factors such as population density, agricultural water consumption, and precipitation on WRCC.

Upon further observation of Figure 6, it is evident that the impact strength of various indicators on the WRCC index has undergone changes during the study period from 2005 to 2021. During this time, indicators such as sewage treatment capacity, industrial wastewater discharge, research and development expenditure of large-scale industries, effective irrigation area, precipitation, and water consumption per 10,000 units of GDP have significantly influenced WRCC. Specifically, the impact strength of indicators such as surface water supply, effective irrigation area, water consumption per 10,000 units of industrial value added, and unit water consumption for agricultural land has gradually increased. On the other hand, the impact strength of indicators such as the tertiary industry proportion, sewage treatment rate, per capita environmental water consumption, and urbanization rate has gradually decreased in their influence on WRCC.

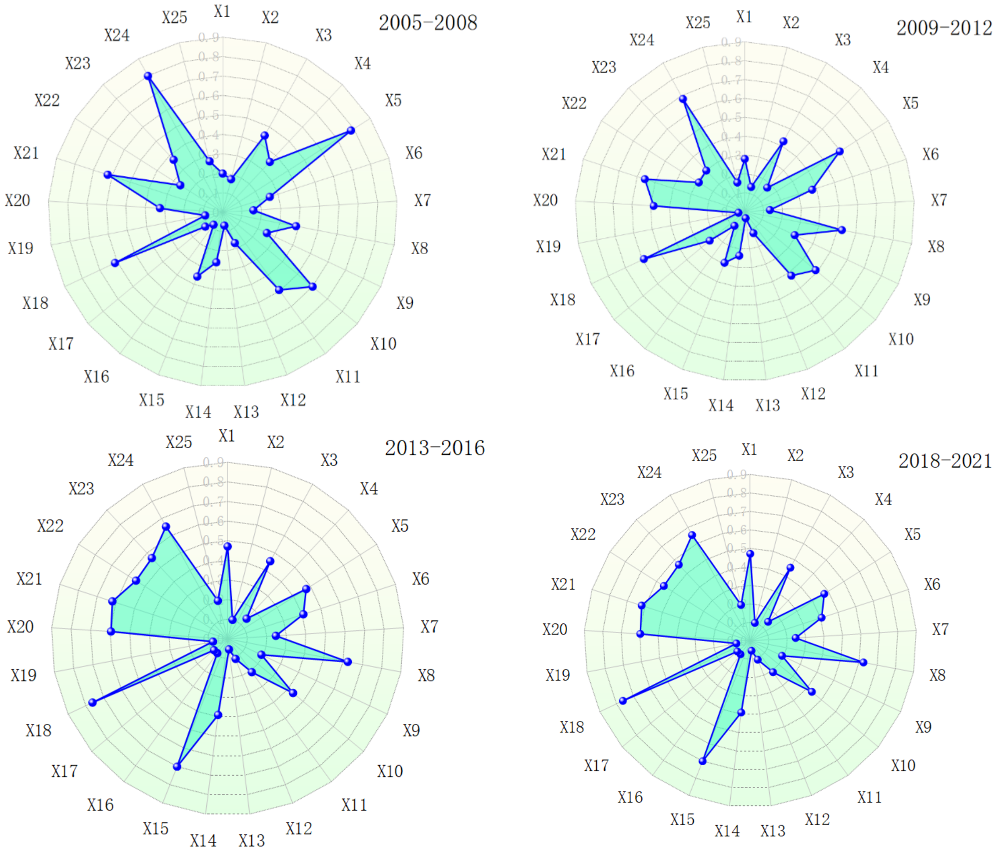

Figure 5. Impact intensity of various driving factors on WRCC in the Yellow River Basin.

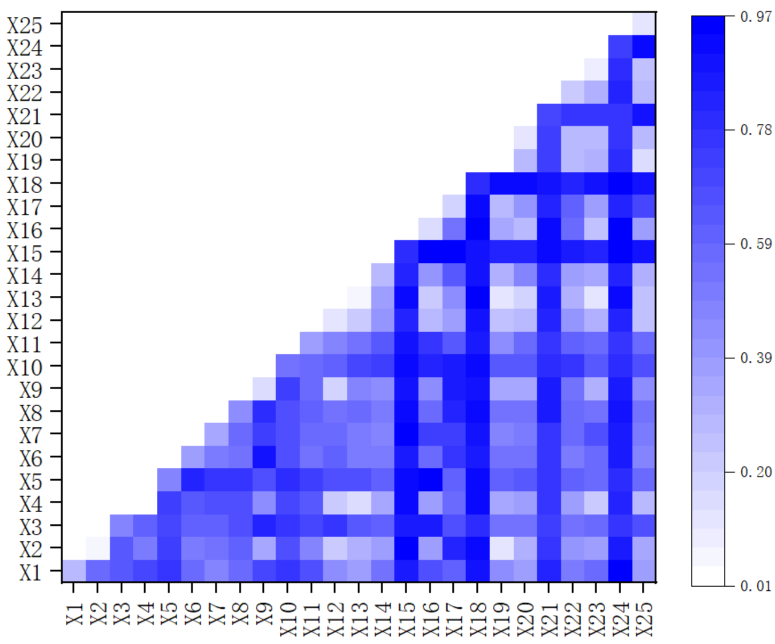

Figure 6. Heatmap of interaction detection results of driving factors on WRCC in the Yellow River Basin.

Considering all these factors, China has made significant progress in recent years in terms of economic transformation, intensified environmental protection efforts, water conservation measures, technological improvements, ecological conservation, and green development. These efforts have yielded a series of positive outcomes in alleviating the pressure on WRCC and promoting sustainable water resource utilization. Specifically, the adjustments in economic structure and increased focus on environmental protection have reduced economic development's impact on water resources, with a gradual decline in industrial wastewater discharge and industrial water consumption. Additionally, water conservation measures and technological improvements have decreased water usage in the agricultural and industrial sectors. The implementation of ecological conservation and green development initiatives has facilitated the restoration of ecological environments and the sustainable utilization of water resources. These policies and efforts demonstrate China's significant progress in seeking a balance between economic development and environmental protection.

4.2. Multi-Factor Interactive Detection Analysis

Figure 6 presents the results of the interaction detection among driving factors influencing the spatiotemporal variation of WRCC from 2018 to 2021. The analysis reveals the formation of 299 combinations of factor interactions. Among these, 55.9% exhibit a synergistic effect, where the joint impact is greater than the maximum impact of the individual factors. The remaining 44.1% exhibit nonlinear enhancement, where the joint impact is greater than the sum of the individual impacts. For example, the single-factor impact intensity of the tertiary industry ratio is 0.029, but when interacting with other driving factors, the maximum joint impact intensity reaches 0.926, with a mean of 0.510. The single-factor impact intensity of the urbanization rate is around 0.058, while the impact intensity of industrial wastewater discharge is 0.482. However, their interaction results in an increased impact intensity of 0.720. Furthermore, the urbanization rate exhibits interaction intensities exceeding 0.80 with factors such as water supply coverage (X17), wastewater treatment capacity (X24), effective irrigated area (X18), and surface water resources (X15). These findings suggest that the regional differences in WRCC in the Yellow River Basin are the combined result of complex factor interactions.

Therefore, comprehensive consideration of the individual effects and interactions among multiple factors is necessary for water resources management and environmental protection in the Yellow River Basin. It is important to focus on factors such as industrial wastewater discharge, wastewater treatment capacity, research and development investments in enterprises, surface water supply, and upgrading of industrial structure. Additionally, timely adjustments in policy priorities should be made to accelerate the establishment of a water-saving societal production system and improve the level of WRCC.

5. Conclusion and Prospects

5.1. Main Conclusions

Through the analysis of the temporal and spatial variation of water resource carrying capacity (WRCC) in the Yellow River Basin, the following conclusions have been drawn:

Continuous increase in WRCC: The measurement and analysis using the composite weighting TOPSIS method revealed that the WRCC index in the Yellow River Basin has been continuously increasing, reaching 3.771 in 2021, which indicates a significant improvement compared to the initial value in 2005. This demonstrates notable progress in water resource management and conservation in the basin over the past sixteen years.

Significance of response and driving force indices: Among the five sub-indices of WRCC, the response (R) and driving force (D) indices experienced the highest growth rates of 397.3% and 128.3%, respectively. This underscores the importance of increased investment in scientific research and enhanced water resource management for improving WRCC in the Yellow River Basin.

Balancing environmental improvement and economic development: The pressure (P) and state (S) indices increased by 19.8% and 21.8%, respectively, indicating an improvement in the water environment and a certain balance achieved between economic development and environmental protection in the Yellow River Basin. However, continuous efforts are required to achieve better sustainable water resource utilization.

Significant differences in WRCC among provinces: The WRCC indices among provinces in the Yellow River Basin showed notable variations. Inner Mongolia and Ningxia provinces demonstrated significant improvements, while Qinghai and Sichuan provinces exhibited slower growth. These differences are primarily influenced by factors such as economic development, population density, industrial wastewater discharge, and precipitation.

5.2. Recommendations

Based on the research and analysis of water resources carrying capacity (WRCC) in the Yellow River Basin, we propose the following recommendations to promote the sustainable development of water resources in the Yellow River Basin:

(1) Strengthen wastewater treatment capacity and industrial wastewater emission control: We recommend increasing investment and enhancing both wastewater treatment capacity and control over industrial wastewater emissions. Optimizing wastewater treatment technologies and facilities to ensure compliant wastewater discharge can help reduce pollution and pressure on water resources;

(2) Boost research investment and technological innovation: We suggest intensifying research investment and fostering technological innovation to advance the scientific and intelligent management and utilization of water resources. Promoting the translation of technological achievements can enhance water resource utilization efficiency and environmental management capabilities;

(3) Reinforce surface water resource supply and irrigation management: It is advisable to strengthen the protection and management of surface water resources to ensure sustainable water supply. Promoting water-saving irrigation techniques and management measures can improve irrigation water efficiency while reducing waste and losses;

(4) Optimize industrial structure and enhance urbanization management: We recommend enhancing industrial structure adjustment to promote green and low-carbon development, thereby reducing the demand for water resources. Simultaneously, strengthening urbanization planning and management, along with controlling the pace and scale of urbanization, can prevent excessive pressure on water resources caused by urbanization.

5.3. Limitations and Prospects

This study attempts to dynamically observe the evolution trends of water resources carrying capacity in various provinces of the Yellow River Basin on a spatiotemporal scale. However, there are several limitations. Firstly, the limitation lies in the scope of study objects. While this research employs provinces as the basic units of analysis, the Yellow River Basin covers a vast range, with significant differences in economic development and natural environments within each province. To provide more accurate data, future studies should consider using counties or cities as the research units. Secondly, the study model's limitations are noteworthy. This research constructs a water resources carrying capacity evaluation model using 25 indicators; however, assessing water resources carrying capacity is highly complex and should involve a deeper investigation incorporating factors such as industrial structure, economic levels, government policies, and natural environments. Thirdly, there are limitations in the research methodology. This paper employs the entropy weight method to calculate the weights of various indicators. In practice, this method still cannot effectively measure the true importance of each indicator. Therefore, it is necessary to utilize expert opinions or other quantitative models to assess the weights of different indicators comprehensively.

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