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Resilience Assessment and Influencing Factors Analysis of Water Security System in the Yellow River Basin

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Abstract: The assessment and regulation of water security system resilience (WSSR) are important ways to alleviate water resource crises. On the basis of the three characteristics of resilience, namely, resistance, restoration, and adaptability, an evaluation index system of the WSSR was built for the Yellow River Basin (YRB). A projection pursuit model based on the sparrow search algorithm (SSA-PP model) was constructed to assess the WSSR at the overall and provincial scales from 2009 to 2022. The factors influencing the spatial distribution patterns of WSSR was identified through factor detector and interactive detector techniques. The results revealed that: (1) From 2009 to 2022, the YRB exhibited a rising trend in WSSR, with the western region attaining the peak level, and the eastern region recording the lowest magnitude. (2) the adaptability capacity of most provinces and regions in the YRB tended to decrease to about 1.0, whereas the resistance and restoration capacities tended to increase towards 2.0. (3) Factors relevant to the restoration and adaptability subsystems, such as the development and utilization ratio of water resources and surface water resources (B2 and B3), water resource load index (C1), water consumption per 10,000 yuan of GDP (C8), and total precipitation (A1), significantly affected the WSSR. The interaction between factors exhibited significant enhancement effects on explanatory. Therefore, targeted countermeasures and recommendations were provided to improve the WSSR in the YRB.

Keywords: water security system; resilience; projection pursuit model; geographical detectors (GDs); Yellow River Basin (YRB)

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Citation: Sun, Y.; Lu, P.; Qu, B.; Li, J. Resilience Assessment and Influencing Factors Analysis of Water Security System in the Yellow River Basin. *Sustainability* **2024**, *16*, 9347. https://doi.org/10.3390/su16219347

Academic Editors: Hossein Bonakdari and Andreas Angelakis

Received: 7 September 2024
Revised: 16 October 2024
Accepted: 25 October 2024
Published: 28 October 2024

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1. Introduction

Water, a vital resource emanating from the natural environment, sustains living organisms and serves as the cornerstone of life on Earth. In recent years, the swift pace of socioeconomic growth, urbanization, and climatic alterations fostered acute disparities in water supply and demand [1]. The global populace faces direct and indirect perils related to water security, stemming from inadequate access to clean water, subpar sanitation infrastructure and service standards, as well as the challenges posed by droughts and floods [2,3]. At present, China's water security issues mainly include water shortages, deterioration of the aquatic environment, floods, droughts, and other security problems related to water [4–8]. The shortage of water resources has become the major obstacles in development of the Yellow River Basin (YRB). For a long time, the YRB has faced a series of complex problems, such as strong imbalances in water supply and demand, complex water–sediment relationships, and unclear patterns in water cycle changes [9]. Furthermore, the uneven allocation of water resources results in economic disparities, ineffective governance, and institutional shortcomings [10–12]. With increasing economic development, it has become apparent that economic growth is being hindered by interconnected issues

pertaining to water scarcity, environmental degradation, and societal challenges. Owing to extensive development and resource utilization, the YRB environment has become increasingly fragile. Hence, assessing water security within the YRB is imperative for regional sustainable development.

Water security is the core of social development, with water as a vital source underpinning human flourishing and overall well-being. It transcends boundaries, presenting a multifaceted challenge that spans the local, regional, national, and global realms. Ever since its initial formulation as a pivotal policy conundrum during the Hague Ministerial Declaration on Water Security at the 2000 World Water Forum, ensuring water security has remained a central theme of discussion among international bodies. Water security is a broad and complex concept that has been defined by scholars from different perspectives [13–16]. for example, the definitions proposed by the Global Water Partnership [17], Grey and Sadoff [18] at the World Water Forum in 2007, UN-Water [19], UNESCO [20], and OECD [21]. The definitions of water security have proliferated, with both commonalities and confusion about the concepts and approaches for measuring water security. Despite the multitude of definitions attributed to water security, numerous international organizations, such as UNESCO's International Flood Programme, the Global Water Partnership, and the World Economic Forum, have underscored the significance of prudent and intelligent stewardship of water resources.

A water security system is a composite system encompassing water resources, water environment, society, and economy subsystems. The behaviour of any subsystem affects the overall function of the water security system [22]. "Resilience" denotes the capacity of withstanding risks, alleviating adverse impacts, and exploring new development paths in the face of disruptions. To address associated risks, the concept of resilience has become increasingly important. Different disciplines have different definitions of resilience, such as engineering resilience, ecological resilience, urban resilience, economic resilience, and water resource resilience [23–26]. According to the concept of water resource system resilience [27–29], we define water security system resilience (WSSR) as follows: the regional water security system can rely on its self-stabilization and self-repair capabilities to resist damage or quickly restore normal operation, after the incidents such as natural disasters and economic crises.

Given the intricacies surrounding the notion of water security, there is currently no standardized evaluation method for water security. Various methods such as the analytic hierarchy process [30], principal component analysis [31], fuzzy comprehensive evaluation method [32], multi-objective decision analysis [33], risk analysis method [34], water footprint method [35], and the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method [36] were widely used. The evaluation models of water security assessment include the system dynamics model [37], BP (Back Propagation) neural network model [38], fuzzy set similarity model [39], and conceptual models such as the pressure-state-response (PSR), driving force-pressure-state-influence-response (DPSIR), and driving force-pressure-state-influence-response-management (DPSIRM) methods [40–42]. For example, Park et al. [43] constructed a water security evaluation framework encompassing five dimensions, namely, social equity, economic efficiency, resilience to water-related disasters, environmental sustainability, and governmental capability. Then, they assessed the water security status of 28 nations through of a comprehensive water security index. Zhao et al. [44] devised a regional water security assessment framework in three dimensions: water resource security, aquatic environmental security, and water disaster control security, and utilized an expedited genetic algorithm-driven fuzzy analytic hierarchy process to evaluate water security in Jiangsu Province. On the basis of the concept of resilience, Yang et al. [45] constructed a comprehensive water security assessment framework, encompassing the dimensions of resilience, restoration, and adaptability. Then, they constructed a three-branch decision analysis framework for water security evaluation and conducted empirical research with the Beijing-Tianjin-Hebei region as an example. Shao et al. [46] established a holistic water security assessment model integrating flood control security,

resource security, and ecological security based on the human development index (HDI). Yao et al. [47] evaluated the water security status of 31 provincial-level administrative regions in China from 2007 to 2016, through calculating the indices of flood control security, resource security, ecological security, and overall water security status within each region. Li et al. [48] constructed a water security assessment framework based on the DPSIR model, and further evaluated the northwest regional water security status from 2010 to 2019 via the five-element connection number approach. In addition, they applied the grey forecasting model to predict the water security status from 2023 to 2030.

A review of relevant research revealed that some shortcomings remain in the current research on the WSSR in the YRB. (1) There are few studies considering water security as a composite system from a systemic perspective. (2) The resilience level is often determined through the calculation of comprehensive indices, which cannot maximize the authenticity of the original data.

Therefore, a comprehensive evaluation index system for the WSSR is established, grounded in the triadic resilience attributes of resistance, restoration, and adaptability. The impacts of factors such as water resources, water environment, and socioeconomic factors on the WSSR are considered. A projection pursuit model based on the sparrow search algorithm (SSA-PP model) is then used to assess the WSSR level in the YRB from 2009 to 2022. Finally, factor detection is applied to identify the main factors affecting the WSSR. The research can provide a certain theoretical basis and reference for future studies on WSSR evaluation methods. There are two main innovations in this paper: (1) Consider the water security system as a composite system, including water resources, the water environment, society, and the economy subsystems. (2) Use a projection pursuit model optimized via the sparrow search algorithm (SSA-PP model) to calculate the WSSR level, which can fully retain the informational content in the time dimension contained in the indicators, thereby maximizing the authenticity of the original data.

Nonetheless, this study is subject to the following limitations. To further improve the credibility of the results, it is necessary to increase the amount of data. Besides, other factors, such as qualitative factors, should also be incorporated into the evaluation index system to reflect the level of the WSSR more comprehensively.

2. Materials and Methods

2.1. Study Area

Originating from the Bayankala Mountains, the Yellow River stretches 5464 km, ranking as the second longest river in China. River courses travel an extensive route, through nine diverse provinces and regions—Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong—before emptying into the Bohai Sea [49]. Severe soil erosion and water scarcity have occurred on the Loess Plateau in the upper and middle reaches of the Yellow River. Downstream, due to sedimentation, an aboveground suspended river has formed, which has caused river mouth breaches and frequent floods. As an important ecological barrier and economic belt in China, water resources in the YRB are the fundamental factors affecting population growth, economic development, and even national security. It plays a unique role in supporting national development. However, development in the YRB is faced with serious problems such as severe water scarcity and fragile ecosystems. There are obvious deficiencies related to resource limitations and the environment, and development in the provinces and regions through which the Yellow River flows varies greatly, with significant differences. The location of the Yellow River Basin is shown in Figure 1.

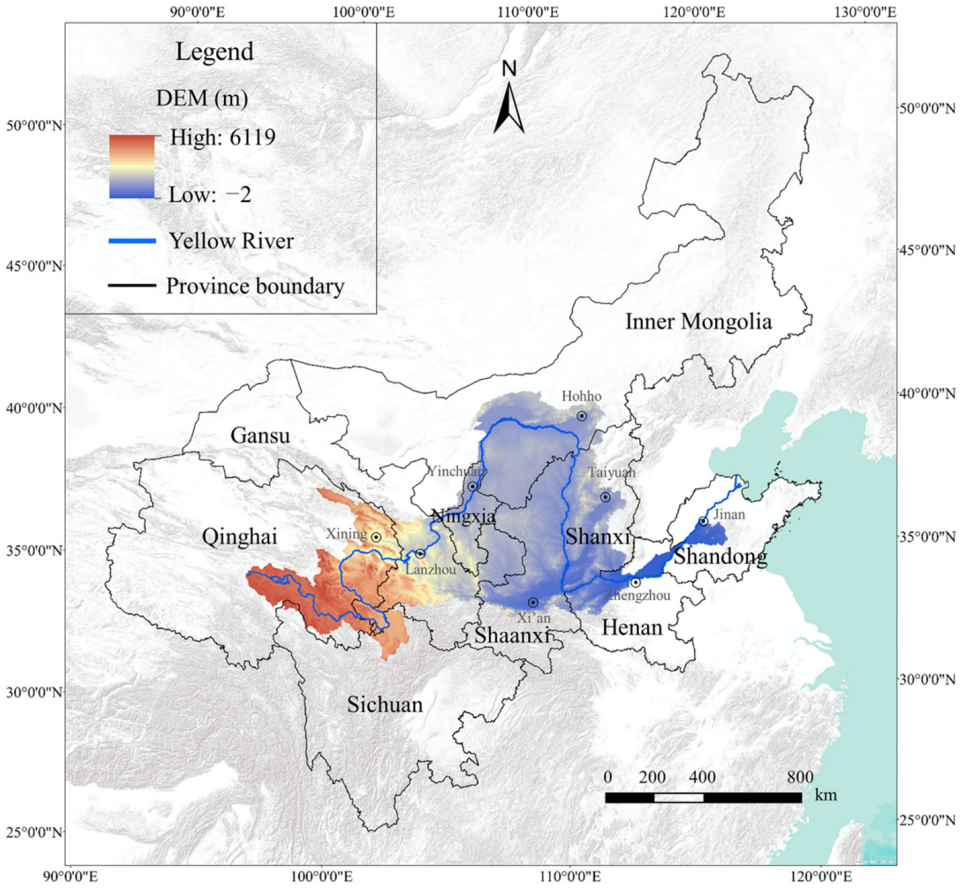

Figure 1. Study area.

2.2. Research Methods

Based on the concept of the WSSR and three characteristics of resilience—resistance, restoration, and adaptability—while considering factors such as water resources, the water environment, and socio-economic, an evaluation index system was devised. Resistance refers to the load caused by external and endogenous pressures on a water security system. It is influenced by factors such as available water resources, sewage discharge, and population pressure. Restoration pertains to the capacity of a water security system to quickly recuperate the initial or higher level through self-adjustment, adaptation, and implementation of strategies acquired from experience when it is damaged. The factors that affect this process include the efficacy of water resource development and utilization, environmental quality, the industrial structure, etc. Adaptability refers to the capacity of the water security system to absorb external disruptions and damage, and to adapt continuously to various uncertain influences to maintain the safe operation of the system. The factors that affect this process include the water resource matching coefficient, environmental investment, and the economic development level.

To standardize the indicators, the extreme value method was employed. A projection pursuit model based on the sparrow search algorithm (SSA-PP model) was subsequently devised for the purpose of evaluating the WSSR. Finally, with the geographical detectors, we investigated the major factors influencing the WSSR level. The comprehensive research framework is illustrated in Figure 2.

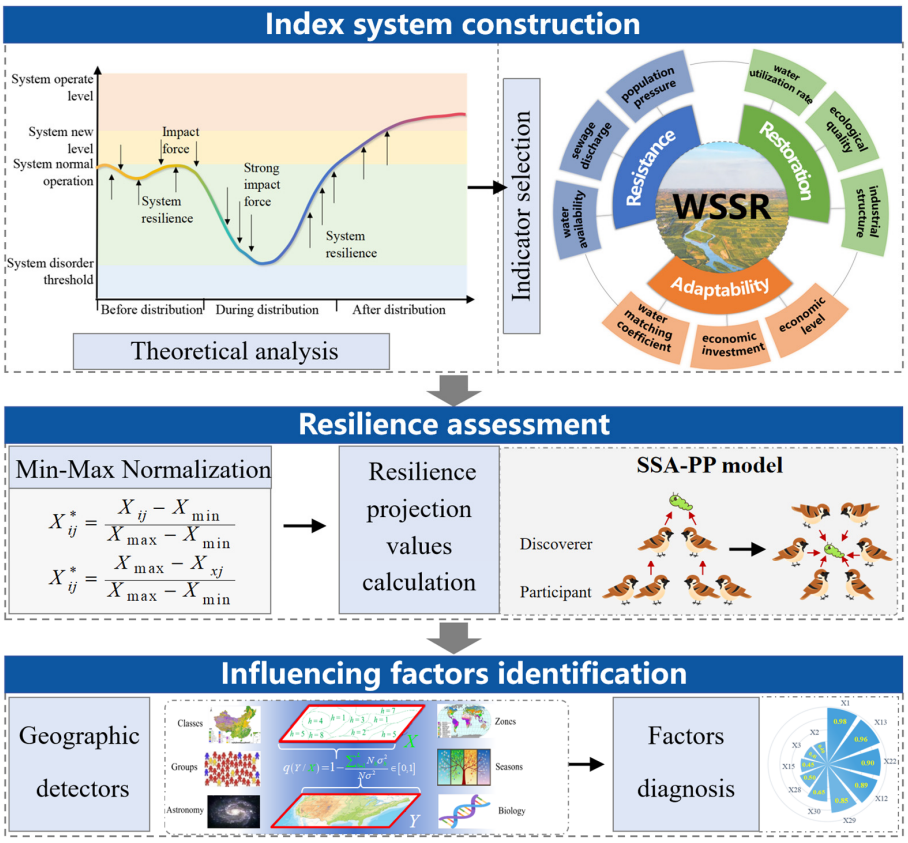

Figure 2. Research Framework.

2.2.1. Evaluation Index System for the WSSR in the YRB

Based on word frequency analysis, expert consultation, and scholarly research on water security, ecological security, sustainable utilization of water resources, and water resource vulnerability in the YRB [50–56], a three-layer evaluation index system was constructed. The target layer is the WSSR, and the criterion layer include three subsystems: resistance, restoration, and adaptability. The index layer consists of 32 indicators, as shown in Table 1.

Table 1. Evaluation index system of the WSSR in the YRB.

Criteria Layer	Indicator Layer	Selection Foundation	Indicator Acquisition Method	Unit	Attribute
Resistance (A)	Total precipitation (A1)	Water resources	Statistic data	10^8 m^3	Positive
	Per capita water resources (A2)		Total water resources/total population	m^3	Positive
	Profit and loss of water resources (A3)		Total water resources-total water supply	10^8 m^3	Positive
	Total wastewater discharge (A4)	Water environment	Statistic data	10^4 tons	Negative
	Wastewater COD discharge (A5)		Statistic data	10^4 tons	Negative
	Ammonia and nitrogen emissions in wastewater (A6)		Statistic data	10^4 tons	Negative
	Population density (A7)	Socio-economic	Population/regional area	person/km^2	Negative
	Natural population growth rate (A8)		Statistic data	‰	Negative
	Per capita GDP (A9)		Statistic data	yuan	Positive
	Per capita disposable income of urban residents (A10)		Statistic data	yuan	Positive

Table 1. *Cont.*

Criteria Layer	Indicator Layer	Selection Foundation	Indicator Acquisition Method	Unit	Attribute
Restoration (B)	Per capita water supply (B1)	Water resources	Total water supply/total population	m^3/person	Negative
	Development and utilization ratio of water resources (B2)		Statistic data	%	Negative
	Development and utilization ratio of surface water resources (B3)		Total surface water supply/surface water resources	%	Negative
	Development and utilization ratio of groundwater resources (B4)		Total groundwater supply/groundwater resources	%	Negative
	Urban sewage treatment rate (B5)	Water environment	Statistic data	%	Positive
	Ecological water use rate (B6)		Statistic data	%	Positive
	Area of soil erosion control (B7)		Statistic data	10^3 hm^2	Positive
	Proportion of primary industry (B8)	Socio-economic	Statistic data	%	Negative
	Proportion of secondary industry (B9)		Statistic data	%	Negative
	Proportion of the tertiary industry (B10)		Statistic data	%	Positive
	Advanced industrial structure index (B11)		Value added of the tertiary industry/value added of the secondary industry	-	Positive
Adaptability (C)	Water resource load index (C1)	Water resources	(Precipitation coefficient × *√population × GDP)/total water resources	-	Negative
	Matching coefficient between water and GDP (C2)		Total water resources/GDP	m^3/yuan	Positive
	Matching coefficient between water and land (C3)		Total water resources/cultivated area	10^4 m^3/hm^2	Positive
	Total wetland area (C4)	Water environment	Statistic data	10^4 hm^2	Positive
	Investment in industrial pollution control (C5)		Statistic data	10^4 yuan	Positive
	Investment in wastewater treatment (C6)		Statistic data	10^4 yuan	Positive
	Annual GDP growth rate GDP (C7)	Socio-economic	GDP growth/current year GDP	%	Positive
	Water consumption per 10,000-yuan GDP (C8)		Statistic data	$m^3/10^4$ yuan	Negative
	Water consumption of industrial added value per 10,000 yuan (C9)		Statistic data	$m^3/10^4$ yuan	Negative
	Urbanization rate (C10)		Urban resident population/total resident population	%	Positive
	Patent application authorization quantity (C11)		Statistic data	piece	Positive

The water resource data used in this study, including total precipitation, per capita water resources, and water resource development and utilization rate, were obtained from the water resource bulletins of various provinces and regions from 2009 to 2022. The water environmental data, such as the discharge of major pollutants in wastewater and the sewage treatment rate, were sourced mainly from the China Environmental Statistical Yearbook from 2010 to 2023. Socioeconomic data, such as population density, per capita disposable income in urban areas, and industrial structure, were obtained from the statistical yearbooks of various provinces and regions from 2010 to 2023. Partial indirect indicators were calculated from the raw data, and linear interpolation was used to supplement missing data.

2.2.2. Projection Pursuit Model Optimized on the Sparrow Search Algorithm (SSA-PP Model)

(1) Standardization of evaluation indicators

To eliminate differences between evaluation indicators, the extreme value method was used for standardization. The range of the processed indicators was (0, 1), where values near 1 denoted heightened resilience, whereas those approaching 0 signified diminished resilience. The formula for computation is outlined as follows:

Positive indicators:

$$X_{ij}^{*} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

Negative indicators:

$$X_{ij}^{*} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}} \tag{2}$$

where X_{ij}* signifies the normalized version of the original indicator value, X_{ij} represents the initial value of the indicator, and X_{max} and $X_{\min}$ represent the maximum and minimum values of the initial indicator, respectively.

(2) SSA-PP model

To fully retain the informational content in the time dimension contained in the indicators and dynamically present differences in the evaluation results, we use the sparrow search algorithm to optimize the projection pursuit (SSA-PP) model to measure the resilience level of the three subsystems and the comprehensive WSSR level [57].

m-dimensional data $\{X_{ij} | j = 1, 2, \ldots, m\}$ were converted into one-dimensional projection values Z_i with $a = (a_1, a_2 \ldots, a_m)$ as the projection direction:

$$Z_i = \sum_{j=1}^{m} a_j X_{ij} \tag{3}$$

where X_{ij} is the jth evaluation index value of the ith group and a is a unit length vector.

The WSSR level can be determined based on the value of Z_i, where a is a unit length vector. To determine the optimal value of a, the projection index function $Q(a)$ was constructed as follows:

$$Q(a) = S_z D_z \tag{4}$$

where Sz signifies the standard deviation associated with the projected value Z_i, whereas Dz represents the localized density of the same projected value Z_i [58]. The calculation formula was as follows:

$$Sz = \sqrt{\sum_{i=1}^{n} (Z_i - E(Z))^2 / (n-1)} \tag{5}$$

$$D_z = \sum_{i=1}^{n} \sum_{j=1}^{m} (R - r(i,j)) \cdot o(R - r(i,j)) \tag{6}$$

where the mean value of the sequence Z_i is denoted as $E(Z)$; R represents the window radius of local density, generally taken as $r_{\max} + p/2 \leq R \leq 2p$; the distance separating the samples is denoted as $r(i,j)$; $r(i,j) = |Z(i) - Z(j)|$; and $o(\tau)$ is the unit step function. When $\tau \geq 0$, the result is 1, and when $\tau < 0$, the result is 0; n is the total number of evaluation samples [59].

Therefore, the projection objective function was as follows:

$$\begin{cases} \max Q(a) = S_z D_z \\ s.t. \sum_{j=1}^{m} a_j^2 = 1, a_j \in [0, 1] \end{cases} \tag{7}$$

Parameter a is the object to be optimized, and projection pursuit is a nonlinear optimization problem in which $\{a(j) | j = 1 \sim m\}$ is chosen as the optimization variable. Owing

to the complexity and diversity of spatial structures, identifying the optimal projection direction poses a significant challenge. Therefore, a new sparrow search algorithm was employed for determining the optimal projection direction [60]. The optimal projection direction value calculated via Equation (7) can be substituted into Equation (3) to obtain the comprehensive evaluation index for the WSSR [61].

2.2.3. Geographical Detectors

To explore the degree of spatial differentiation of the WSSR in the YRB, factor detector within geographical detectors was employed to determine the influencing factors. The formula utilized for the specific calculation is as follows:

$$q_{W/s} = 1 - \left[\sum_{s=1}^{L} (N_s\sigma_s^2)/(N\sigma^2)\right] \quad (8)$$

where s = 1, 2 ..., L represents the various indicator classifications. The ArcGIS natural breakpoint approach is applied to categorize each detection factor into three distinct layers: low, moderate, and high; W is the evaluated value of the WSSR; the total count of evaluation indicators pertaining to the WSSR is denoted by Ns; the quantity of evaluation units is represented by N; and σ_s^2 and σ^2 are the variances of the index layers and the whole-region W values, respectively. $q_{W/s}$ are factor detection values, as the detection value increases, the influencing factors contribute more significantly to the WSSR, resulting in more pronounced disparities in the spatial distribution of the WSSR.

Furthermore, interactive detector was adopted to deeply analyze the interactions between different factors and explore whether they enhance or weaken the explanatory power of the WSSR, thereby gaining a more comprehensive understanding of the factors that affect the WSSR. There are five forms of interaction between factors: nonlinear attenuation, single factor nonlinear attenuation, dual factor enhancement, independence, and nonlinear enhancement [62].

3. Results

3.1. Development Capacity of Each Subsystem

3.1.1. Development Capacity of Each Subsystem in the YRB

As shown in Figure 3, the resilience values of the resistance subsystem within the YRB and its nine provinces and regions exhibited an increasing trend spanning from 2009 to 2022. Henan and Shandong consistently presented a low level of development, whereas Qinghai consistently presented a higher development level. Henan and Shandong are characterized by scarce water resource endowments, featuring per capita water availability notably lower than that of other provinces and regions, alongside high rates of water resource development and utilization. The total amount of wastewater discharge and the discharge of pollutants in wastewater were much greater in Henan and Shandong than those in other provinces and regions. The population density was high in Henan, and the per capita disposable income of urban residents was relatively low, resulting in a lower standard of living for residents. Qinghai has a low population density, relatively low pressure on resources and the environment from human activities, and a large total amount of precipitation. Owing to the good water resource endowments, the water resource utilization efficiency in Qinghai was much higher than that in other provinces and regions. On the other hand, the discharge of pollutants in Qinghai wastewater was much lower than that in other regions, and the environment was in good condition.

Figure 4 shows that the resilience values of the restoration subsystem in the YRB exhibited increasing tendencies from 2009 to 2022, and the differences between provinces and regions were relatively small. The development level in Ningxia was relatively low; although it showed an increasing trend, it consistently fell below the average level within the YRB. Ningxia has a significantly greater per capita water supply and water utilization efficiency than other provinces and regions. The proportion of secondary industries was relatively high in Ningxia, and its decrease was relatively slow. On the other hand, the

water use rate in Ningxia was relatively low, but it showed an increasing trend, and the industrial upgrading index also showed an increasing trend.

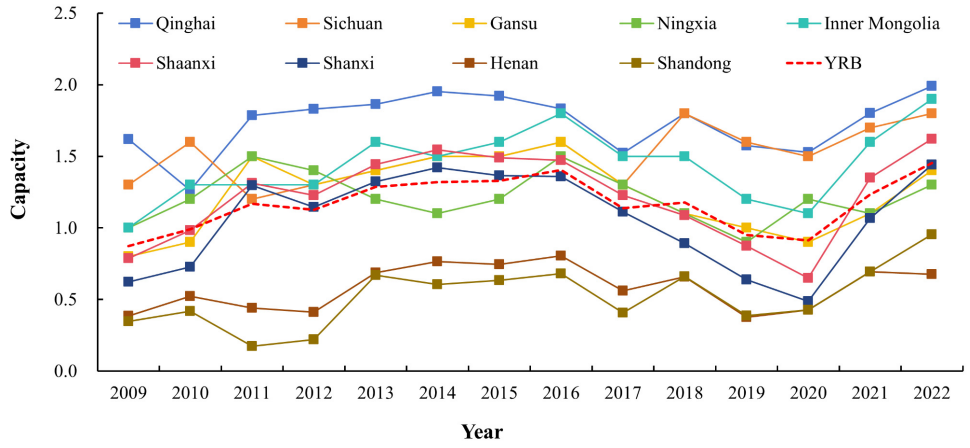

Figure 3. Development capacity of the resistance subsystem in the YRB.

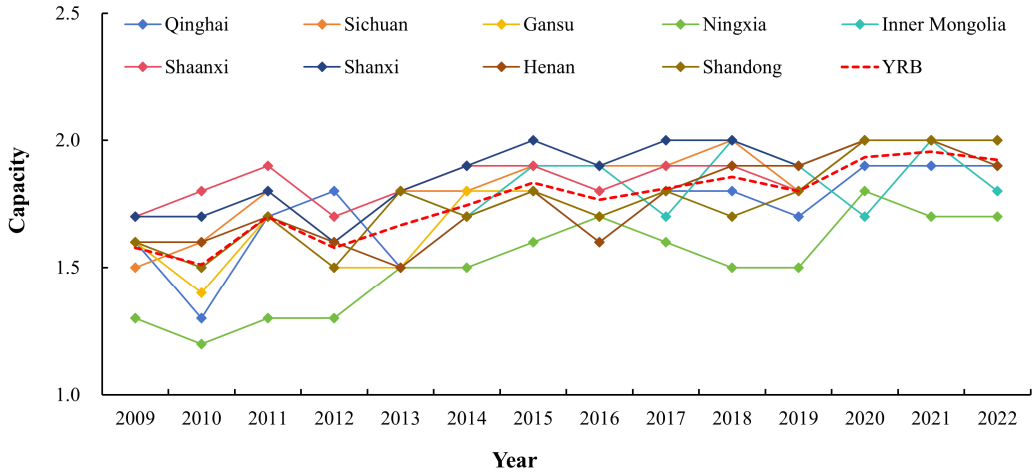

Figure 4. Development capacity of the restoration subsystem in the YRB.

Figure 5 shows that the resilience values of the adaptability subsystem tended to increase in Ningxia and Shandong, and that in the YRB and the remaining provinces and regions tended to decrease. The development level in Qinghai was relatively high. Although the development level was low in Sichuan, it showed an increasing trend, and it decreased after 2021 but was consistently higher than its previous level of development. Although the water resource load indices of Ningxia and Shandong were high, they tended to decrease. Both regions focus on the treatment of pollutants, and investment in industrial pollution treatment and wastewater treatment is much greater in Ningxia and Shandong than that in other provinces and regions. In addition, water use efficiency improved, and the water consumption per 10,000 yuan of GDP and industrial added value decreased annually. Qinghai has good resource endowments, abundant precipitation, and a large proportion of wetland area. The water resource load index significantly lagged behind those of other provinces and regions, indicating a relatively low level of development and utilization of water resources. The matching coefficient of water, GDP, and land resources surpassed those of other provinces and regions, whereas the industrial sector consistently demonstrated enhanced water usage efficiency. The matching coefficient of water and GDP in Sichuan showed a decreasing trend annually, paralleling a decline in the annual GDP growth rate. The yearly trend for the correspondence index between water and GDP in Sichuan displayed a decline, mirroring a concurrent slowdown in the annual growth rate of

GDP. On the other hand, the water resource load index in Sichuan was consistently at a low level, although it fluctuated and increased annually. The wetland area and the volume of patent applications demonstrated an increasing trajectory.

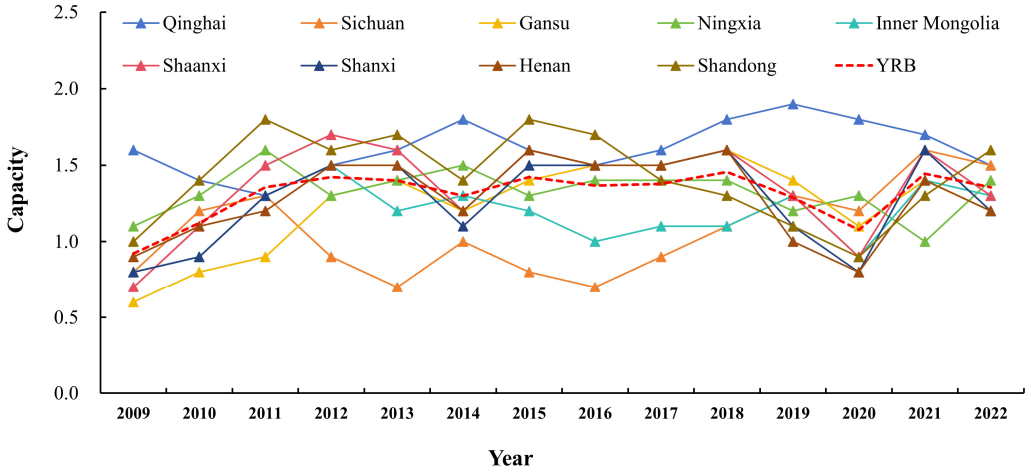

Figure 5. Development capacity of the adaptability subsystem in the YRB.

3.1.2. Development Capacity of Each Subsystem at the Provincial Scale

Figure 6 illustrates the evolution of development capacity within the YRB and nine associated provinces and regions spanning from 2009 to 2022.

As shown in Figure 6, from the perspective of spatial trends, the resistance of the water security system was ranked as Qinghai > Inner Mongolia > Shaanxi > Gansu > Ningxia > Sichuan > Shanxi > Henan > Shandong, with a gradual decline moving from west to east. For the restoration of the water security system, the order was Shaanxi > Shanxi > Sichuan > Gansu > Shandong > Henan > Qinghai > Inner Mongolia > Ningxia, which was greater in central China than in East China and was greater in West China. In terms of the adaptability capability of the water security system, the order was Qinghai > Shandong > Henan > Shaanxi > Gansu > Shanxi > Ningxia > Inner Mongolia > Sichuan, and the overall performance gradually decreased from west to east.

Considering temporal trends, the resistance of the water security system in the YRB provinces and regions manifested an upwards trajectory, except Henan and Shandong, which were far lower levels than the average level in the YRB. For example, Shandong has the lowest resistance, and economic growth and intensive water resource utilization have given rise to ecological and environmental challenges, resulting in a subdued resistance level and hindering improvement. Qinghai has the highest resistance, as there are rich water resources, superior ecological environment, and low population density. For the restoration of the water security system, the nine provinces and regions demonstrated a growing trend, but the development level of Ningxia was consistently lower than the average level. The development and utilization rates of water resources in Ningxia surpassed those of other provinces and regions, and the proportion of secondary industries was relatively high. Owing to the continuous optimization of the industrial structure and continuous improvements in the industrial upgrading index, the water recoverability demonstrated an increasing trend in Ningxia. For the adaptability of the water security system, except for Ningxia and Shandong, the other provinces exhibited decreasing trends. In Sichuan, which had the lowest adaptability, the water resource load index was initially low, but it fluctuated and increased. The matching coefficients of water, GDP and land resources tended to fluctuate and decrease, and investment in environmental remediation also fluctuated and decreased. In Qinghai, which had the highest adaptability, the water resource load index was far lower than that of other provinces, and the matching coefficient of water, GDP, and land resources was far greater than that in the other provinces. In addition, as the

source area for the upper reaches of the Yellow River, the environment of Qinghai is in good condition, and the rates of resource development and utilization are reasonable.

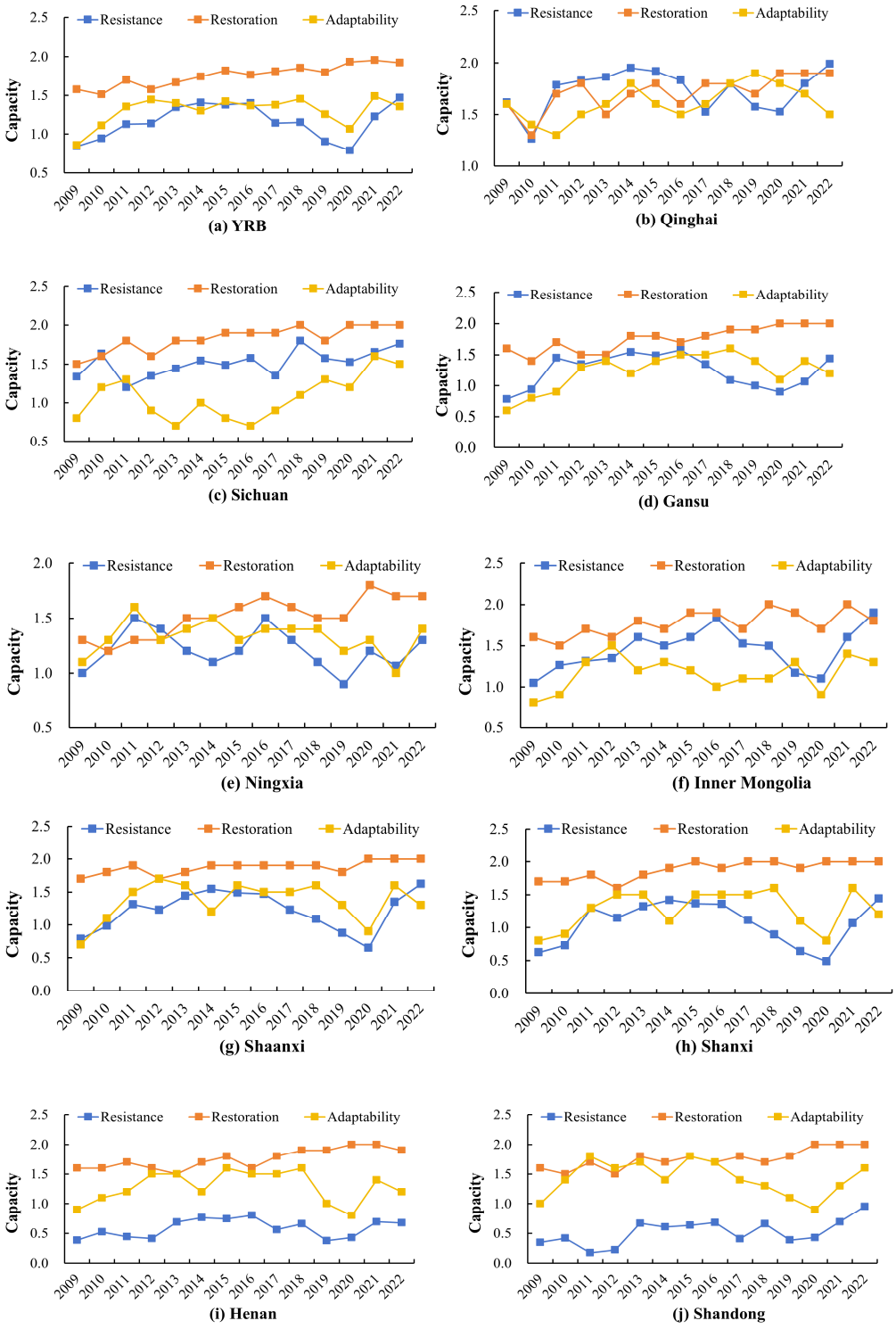

Figure 6. Resistance, restoration, and adaptability of the water security system in the YRB and at the provincial scale.

3.2. Assessment of the WSSR in the YRB

3.2.1. Temporal Trends in the WSSR in the YRB

As shown in Figure 7, the WSSR in the YRB and nine provinces and regions from 2009 to 2022 showed an increasing trend. The development level of Ningxia was low,

and the WSSR in Henan and Ningxia was consistently lower than the overall level in the YRB. Most provinces and regions, such as Shandong, Henan, and Ningxia, began to show a significant increasing trend after the WSSR was at its lowest value in 2014 and showed an increasing trend after it reached its highest value. Inner Mongolia maintained a high level of development in all years except 2020, when it showed a lower level of development than the overall level in the YRB. Qinghai had the lowest value in 2019, and since then, it has shown an increasing trend each year.

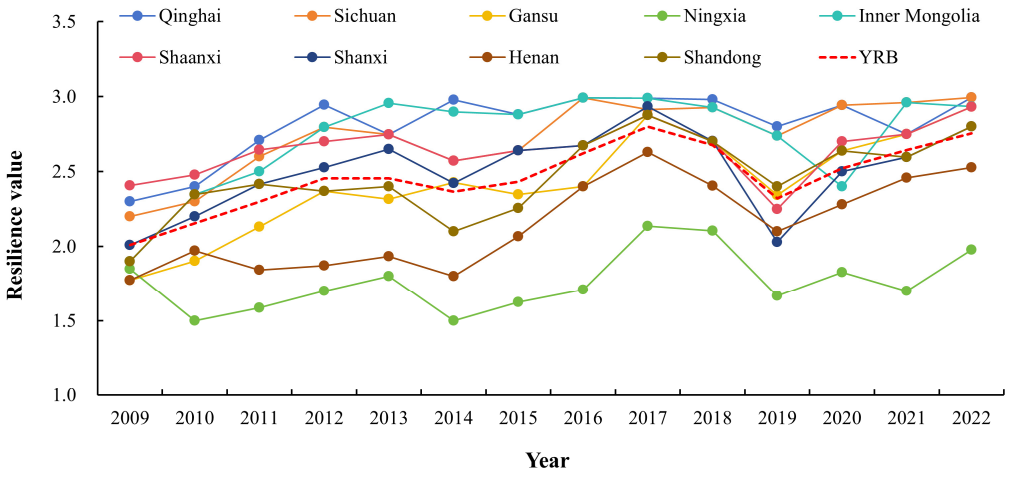

Figure 7. Trends of the WSSR in the YRB from 2009 to 2022.

3.2.2. Spatial Distribution of WSSR in the YRB

By employing the ArcGIS natural breakpoint approach, a spatial map of the WSSR was generated for the YRB (Figure 8). As shown in Figure 8, the YRB presented the highest WSSR in its western section, trailed by the central area, with the eastern region recording the lowest levels. The overall level of the WSSR has increased, but there are still some problems related to the flexibility level of individual provinces.

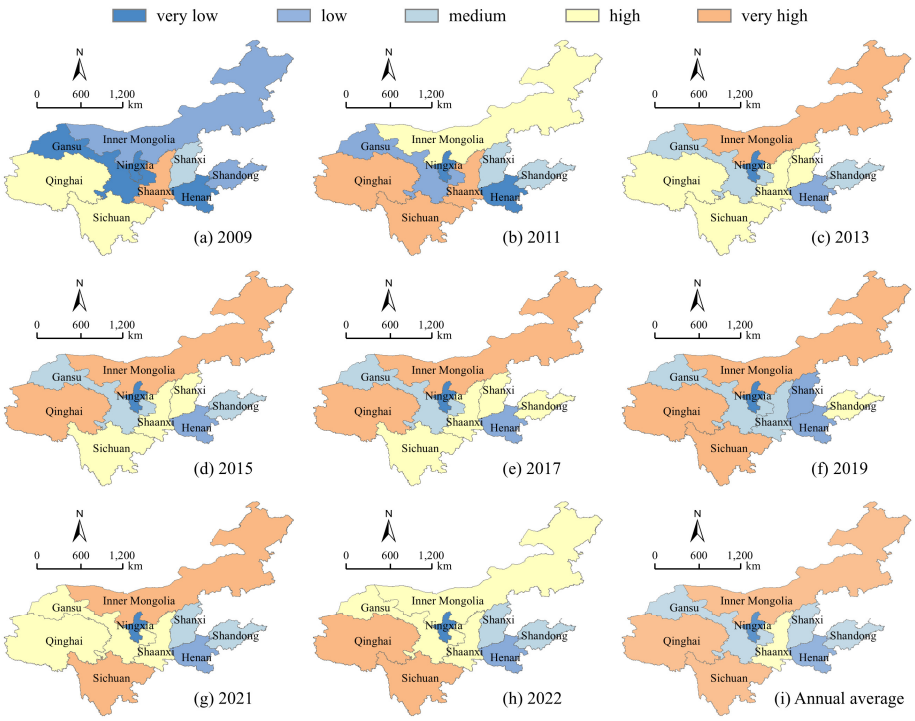

Figure 8. Distribution of WSSR levels in the YRB from 2009 to 2022.

The WSSR in the western region (Qinghai, Sichuan, Gansu, Ningxia, and Inner Mongolia) showed overall improvement. The development levels of Qinghai and Sichuan were high from 2009 to 2022, whereas the development level of Ningxia was not optimal. The initial development level of Gansu was low, but it tended to gradually improve. The western region of the YRB is the source area for the upper reaches of the Yellow River, and attention is given to the protection and governance of the environment in this region. Qinghai exhibited high resistance and adaptability, whereas Sichuan presented high resistance and restoration. The levels of resistance, restoration, and adaptability in Ningxia were relatively low and slowly increased. The resistance, restoration and adaptability of Gansu were at moderate levels, and the resistance and restoration fluctuated and increased, indicating gradual overall improvement.

The WSSR in the central region (Shaanxi, Shanxi) showed an overall improving trend. The WSSR in Shaanxi remained high in all years except 2019, during which it was at a moderate level. The WSSR in Shanxi consistently fluctuated between the moderate and high levels. Shaanxi showed a high level of resistance and restoration, but its adaptability was at a moderate level. In 2019, investment in industrial pollution control in Shaanxi significantly decreased, and the emphasis on environmental remediation was low. The level of resistance and adaptability in Shanxi was low, the adaptability tended to fluctuate and decrease, and the level of restoration was relatively high. Owing to the influence of economic development and the water resource matching coefficient, the WSSR in Shanxi was relatively unstable.

The WSSR in the eastern region (Henan and Shandong) was the lowest. The WSSR in Henan was consistently low, whereas that in Shandong fluctuated between moderate and high levels. Eastern China's economic development level is relatively high, with a high degree of resource development and utilization. However, attention to ecological and environmental protection is lacking, and there are numerous problems. The resistance of Henan and Shandong was low, and growth has been slow in these regions. Relatively, the adaptability was high, and that in Shandong was better than that in Henan.

3.3. Identification of the Factors Influencing the WSSR in the YRB

3.3.1. Single Factor Detection Analysis

To investigate the major factors influencing the WSSR, we used factor detector to calculate the *q*-values of 32 indicators (Table 1) from 2009 to 2022, and further determined the top 10 factors with the most significant influences (Figure 9). The *p*-values of all the influencing factors are less than 0.05, indicating that they have passed the test of statistical significance.

As shown in Figure 9, the top five factors affecting the WSSR in the YRB within the study area were the development and utilization ratio of water resources (B2), the water resource load index (C1), the development and utilization ratio of surface water resources (B3), water consumption per 10,000 yuan of GDP (C8), and total precipitation (A1), which were distributed mainly in the restoration subsystem and the adaptability subsystem.

For the evolving pattern of the influencing factors within each subsystem, it could be concluded that the development and utilization ratio of water resources (B2) was the highest year-round, followed by the total precipitation (A1) in the resistance subsystem. Over time, the influence of per capita water resources (A2) in the resistance subsystem, the development and utilization ratio of surface water resources (B3), the water resource load index (C1) in the adaptability subsystem, the water consumption per 10,000 yuan of GDP (C8), and the water consumption per 10,000 yuan of industrial added value (C9) in the adaptability subsystem gradually increased. These findings indicate that the total volume of water resources, the degree of development and utilization, and water use efficiency strongly affected the progression of the WSSR in the YRB.

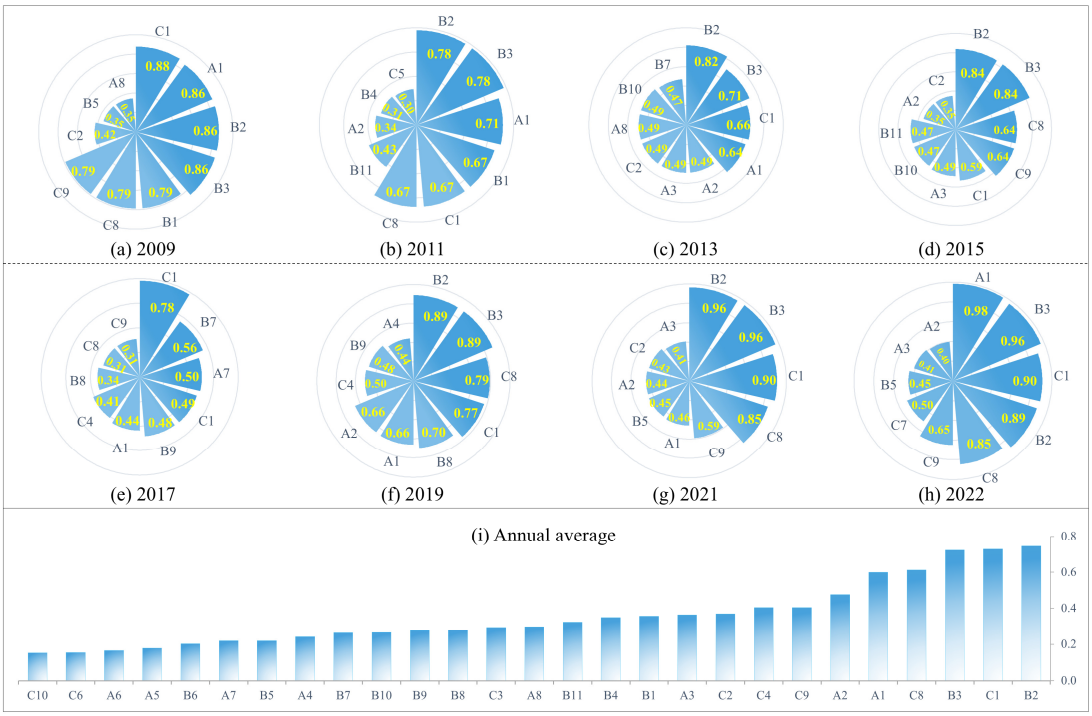

Figure 9. Top 10 influencing factors of the WSSR in the YRB from 2009 to 2022.

3.3.2. Interaction Detection Analysis

Interactive detector was employed to measure the interactive effects of two factors on the spatial differentiation of resilience levels in the WSSR. A total of 496 interaction results were formed by 32 influencing factors, and they are shown in Table 2 and Figure 10.

Table 2. Top five factors of the WSSR for the interactive detector in the YRB from 2009 to 2022.

Year \ Rank	1	2	3	4	5
2009	B10 ∩ A8 (0.996)	C4 ∩ A7 (0.993)	B5 ∩ A10 (0.991)	B10 ∩ A1 (0.979)	C11 ∩ A1 (0.979)
2010	C1 ∩ B11 (0.999)	C10 ∩ B2 (0.999)	B8 ∩ B2 (0.983)	B9 ∩ B3 (0.983)	C7 ∩ B11 (0.983)
2011	B8 ∩ B2 (0.988)	B8 ∩ B3 (0.988)	C9 ∩ B11 (0.988)	C10 ∩ B2 (0.988)	C11 ∩ B3 (0.988)
2012	B10 ∩ A8 (1.000)	B10 ∩ B2 (1.000)	B10 ∩ B3 (1.000)	B11 ∩ B2 (1.000)	B11 ∩ B3 (1.000)
2013	B7 ∩ A1 (0.992)	B10 ∩ C11 (0.992)	B7 ∩ C3 (0.989)	B9 ∩ B2 (0.982)	B11 ∩ B2 (0.982)
2014	B5 ∩ A8 (1.000)	B4 ∩ A8 (0.990)	B10 ∩ A8 (0.990)	A6 ∩ B11 (0.984)	B6 ∩ A6 (0.984)
2015	B9 ∩ A8 (1.000)	B10 ∩ A8 (1.000)	B11 ∩ A8 (1.000)	C1 ∩ A8 (1.000)	C4 ∩ A8 (1.000)
2016	B8 ∩ A7 (1.000)	B10 ∩ A7 (1.000)	B11 ∩ A7 (1.000)	C4 ∩ A7 (1.000)	C4 ∩ A8 (1.000)
2017	B7 ∩ A1 (1.000)	B8 ∩ A8 (1.000)	B8 ∩ A4 (0.999)	B8 ∩ A5 (0.999)	B8 ∩ A6 (0.999)
2018	B8 ∩ B1 (1.000)	C9 ∩ B4 (1.000)	A10 ∩ A1 (0.988)	B7 ∩ A1 (0.988)	B10 ∩ A1 (0.988)
2019	B10 ∩ B2 (1.000)	B10 ∩ B3 (1.000)	C4 ∩ A7 (1.000)	C10 ∩ B2 (1.000)	C10 ∩ B3 (1.000)
2020	A4 ∩ A1 (0.997)	A5 ∩ A1 (0.997)	B9 ∩ A7 (0.997)	C7 ∩ A8 (0.997)	C9 ∩ A1 (0.996)
2021	A4 ∩ A1 (1.000)	A5 ∩ A1 (1.000)	B4 ∩ A1 (1.000)	C9 ∩ B5 (1.000)	C10 ∩ B5 (1.000)
2022	A4 ∩ A1 (1.000)	A5 ∩ A1 (1.000)	A10 ∩ A1 (1.000)	B3 ∩ A2 (1.000)	C2 ∩ C13 (1.000)



Figure 10. Interactive detection of influencing factors in the YRB from 2009 to 2022.

The interaction between any two factors has a greater explanatory power for the spatial differentiation of the WSSR than the effect of a single factor. In addition, the interaction between resistance dimension factors and other factors has shown a significant enhancement in explaining the spatial differentiation of the WSSR. We counted the frequency of occurrence of factors contained in the top 70 pairs of interaction detection values each year. The results show that per capital water resources (A1) appears up to 16 times, followed by natural population growth rate (A8), development and utilization ratio of water resources (B2), proportion of the tertiary industry (B10), proportion of primary industry (B8), and advanced industrial structure index (B11). The top five factors with the highest frequency of occurrence are mainly derived from the restoration subsystem and the resistance subsystem. This means factors such as available water resources, population pressure, sewage discharge, water resource development and utilization rate, environmental quality, and industrial structure play a crucial role in improving the WSSR development level.

It is shown in Figure 10 that the high-value areas of interaction detection (represented in red in the figure) are concentrated in the middle and left sides. However, over time, these high-value areas gradually turn green (green represents low detection values), indicating a decreasing trend in detection values. The detection values of the interaction between the development and utilization ratio of water resources (B2) and the development and utilization ratio of surface water resources (B3) in the restoration subsystem and other factors are consistently high. The detection values of the total precipitation (A1) in the resistance subsystem, the water resource load index (C1), water consumption per 10,000-yuan GDP (C8), water consumption of industrial added value per 10,000 yuan (C9), and urbanization rate (C10) in the adaptability subsystem in the interaction with other factors show an increasing trend. This fully indicates that factors including water resource matching coefficient, environmental investment, and economic development level in the adaptability subsystem have a positive promoting effect on the WSSR in the YRB.

4. Discussion

Water security in the YRB is related to national ecological security and sustainable economic and societal development. Especially after the ecological preservation and premium development strategy of the YRB was implemented, the state has put forward stricter requirements for water security in the YRB. Numerous studies on water security in the YRB have been conducted. Shang et al. [63] devised an evaluation framework for water security from the five perspectives of resources, economy, ecology, environment and disaster prevention. Then, they established a fuzzy logic evaluation model considering the relationships among evaluation indices and proposed a sensitivity analysis of evaluation methods and a diagnostic method for improving water security. Drawing upon three subsystems—water resources, the water environment, and socioeconomic, Jia et al. [64] formulated an evaluation index system tailored specifically for assessing water security. To avoid the shortcomings of single-evaluation models and improve the stability of the evaluation structure, a comprehensive multi-attribute decision-making (MADM) model for water security evaluation, which integrates set pair analysis (SPA) and the fuzzy analytic hierarchy process (FAHP), was employed to assess the water security status of the YRB. These studies provide important support for YRB water security. A water security system is a composite system that encompasses many subsystems, including water resources, water environment, society, and the economy. Compared with the concept of water security, the water security system is more comprehensive, as it covers the social economy factors and emphasizes the relationship between humans and water. On the basis of the concept of a water security system, this paper considers the impact of water resources, water environment, and socio-economic factors on regional water security, and constructs a WSSR evaluation index system based on resistance, restoration, and adaptability. It provides a comprehensive view of water security, supplementing relevant research on water security. Besides, it provides more systematic theoretical support for regional water security.

Compared with the comprehensive index evaluation method, the projection pursuit method is able to preserve the information of the original data to the greatest extent possible and is applicable to the processing of nonnormal and nonlinear high-dimensional data. The core essence of projection pursuit lies in projecting high-dimensional data onto a reduced-dimensional subspace [65]. It facilitates the examination of high-dimensional datasets through the analysis and identification of projection features within the lower-dimensional space [66]. Many scholars have coupled projection pursuit and optimization algorithms to measure regional water security levels. For example, Xiang et al. [67] assessed the water security of the Dongting Lake region and its three major cities from a 2011 vulnerability range diagram (VSD), coupled projection pursuit (PP), sparrow search algorithm, and contribution model. The results shows that the coupled model is potentially suitable for water security evaluations, as it efficiently produces precise, comparable, sensitive, and comprehensive assessments. Employing a projection pursuit model based on particle swarm optimization (PSO-PEE), Wang et al. [68] assessed water security across five Central Asian nations, specifically Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. In this study, a projection pursuit model based on the sparrow search algorithm was implemented to appraise the status of water security within the YRB. The findings are consistent with the prevailing realities and conditions observed within the study area. Therefore, this model can be used as a decision-support tool for promoting the WSSR development level in the YRB.

In addition, there are also some shortcomings. We only focused on the development level of the WSSR in the YRB from 2009 to 2022. In the future, it is necessary to expand the time span and increase the amount of data to improve the credibility of the results. Furthermore, we took only the provinces and regions flowing through the Yellow River as the study area. In fact, through Water Diversion Projects, the scope of the YRB has been expanded to a larger area, including Hebei Province, Beijing City, and Tianjin City [69]. Therefore, future research should pay more attention on a wider YRB from a larger spatial perspective.

5. Conclusions

5.1. Main Conclusions

From 2009 to 2022, the WSSR in the YRB showed a steady upwards trend despite fluctuations. Among the provinces and regions, Ningxia presented the lowest level of development, and the WSSR in Henan and Ningxia was consistently lower than the average level in the YRB. In terms of spatial distribution, the YRB had the highest WSSR in the western area, surpassing the central region, while the eastern region recorded the lowest level. Overall, the WSSR level increased over the years, but some problems still exist with respect to the flexibility level of individual provinces. From the perspective of the three subsystems, the adaptability capacity of most provinces and regions in the YRB showed a decreasing trend, whereas the resistance and restoration capacities showed an increasing trend. The factors relevant to the restoration and adaptability subsystems significantly affected the WSSR. The impact of indicators such as per capita water resources (A2) in the resistance subsystem, the development and utilization ratio of surface water resources (B3) in the restoration subsystem, the water resource load index (C1) in the adaptive subsystem, water consumption per 10,000 yuan of GDP (C8), and water consumption per 10,000 yuan of industrial added value (C9), is gradually increasing. In addition, the interaction between factors exhibits a significant enhancement effect on explanatory, with the strongest enhancement effect observed in the interaction between factors in the restoration subsystem and other factors.

5.2. Suggestions

To improve the WSSR in the YRB and realize high-quality development, it is necessary for governance agencies in the nine provinces and regions to collaborate with one another and break down administrative barriers. First, the development speed should keep step with the sustainable limits imposed by available water resources. Improving water use efficiency in industries and agriculture, controlling regional population growth, and increasing public awareness regarding water conservation are necessary. Second, sustainable water consumption should be emphasized. The water pollution problems in the YRB are severe. Therefore, it is imperative to implement comprehensive management of water quantity and water quality. Finally, targeted ecological compensation measures and an internal water rights trading system should be implemented across the whole basin, to conserve water resources more effectively and ensure sustainable development in the whole basin.

On the other hand, each region and province should analyze the current status of the WSSR and take countermeasures against existing problems. The western region (Qinghai, Sichuan, Gansu, Ningxia, and Inner Mongolia) is the water source area for the Yellow River, and thus ecological protection is a top priority. It is important to protect areas with key ecological functions and implement ecosystem protection and restoration projects. The central region (Shaanxi, Shanxi) is faced with water scarcity, water pollution, and a fragile environment. It is necessary to carry out water-saving, water pollution-control and ecological-restoration measures to increase water efficiency and vegetation coverage. The eastern region (Henan, Shandong) is a key area of economic development, with serious water issues. These two provinces should optimize their industrial structures and develop high-tech industries and modern service industries. In addition, water resource management systems should be improved and perfected, and water resource protection and conservation measures should be strengthened.

Author Contributions: Conceptualization and methodology: Y.S. and P.L.; Analysis and investigation: Y.S., P.L., B.Q. and J.L.; Writing—original draft preparation: Y.S., P.L., B.Q. and J.L.; Writing—reviewing and editing: B.Q. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number U2243601), the Henan Province Science and Technology Research Project (grant number 242102520050), and the Central Public-Interest Scientific Institution Basal Research Fund (grant number HKF202114, HKF202315, HKF202402).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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

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