



Water resource carrying capacity and obstacle factors in the Yellow River basin based on the RBF neural network model

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Abstract

The Yellow River basin (YRB) plays an important role in China's economic and social growth. Based on different dimensions, we adopted the radial basis function (RBF) neural network model and the obstacle degree model to examine the water resource carrying capacity (WRCC) of the YRB. From 2005 to 2020, the WRCC of the entire YRB, as well as the upstream and midstream regions, improved, but the WRCC of the downstream region remained poor, revealing spatial differences. The overall improvement in the WRCC of the Yellow River's nine provinces is good, but the WRCC of Inner Mongolia and Henan is poor, suggesting regional differences. From the standpoint of obstacle factors, the development and usage rate of surface water resources are the main challenges. In 2020, the obstacle degree of the YRB reached 87.4871%. The irrigated area rate in Gansu was the primary obstacle factor, and the obstacle degree reached 73.0238%. Qinghai's industrial aspects mostly hindered the improvement of its WRCC, with an obstacle degree of 31.36%. The results provide a theoretical reference for the high-quality development of the YRB.

Keywords Yellow River basin · Water resource carrying capacity · RBF neural network · Obstacle factor

Introduction and motivation

The Yellow River is China's chief river. The Yellow River basin (YRB) plays a critical role in China's economic and social growth and ecological security. On the morning of September 18, 2019, President Xi Jinping pointed out that protecting the Yellow River was a long-term plan related to rejuvenating the country. He also stressed that ecological protection and high-quality development of the YRB should be elevated to an effective national strategy.

The "87" water distribution scheme of the Yellow River, promulgated in 1987, provides basic guidelines for environmental protection and management in the YRB; it also forms the basis for determining the water consumption index of each province and has played a vital historical role in the orderly use of water in the YRB. However, with climate change, human activity, and the commencement of

the South-North Water Transfer Project, the Yellow River's water resources are facing a new situation (Zhu et al. 2021). In January 2020, Xi Jinping indicated that great efforts must be made to protect and treat the YRB in pursuit of ecological conservation and high-quality development.

Water is the core of economic growth and social welfare and supports ecosystems (Ostad-Ali-Askari 2022a, b, c; Santos Coelho et al. 2022). Properly controlled water resources are a crucial part of development (Vanani et al. 2022; Xiang et al. 2021).

Water resource carrying capacity (WRCC) refers to the ability of water resources to support the coordinated expansion of a region's population, society, economy, and environment. The rational use of water resources by humans enables the promotion of economic and social growth (Ostad-Ali-Askari 2022a, b, c; Qiao et al. 2021).

Some studies have evaluated WRCC in the YRB. However, most studies have not considered analysis from multiple dimensional perspectives. Most research has analyzed WRCC in the YRB based on a single spatial dimension (Cui et al. 2022; Wang et al. 2021b; Hu et al. 2022). Some studies have examined representative regional and provincial WRCC in the YRB, such as irrigation areas (Cui et al. 2022), the region's nine provinces (Wang et al. 2021b), and

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the Inner Mongolia Autonomous Region (Hu et al. 2022). In terms of time selection, most studies have investigated regional WRCC in the current year (Xu et al. 2022) or predicted future WRCC (Yan and Xu 2022). In terms of method selection and model construction, most research has used a comprehensive evaluation model for regional WRCC analysis (Hu et al. 2020) without fully considering the limitations of indicator weight determination.

This study expands the scientificity and rationality of regional WRCC evaluation research from several angles. First, by assessing the WRCC in the YRB from different standpoints, we can more objectively and comprehensively examine the spatial distribution and comparative differences in WRCC across regions with dimensions. Second, we selected the time range as 2005–2020. The extension of the timeline is conducive to a more comprehensive

and detailed understanding of the long-term development trends and spatial differences in WRCC in the YRB. Third, we introduced the radial basis function (RBF) neural network model, which avoids the influence of artificially determined weights on the evaluation indicators in the model, can quickly converge and effectively solve the non-linear problem of the water resource system, and has a strong classification function that is helpful for assessing the Yellow River’s WRCC basin for objective and effective analysis.

The remainder of this paper is organized as follows. “Literature review” presents the literature review, “Study area and research methods” outlines the study area and methodology, “Results” covers the results, “Discussion” discusses them, and “Conclusions” concludes the paper. A flowchart of this study is displayed in Fig. 1.

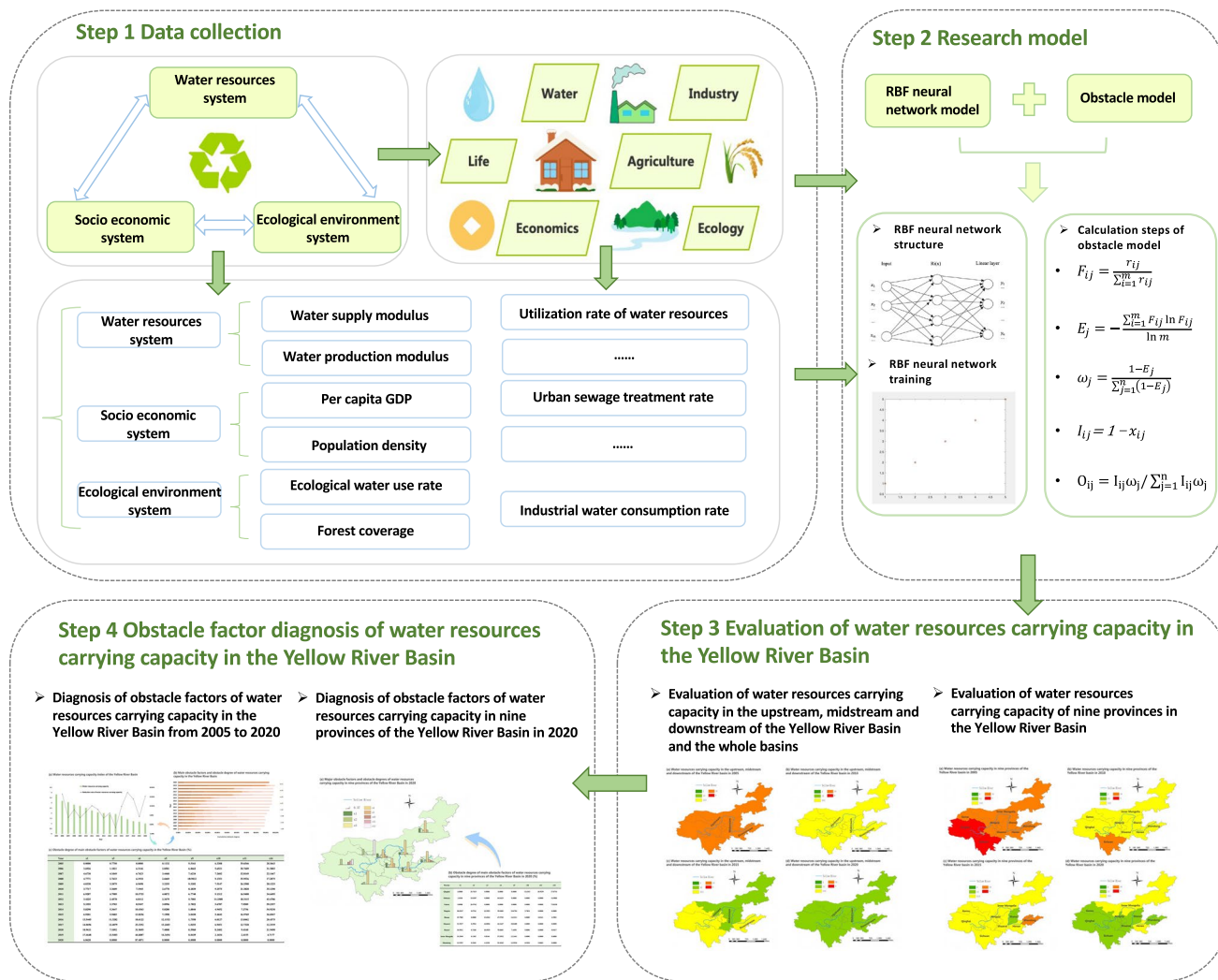


Fig. 1 Research flowchart

Literature review

Research on water resources focuses on water resource management (Talebmorad et al. 2022; Varis and Vakkilainen 2001), water security (Ghashghaie et al. 2022; Van Ginkel et al. 2018), and water resource and sustainable development direction (Ostad-Ali-Askari 2022a, b, c; Nyam et al. 2021).

Yuan et al. (2006) proposed that WRCC is the scale of water resources' support for economic and social growth and that the concept has obvious spatial and temporal connotations. Li and Liu (2019) further considered the relationship between subjects and objects.

In choosing a research perspective, most scholars study regional WRCC from a single dimension. Meng et al. (2009) evaluated WRCC in the Tarim River basin. Cui et al. (2022) examined representative areas for the study of WRCC in an irrigated part of the YRB. In addition, some scholars have conducted regional WRCC research from the standpoint of provinces and cities. Meng et al. (2009) combined water supply demand and S-curve threshold analyses to assess WRCC in Inner Mongolia. Song et al. (2011) looked at the current WRCC and its dynamic trends in Tianjin. The spatial distribution and changing trends of WRCC differed across dimensions. Prior to this study, most research has not comprehensively analyzed regional WRCC based on different dimensions.

From the perspective of time, most scholars choose the current year or the past few years to evaluate regional WRCC (Xu et al. 2022). Alternatively, future years should be chosen to make reasonable scientific forecasts of regional WRCC. Yan and Xu (2022) predicted the impact of different water quotas and industrial structures by developing a WRCC assessment model to explore the regulation and control methods for WRCC in this region. Yang and Wang (2022) predicted the urban WRCC of Qingdao from 2010 to 2030 grounded in the basin unit and put forward reasonable suggestions on this basis. Evaluating and forecasting regional WRCC over a period of a few years is not conducive to investigating the long-term development trends of regional WRCC.

At present, research on WRCC focuses on its evaluation, for which methods can be divided into two categories. One is to use a comprehensive technique to assess WRCC. Approaches include principal component analysis (Hu et al. 2020), fuzzy comprehensive evaluation (Abedi-Koupai et al. 2022; Feng et al. 2020), and fuzzy set pair analysis (Zhang et al. 2020). Therefore, combined with the TOPSIS model, the combined weighted TOPSIS model (Sun et al. 2020) was further developed to assess WRCC. This method has the limitation of artificially establishing the weight in the determination of the indicator weight, which affects

the scientificity of the outcome. The second category of approaches evaluates WRCC using non-integrated assessment methods. Techniques include the normal cloud model (Rabiei et al. 2022; Zhang et al. 2019), the system dynamics method (Wang et al. 2021a; Yang and Wang 2022), and the ecological footprint method (Dai et al. 2019). The normal cloud model has symmetric characteristics, and the evaluation cannot reflect the uncertainty in a standardized manner. The system dynamics method cannot couple complex water resource system models and is unsuitable for simulating long-term regional growth. There are ecological biases in the ecological footprint method, and there are estimated omissions. This approach has limitations in its application, which affects the accuracy of the results.

Overall, the current literature on WRCC has the following gaps: (1) The research perspective of WRCC does not fully consider different dimensions. Regional WRCC, as seen from different dimensions, has unique development trends and spatial distribution characteristics. Analyzing regional WRCC based on a single dimension only is not conducive to a comparative analysis of WRCC across dimensions. (2) We did not consider the long-term development trend of regional WRCC. Most of the literature examines or forecasts individual years of regional WRCC without considering the time factor and lacks long-term development research on regional WRCC. This is not ideal for exploring the long-term history and development trends of regional WRCC. (3) The selection of the WRCC evaluation method does not fully consider the determination of the index weight. The comprehensive assessment methods and models used in the literature have often artificially established weights for the evaluation indicators, which carry limitations. This is not good for obtaining accurate scientific results.

In this study, we adopted the following methods and models. First, based on the characteristics of water resources, we divided the YRB's water resource system into three subsystems—the (1) water resource, (2) socioeconomic, and (3) ecological environment systems—according to which we built the index system of the YRB's WRCC. We divided each evaluation index into five grades from I to V. Second, we harnessed the RBF neural network model to assess WRCC in different dimensions of the YRB from 2005 to 2020. Finally, we employed the obstacle degree model to further explore the factors affecting the improvement of WRCC in the YRB. We thus formulated targeted policy recommendations for enhancing WRCC and promoting high-quality development in the YRB.

Study area and research methods

Study area

The Yellow River originates in the Bayankara Mountains of China's Qinghai Province. From west to east, it flows

through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, totaling nine provinces in all. The river finally flows into the Bohai Sea in Kenli District, Dongying City, Shandong Province, with a total length of 5464 km and a watershed area of 795,000 km². According to administrative divisions, Qinghai, Gansu, Ningxia, and Sichuan are classified as Yellow River upstream areas, while Inner Mongolia, Shaanxi, and Shanxi are classified as midstream areas, and Henan and Shandong are classified as downstream areas. Thus, based on different spatial dimensions, we considered the YRB as the research area and examined the region in its entirety as well as its upstream, midstream, and downstream zones. The provinces are the research objects. We, therefore, performed a reasonable scientific evaluation of the YRB's WRCC and identified relevant obstacle factors.

The YRB is an important grain production base in China, an ecological barrier for maintaining environmental security, and an economic belt for economic and social growth (Wang et al. 2022). As displayed in Fig. 2, by the end of 2020, the YRB's overall population was 421 million people, accounting for 29.85% of China's total population. Henan and Shandong, in the lower reaches of the Yellow River, are the most populous provinces, with approximately 100

million people. The YRB has a large population and is an important economic zone in China. The YRB's gross domestic product (GDP) is 25.39 trillion yuan, and the industrial added value is 798 million yuan, accounting for about a quarter of China's GDP. The lower reaches of the Yellow River have undergone development. The YRB is also a vital food production base in China. The YRB's grain output was predicted to reach 239 million tons in 2020, accounting for one third of the country's output, especially Henan and Shandong, which are located in the lower reaches of the Yellow River and are major agricultural provinces. However, the basin's ecological environment is fragile, the relationship between water and sediment is not harmonious, and problems with water resources are prominent. In recent decades, the YRB has been severely affected by human activity (Geng et al. 2022).

Constructing the WRCC evaluation index system and determining the index weight

Constructing the WRCC evaluation index system

Many factors affect the carrying capacity of regional water resources (Yang et al. 2019). Based on the principle of index

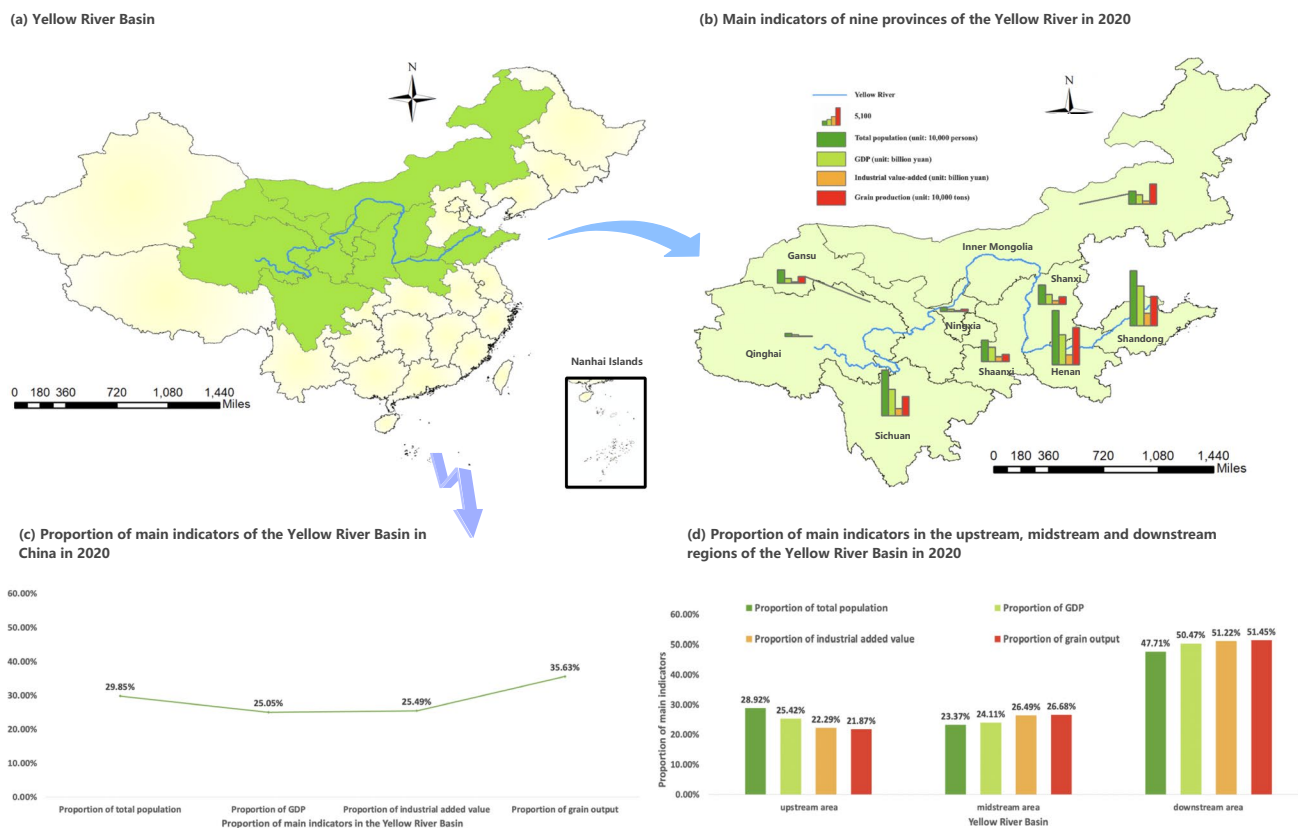


Fig. 2 Basic information about the YRB

system construction, we referred to the index system of internal and external water resource evaluations (Deng et al. 2021). When combined with the features of the YRB’s water resources, the index system of WRCC evaluation in the YRB is divided into the water resource, socioeconomic, and ecological environment systems. According to the principles of science, coordination, representation, and operability (Zhang et al. 2018; Wang et al. 2018), we selected 16 influencing factors as the evaluation indices of WRCC in the YRB, as seen in Table 1.

Data sources: We obtained the data from the Water Resources Bulletin (2005–2020) and each Statistical Yearbook (2005–2020) of the YRB’s nine provinces, the China

Statistical Yearbook (2005–2020), the Ministry of Environmental Protection, the National Bureau of Statistics, the Ministry of Agriculture, the State Forestry Administration, and the Ministry of Water Resources.

This study is rooted in the current situation of water resource development in the YRB and of water resources in the YRB’s provinces. This is grounded in the evaluation criteria for water resources (Wang et al. 2021b; Zhang et al. 2019). We divided each evaluation index into five levels: level I=loadable state, level II=weak bearable state, level III=critical state, level IV=overload state, and level V=severe overload state. The findings are presented in Table 2.

Table 1 The WRCC evaluation index system

Target layer	System layer	Indicator layer	Calculation formula	Indicator content
WRCC	Water resources systems	×1 water resource usage rate (%)	Total water supply/total water resources	Reflecting the extent of water resources development and utilization
		×2 water supply modulus (10,000 m ³ /km ²)	Total water supply/area	Reflects water supply per unit area
		×3 water production modulus (10,000 m ³ /km ²)	Total water resources/area	Reflecting on the regional water resources situation
		×4 surface water resource development and usage rate (%)	Surface water supply/surface water resources	Reflecting the status and potential of surface water resource development
		×5 water resources per capita (m ³ /person)	Total water resources/total population	Reflects regional water resources abundance, scarcity and development potential
	Socio-economic system	×6 population density (person/km ²)	Total population/area	Reflects water demand pressure due to population size
		×7 urbanization rate (%)	Urban population/total population	Reflecting the degree of regional urbanization
		×8 GDP per capita (10,000yuan/person)	10,000-yuan GDP/total population	Reflecting socio-economic development
		×9 water consumption of 10,000-yuan GDP (m ³ /10,000yuan)	Total water consumption/10,000-yuan GDP	Reflects overall economic water use
		×10 industrial water consumption rate (%)	Industrial water consumption/total water consumption	Reflects the share of industrial water use
		×11 water consumption of 10,000-yuan industrial value-added (m ³ /10,000yuan)	Industrial water consumption/10,000-yuan industrial value-added	Reflecting the level of industrial water use
		×12 irrigated area rate (%)	Effective irrigated area/cultivated land area	Reflects the level of irrigation on regional cropland
	Ecosystem	×13 water consumption per unit of irrigated farmland area (m ³ /hectare)	Agricultural irrigation water consumption/effective irrigated area	Reflects the level of agricultural development and water use efficiency
		×14 ecological water consumption rate (%)	Ecological water consumption/total water consumption	Reflects the degree of human social and ecological sustainability
		×15 forest coverage rate (%)	Forest area/area	Reflects the integrity of the ecosystem
		×16 municipal wastewater treatment rate (%)	Total urban sewage treatment/total urban sewage discharge	Reflecting the city’s wastewater treatment capacity

Determining the index weight

1. Normalizing the data

Suppose, $\overline{a_{ij}^*}$ indicates the value of the j th evaluation index of the i th evaluation level, where $i = 1, 2, \dots, n; j = 1, 2, \dots, m$. The regional WRCC evaluation indices generally include benefit- and cost-type indices. The data of these two kinds of indices are normalized in different ways as follows (Shao and Liu 2007):

For benefit-type indicators, the normalization formula is

$$\begin{cases} \overline{a_{ij}} = \overline{a_{ij}^*} \\ a_{ij} = \overline{a_{ij}}/f_{\max}(j) \end{cases} \quad (1)$$

For cost-type indicators, the normalization formula is

$$\begin{cases} \overline{a_{ij}} = 1/\overline{a_{ij}^*} \\ a_{ij} = \overline{a_{ij}}/f_{\max}(j) \end{cases} \quad (2)$$

Among them $f_{\max}(j)$ is the maximum value of the j th index in $\overline{a_{ij}}$.

2. Determining the index weight

For the weight ω_j of a single factor, because the index weight setting process of the entropy weight method is not affected by subjective factors, the weight distribution generated by this approach has greater validity and objectivity (Du et al. 2022). Hence, we used the entropy weight

method to calculate the weight of each indicator. The steps were as follows (Peng and Deng 2020):

1. The normalized index obtained from formulas (1) and (2) is r_{ij} ;
2. The information entropy E_j of the j th index is computed using the following formula:

$$E_j = \frac{\sum_{i=1}^m F_{ij} \ln F_{ij}}{\ln m}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (3)$$

$$F_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \quad (4)$$

3. Calculate the weight ω_j of the j th indicator; its calculation formula is:

$$\omega_j = \frac{1 - E_j}{\sum_{j=1}^n (1 - E_j)} \quad (5)$$

Research methods

The RBF neural network model for WRCC evaluation

Artificial neural network (ANN) model can adequately approach complex non-linear functions (Sun et al. 2022b; Li et al. 2017). The RBF neural network is a typical local approximation ANN, consisting of 3 layers of interconnected artificial neurons (Zou et al. 2015): The first layer is the input layer, which contains

Table 2 WRCC evaluation index grading criteria

Indicators	Grading criteria				
	Level I	Level II	Level III	Level IV	Level V
×1 Water resource usage rate (%)	< 15	15~35	35~45	45~65	> 65
×2 Water supply modulus (10,000 m ³ /km ²)	> 20	15~20	10~15	5~10	< 5
×3 Water production modulus (10,000 m ³ /km ²)	> 60	35~60	20~35	15~20	< 15
×4 Surface water resource development and usage rate (%)	< 10	10~20	20~40	40~60	> 60
×5 Water resources per capita (m ³ /person)	>2 200	1700~2200	1000~1700	500~1000	< 500
×6 Population density (person/km ²)	< 550	550~600	600~650	650~700	> 700
×7 Urbanization rate (%)	> 60	52~60	46~52	40~46	< 40
×8 GDP per capita (10, 000yuan/person)	> 4.1	3.4~4.1	2.7~3.4	2~2.7	< 2
×9 Water consumption of 10,000-yuan GDP (m ³ /10, 000yuan)	< 24	24~60	60~140	140~220	> 220
×10 Industrial water consumption rate (%)	< 10	10~14	14~18	18~22	> 22
×11 Water consumption of 10,000-yuan industrial value-added (m ³ /10, 000yuan)	< 15	15~50	50~100	100~300	> 300
×12 Irrigated area rate (%)	> 80	70~80	60~70	50~60	< 50
×13 Water consumption per unit of irrigated farmland area (m ³ /hectare)	< 5500	5500~6000	6000~8500	8500~11,000	> 11,000
×14 Ecological water consumption rate (%)	> 6	3~6	1~3	0.5~1.0	< 0.5
×15 Forest coverage rate (%)	> 40	30~40	20~30	15~20	< 15
×16 Municipal wastewater treatment rate (%)	> 92	86~92	80~86	74~80	< 74

signal source nodes $x_p (p = 1, 2, \dots, n)$. The second layer is the hidden layer, and the number of nodes depends on the specific problem. The third layer is the output layer $y_q (q = 1, 2, \dots, m)$ (Sun et al. 2022a). The network structure is shown in Fig. 3.

The output of the i th node of the hidden layer of the RBF neural network is (Shao and Liu 2007):

$$r_i(x) = R_i(\|x - c_i\|/\sigma_i), i = 1, 2, \dots, k \tag{6}$$

In this formula, x is the dimensional input variable. c_i is the center of the j th basis function, which has the same dimension as x . σ_i is the i th perceptual variable, which determines the width of the function around the center point; that is, the size of the perceptual field of view. k is the number of sensing units. $\|\cdot\|$ is a vector parametrization, generally a Euclidean parametrization.

Although radial basis functions have various forms, such as square root, Gaussian, and slate-like functions, the most commonly used is the Gaussian function:

$$R_i(x) = \exp\left[-\frac{\|(x - c_i)\|^2}{2\sigma^2}\right], i = 1, 2, \dots, k \tag{7}$$

In the WRCC evaluation model of the YRB established in this study, we also chose the Gaussian function as the basis function. The output of the established RBF neural network model can be expressed as

$$y_q = \sum_{i=1}^k w_{iq} \exp\left[-\frac{\|(x - c_i)\|^2}{2\sigma^2}\right], q = 1, 2, \dots, m \tag{8}$$

Here, q is the number of output nodes, and w is the weight connecting the implicit and output layers. We used the RBF neural network to adjust the parameter centers c_i and weights w using the input and output errors to adjust the coefficients within the network.

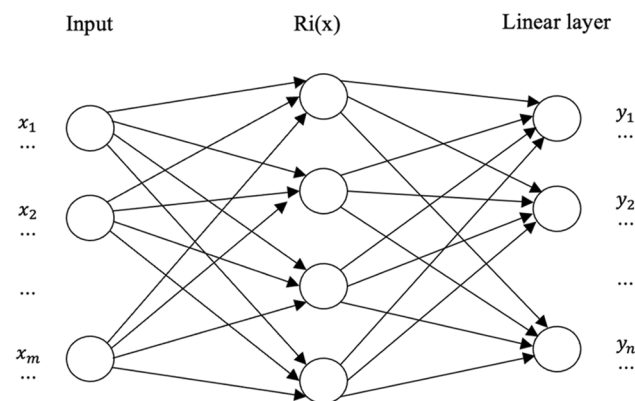


Fig. 3 RBF neural network structure

As such, we established an RBF neural network model for WRCC evaluation in the YRB using MATLAB R2017b.

First, according to formulas (1) and (2), we normalized the standard value of the WRCC evaluation classification outlined in Table 2, and we obtained input vector x and output vector y of the RBF network training sample.

We then built the RBF neural network model using the newrb function. Its format is $\text{net} = \text{newrb}(x, y, \text{goal}, \text{spread})$ where x, y, goal , and spread are the input vector, target vector, mean squared error, and RBF distribution, respectively. Moreover, we needed to choose the largest possible spread value to ensure that the input range of the RBF would be sufficiently large, such that the output of the network would be smoother and the generalization ability stronger. In this model, the spread value is 1.

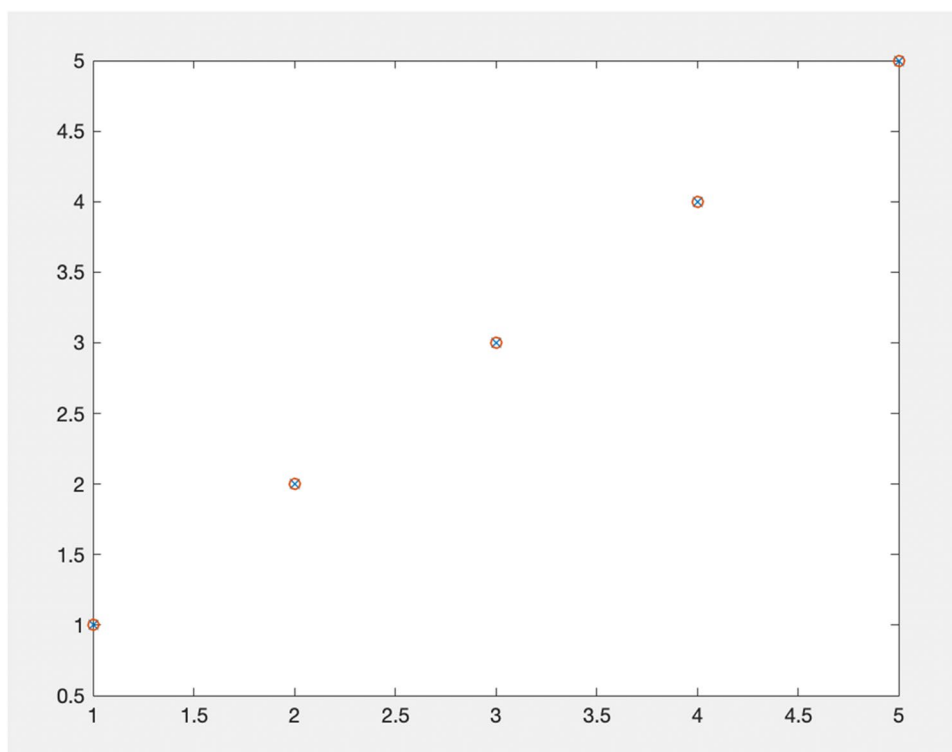
We used the sim function to obtain the sample training results of the network in the format $t = \text{sim}(\text{net}, x)$. The plot command is executed to obtain the graphical output of the network training (see Fig. 4) in the format of $\text{plot}(y, y, \text{ex}, y, t, \text{eo}, \text{e})$. Among them, y is the level vector, x represents the target output of each level, and o denotes the output value of each level of network training. According to the graph, the training error of the model for the sample is 0; thus, the model can be used to evaluate the WRCC of the YRB.

Obstacle degree model for WRCC

When assessing WRCC, it is not only necessary to measure it; a more practical issue is to understand the factors that impede it in different regions so that a pathological diagnosis can be made of WRCC in each respective region (Wang et al. 2019). The obstacle degree model is often used to identify the obstacle factors affecting the development of objects; three measurement factors are involved: (1) factor contribution, (2) index deviation, and (3) obstacle degree. The primary obstacle impacting the improvement of a region’s WRCC can be diagnosed according to the size of the obstacle degree (Zhou 2022). Hence, we introduced an obstacle degree model into WRCC analysis. We conducted an extended study for the entire YRB and its nine provinces along the Yellow River to explore the chief obstacle factors affecting the YRB’s WRCC. The steps for computing the obstacle degree are as follows (Yang et al. 2021):

1. Calculate the factor contribution degree, that is, the contribution degree of a single factor to the overall goal, which is denoted by the weight ω_j of a single factor. The corresponding index weight value ω_j is obtained according to formulas (1)–(5).
2. Calculate the index deviation degree I_{ij} , that is, the gap between the single factor index and the system develop-

Fig. 4 Output graph for the training results of the RBF neural network



ment goal, where the difference is between the standardized value of the single index and 100%. The calculation formula is as follows:

$$I_{ij} = 1 - x_{ij} \quad (9)$$

3. Calculate the obstacle degree O_{ij} , that is, the degree of influence of a single index or criterion-level factor on WRCC. The calculation formula is (Sun et al. 2022c)

$$O_{ij} = I_{ij} \omega_j / \sum_{j=1}^n I_{ij} \omega_j \quad (10)$$

Results

Evaluating the YRB's WRCC

The basin-wide dimension and its upstream, midstream, and downstream dimensions

We input the normalized datasets of the entire YRB and its upstream, midstream, and downstream indicators from 2005 to 2020 into the established RBF neural network model. The outputs of the RBF neural network model are portrayed in Table 3.

From the time dimension, we can see in Table 3 that the WRCC indices of the entire YRB and its upstream and midstream areas show an annual falling trend from 2005 to 2020. The WRCC index fluctuated more downstream of the YRB.

First, the trend of the WRCC index in the entire YRB and its upstream and midstream areas from 2005 to 2020 was the same, indicating a declining trend year by year. The WRCC index, for the entire YRB, dropped from 3.8373 in 2005 to 1.0022 in 2020. The WRCC index in the upstream area declined from 3.9034 in 2005 to 1.0258 in 2020. The WRCC index in the midstream area decreased from 3.5104 in 2005 to 1.6617 in 2020. The WRCC changed from level IV in 2005 to level II in 2020, indicating a weak bearable state. Overall, development is moving in positive direction.

Second, the trend of the WRCC index in the downstream area from 2005 to 2011 was the same as that of the entire YRB and the upstream and midstream areas. The trend also revealed an annual decreasing trend. However, the WRCC index fluctuated more and was significantly larger than that of the entire YRB and the upstream and midstream areas from 2011 to 2020. The WRCC index of the lower YRB fell from 3.7455 in 2005 to 2.3831 in 2011. Accordingly, the WRCC level changed from level IV in 2005 to level III in 2011. However, from 2011 to 2017, the WRCC index exhibited an increasing trend and remained at level III. In 2019, the WRCC index rose significantly to 3.3298. The WRCC reached level IV, which was much lower than that of the entire YRB and its upstream and midstream areas. In 2020, the WRCC level improved significantly to level II.

Table 3 WRCC index in the entire YRB and its upstream, midstream, and downstream indicators (2005–2020)

Year	The entire YRB	Upstream area	Midstream area	Downstream area
2005	3.8373	3.9034	3.5104	3.7455
2006	3.2048	3.4879	3.1698	3.2347
2007	3.0830	3.3990	3.0172	3.0216
2008	2.8323	3.2063	2.7908	2.6673
2009	2.7260	3.1918	2.5758	2.7057
2010	2.5374	2.9701	2.2445	2.4658
2011	2.2776	2.6970	2.0117	2.3831
2012	2.0911	2.6925	1.8175	2.4665
2013	2.0168	2.4267	1.7335	2.7088
2014	1.8907	2.1960	1.7412	2.9295
2015	1.9222	2.2596	1.7696	2.8131
2016	1.7329	2.1220	2.0409	2.5147
2017	1.4320	1.9001	1.8617	2.0652
2018	1.2350	1.6079	1.7755	1.9250
2019	1.1824	1.3564	1.5637	3.2468
2020	1.0022	1.0258	1.6617	1.6565

From the spatial dimension, the WRCC levels of the entire YRB and its upstream, midstream, and downstream regions are weak. The WRCC levels show an increasing trend each year, but none of them reach level I. The spatial variability is not significant.

First, from the perspective of the long-term development of the spatial distribution, in 2005, Fig. 5a indicates that the WRCC levels of the entire YRB and its upstream, midstream, and downstream areas are all at level IV. There is no significant difference in the spatial distribution. In 2010, Fig. 5b demonstrates that the WRCC levels in the upstream, midstream, and downstream areas are at level III, which is consistent with the evaluation level of the WRCC of the entire YRB. Compared with 2005, the overall WRCC level has improved, and there is no significant difference in the spatial distribution. In 2015, Fig. 5c reveals that the WRCC level of the upstream area has increased to level II, which is the same as that of the entire YRB. However, the midstream and downstream areas are in a critical state, and the upstream area is significantly different from the midstream and downstream areas. In 2020, Fig. 5d suggests that the lower YRB's WRCC level has improved and risen to a weakly bearable state. There are no significant spatial differences in the WRCC levels in the YRB.

Second, we examined the indicators and regional development status. Along with the economic growth of each region, each region's level of economic development, GDP per capita, and urbanization rate have improved. With the strengthening of water conservation measures and the advancement of science and technology, the water consumption of 10,000 yuan of GDP and the water consumption of 10,000 yuan of industrial added value are declining,

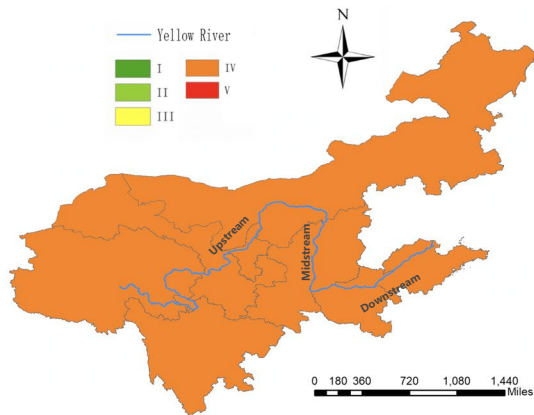
while the urban sewage treatment rate is rising annually. With the management of the YRB and the deepening of water conservation awareness, the ecological water consumption rate has increased each year, implying that the regions are paying more attention to the development of ecological protection. Thus, the WRCC in the entire YRB and the upper, middle, and lower reaches shows a trend of increasing annually. However, as the middle section of the river flows through the Loess Plateau, a large amount of sediment is trapped. This has resulted in the accumulation of sediment in the lower reaches of the Yellow River and the continuous elevation of the riverbed, forcing the area of the YRB to shrink sharply, forming a “hanging river on the ground.” At the same time, the threat of floods, the difficulties of flood control, deterioration of the ecological environment, and a reduction in estuarine biodiversity have restricted the coordinated expansion of the economy, society, and the environment. As such, the WRCC in the lower Yellow River fluctuates greatly, the spatial difference between WRCC in other regions is significant, and the water resources problem has become more serious.

The provincial dimensions

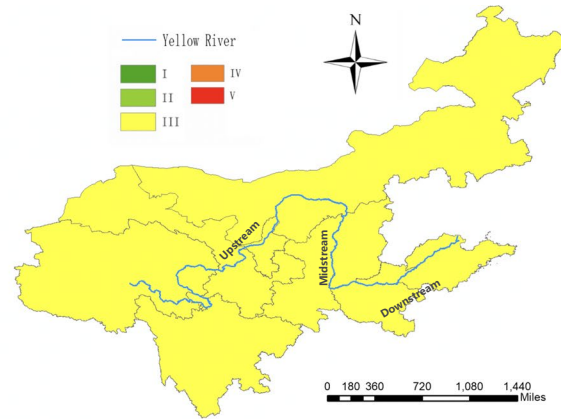
We input the normalized indicator datasets of the YRB's nine provinces, covering 2005 to 2020, into the established RBF neural network model, whose outputs are presented in Table 4.

From the time dimension, we can see in Table 4 that the WRCC indices of six provinces—Qinghai, Sichuan, Gansu, Ningxia, Shaanxi, and Shanxi—exhibit a falling trend from 2005 to 2020. The WRCC indices of Inner Mongolia, Henan, and Shandong provinces reveal the same declining

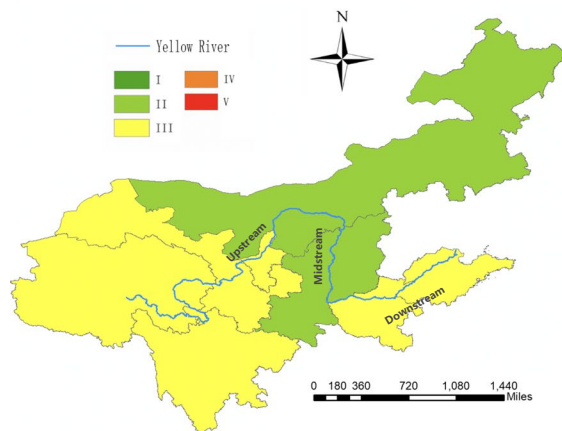
(a) Water resources carrying capacity in the upstream, midstream and downstream of the Yellow River basin in 2005



(b) Water resources carrying capacity in the upstream, midstream and downstream of the Yellow River basin in 2010



(c) Water resources carrying capacity in the upstream, midstream and downstream of the Yellow River basin in 2015



(d) Water resources carrying capacity in the upstream, midstream and downstream of the Yellow River basin in 2020

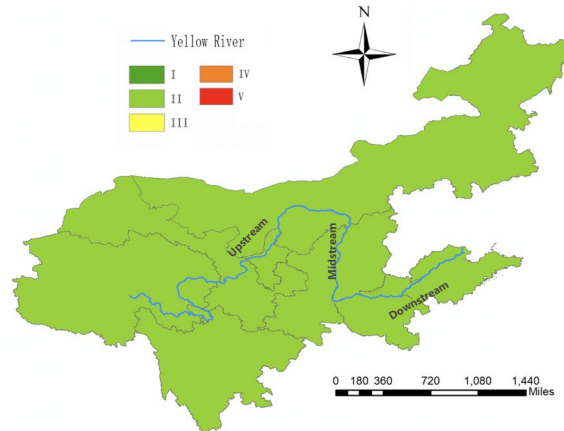


Fig. 5 Spatial distribution of the WRCC evaluation in the YRB's upstream, midstream, and downstream areas

trend as the other six provinces from 2005 to 2012, but they fluctuate more from 2012 to 2020.

First, from 2005 to 2020, Qinghai and Sichuan's WRCC levels change from level V to level II and are in a weakly bearable state. In Gansu, Ningxia, Shaanxi, Shanxi, and Shandong, the WRCC levels change from level IV to level II; they are also in a weak bearable state. However, the WRCC levels of Inner Mongolia and Henan only rise from level IV to level III, which indicates a critical state. The carrying capacity is fairly weak. From 2012 to 2020, the WRCC levels in Inner Mongolia, Henan, and Shandong span three levels with large fluctuations.

Second, from 2005 to 2020, the WRCC indices of the nine provinces fall, and the WRCC levels further improve. In 2005, the proportion of severely overloaded areas is 22.22% and the share of overloaded areas is 77.78%. By 2020, there

are no (severely) overloaded areas; the critical areas account for 22.22%, and weakly bearable areas comprise 77.78%. The overall development trend is positive.

From the spatial dimension, we can see that the overall WRCC of the YRB's nine provinces is somewhat weak. The WRCC of all provinces' has not reached level I. There are apparent spatial differences in the WRCC levels among the provinces.

First, from the perspective of the long-term development of the spatial distribution, in 2005, Fig. 6a shows that the WRCC levels of Qinghai and Sichuan are at level V, and the remaining seven provinces are at level IV. Qinghai and Sichuan's WRCC is relatively weak and demonstrates significant spatial differences compared to other provinces. In 2010, Fig. 6b indicates that the WRCC levels of all eight provinces are at level III, except Sichuan, which is at level IV. Compared with 2005, the WRCC in the

Table 4 WRCC index of the YRB's nine provinces from 2005 to 2020

Year	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi	Henan	Shandong
2005	4.1173	4.0329	3.6506	3.5052	3.3141	3.9972	3.4266	3.9627	3.6628
2006	3.9395	3.5112	3.5593	3.4229	3.2064	3.4525	3.3323	3.3251	3.3020
2007	3.7123	3.5304	3.3152	3.1311	3.2963	3.3546	3.3736	3.1844	3.0868
2008	3.3663	3.4759	3.1759	2.9152	2.8450	3.1675	2.8544	2.7929	2.7150
2009	2.9721	3.3294	3.1170	3.0344	2.8339	3.0090	2.5560	2.8458	2.6754
2010	2.7426	3.2068	2.9368	2.4676	2.7804	2.9068	2.0803	2.8365	2.4692
2011	2.3407	2.8999	2.7117	2.3747	2.7889	2.8558	1.8169	2.5825	2.3232
2012	2.7175	2.8354	2.6286	2.1000	2.4707	2.2337	1.7174	2.6965	2.2487
2013	2.9027	2.5599	2.6226	1.9324	1.8459	2.2621	1.5090	3.0401	2.2276
2014	2.7124	2.2154	2.7973	1.9246	2.5027	2.1937	1.4744	2.6970	3.1903
2015	2.5411	2.4044	2.8267	2.0199	2.4565	2.2120	1.9249	2.5848	3.0232
2016	2.1555	2.3592	2.7448	1.9693	2.9418	2.5220	1.6743	2.3181	2.6466
2017	1.5424	2.1488	2.2501	1.7345	3.1927	1.6372	1.3989	1.8392	2.5075
2018	1.2452	1.7721	1.7819	1.5747	2.6128	2.0491	1.2186	2.2493	1.7270
2019	1.2736	1.4357	1.6924	1.5113	2.8254	1.2672	1.7400	3.4983	2.7520
2020	1.2742	1.0436	1.0734	1.8358	2.7164	1.6932	1.2639	2.0750	1.3813

YRB's nine provinces shows a decreasing trend in terms of spatial differences. In 2015, Fig. 6c reveals that Shanxi's WRCC level is level II. Shandong's WRCC level is level IV, while the remaining seven provinces are at level III. The WRCC levels of the nine provinces span three levels with large spatial variability. In 2020, Fig. 6d portrays that the WRCC levels of Qinghai, Sichuan, Gansu, Ningxia, Shaanxi, Shanxi, and Shandong are at level II, and Inner Mongolia and Henan are at level III. Overall, WRCC indicates a rising trend. However, Inner Mongolia and Henan are still spatially and significantly different from the other provinces, and the differences widen.

Second, from the standpoint of various indicators and regional development status, with the progress of the economy and technology, the economic growth rate and technology level of each region are improving. Water saving measures have become better. People's awareness of water conservation is deepening each year. WRCC in various regions continues to improve. Qinghai and Sichuan have superior water resources and rapid economic and social growth, and the comprehensive usage of water resources in the two provinces has become better. Ningxia suffers from water scarcity and an underdeveloped economy. A large amount of water resources is diverted from the Yellow River, which enhances its WRCC. Henan and Shandong have large populations and small land areas, and the high population density in these regions intensifies the pressure on water resources. Inner Mongolia has a large land area and its water resources are unevenly distributed geographically. Except for some transit water along the Yellow River, water resources are scarce in most places. The rate of improvement of WRCC in this region is slow compared to that of other regions.

Identifying WRCC obstacle factors in the YRB

Identifying obstacle factors on a basin-wide dimension from 2005 to 2020

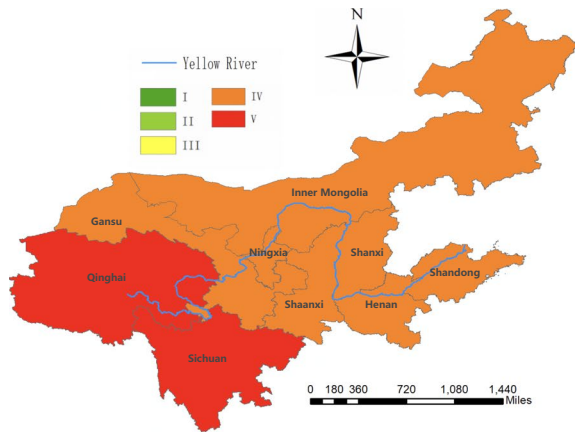
According to formulas (9) and (10), we calculated the obstacle degree of each indicator of the YRB's WRCC from 2005 to 2020. We selected eight indicators with a high obstacle degree as the main obstacles.

As outlined in Fig. 7, the following eight indicators are the main obstacles to the YRB's WRCC from 2005 to 2020: (1) the water resource usage rate, (2) the water production modulus, (3) the surface water resource development and usage rate, (4) per capita water resources, (5) water consumption worth 10,000 yuan of GDP, (6) the industrial water consumption rate, (7) water consumption worth 10,000 yuan of industrial added value, and (8) the ecological water consumption rate. The water resource system has gradually become the most important indicator layer affecting the improvement of the YRB's WRCC.

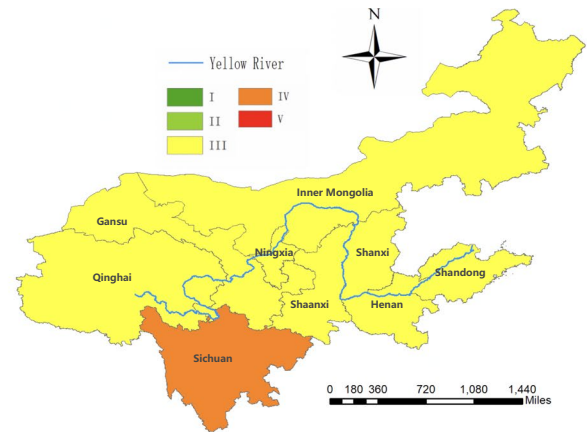
In the water resources system, Fig. 7b demonstrates that the water resource usage rate, the water production modulus, the surface water resource development and usage rate, and the per capita water resource obstacle degree show an increasing trend from 2005 to 2019. By 2020, Fig. 7c indicates that the obstacle degree of the surface water resource development and usage rate is as high as 87.4871%, which is the most crucial obstacle factor. This suggests that the development and effective usage of water resources in the YRB need to be further optimized.

In the socioeconomic system, Fig. 7b illustrates that water consumption worth 10,000 yuan of GDP, the industrial water consumption rate, and water consumption worth

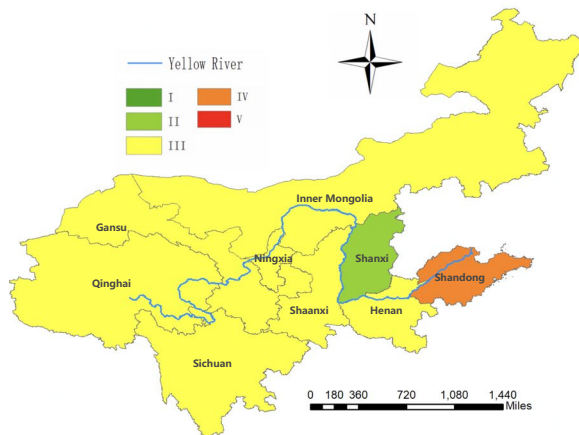
(a) Water resources carrying capacity in nine provinces of the Yellow River basin in 2005



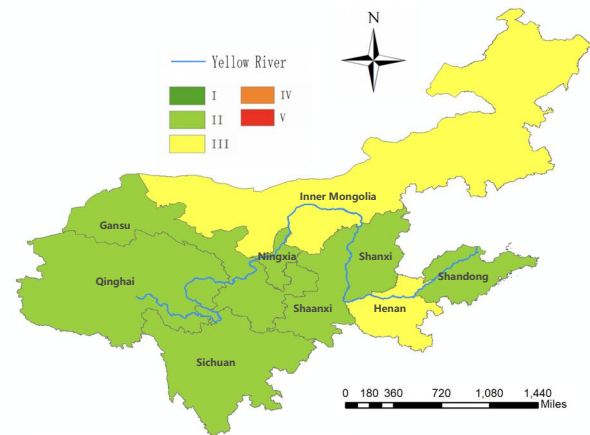
(b) Water resources carrying capacity in nine provinces of the Yellow River basin in 2010



(c) Water resources carrying capacity in nine provinces of the Yellow River basin in 2015



(d) Water resources carrying capacity in nine provinces of the Yellow River basin in 2020

**Fig. 6** Spatial distribution of the WRCC evaluation in the YRB's nine provinces

10,000 yuan of industrial added value show a falling trend from 2005 to 2020. They all decline to 0% by 2020. This suggests that with the ongoing development of the economy and the improvement of the industrial modernization level, water consumption worth 10,000 yuan of GDP, the industrial water consumption rate, and water consumption worth 10,000 yuan of industrial added value are no longer the main obstacles affecting the improvement of the YRB's WRCC.

In the eco-environmental system, Fig. 7c reveals that the obstacle degree of the ecological water usage rate reaches 28.3643% in 2005, which becomes the main obstacle factor. However, with the implementation of ecological protection measures and the deepening of people's awareness of ecological protection, the obstacle degree is declining, and the obstacle degree value is 0% by 2020. This implies that ecological protection has become effective in recent years.

Identifying obstacle factors based on provincial dimensions in 2020

According to formulas (9) and (10), we calculated the obstacle degree of each indicator of WRCC in the YRB's nine provinces in 2020. We selected eight indicators with higher obstacle degrees as the main obstacle factors.

As seen in Fig. 8, the main obstacle indicator layer of Qinghai and Gansu is the socioeconomic system, especially the irrigated area rate, which is the most important obstacle factor. The primary obstacle indicator layer of the remaining provinces is the water resource system, and the chief obstacle factor is the surface water resource development and usage rate. Figure 8b shows that the obstacle degree reaches more than 35%.

In the water resource system, Fig. 8a demonstrates that Sichuan, Ningxia, Henan, Shaanxi, Shanxi, Inner

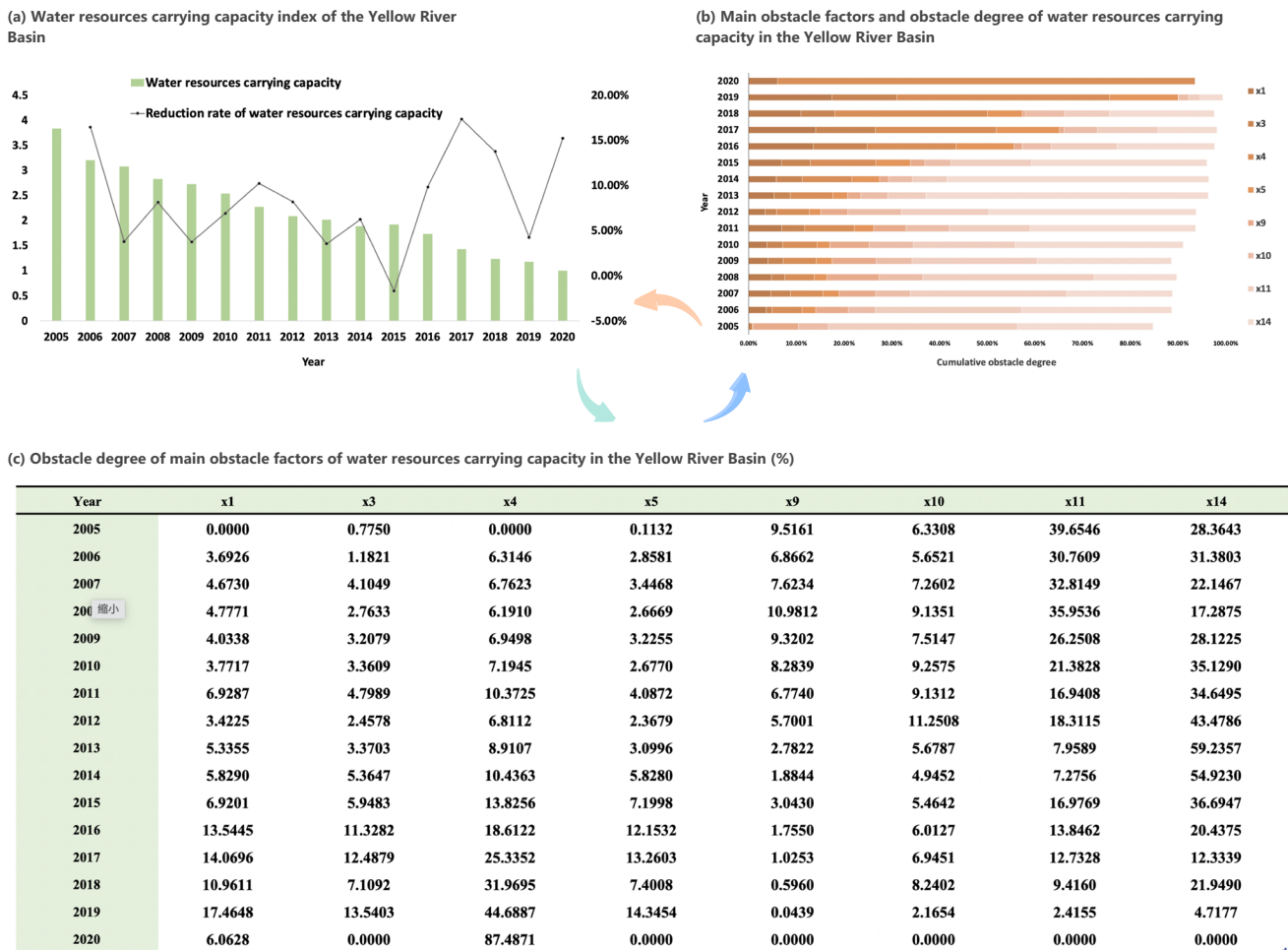
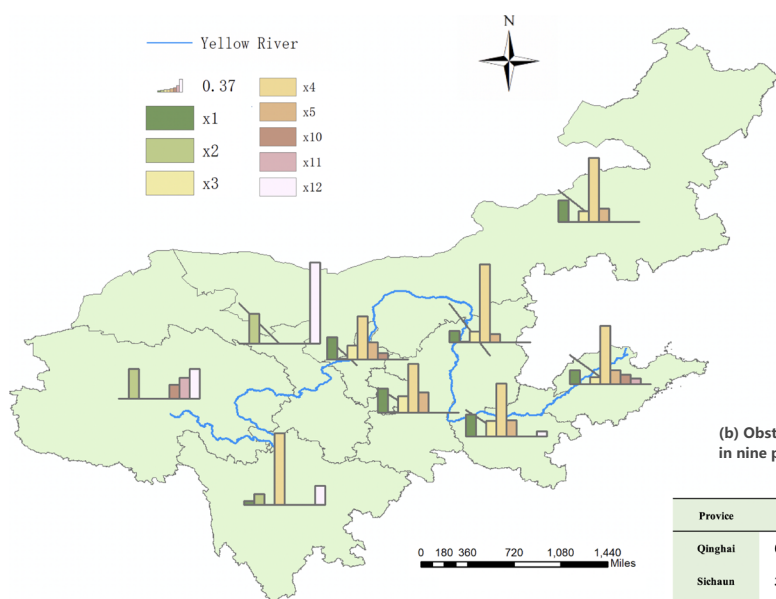


Fig. 7 Obstacle degree of the main obstacle factors of the YRB’s WRCC (2005–2020)

Mongolia, and Shandong all have a cumulative obstacle degree of more than 75%, which is the central obstacle indicator layer. The obstacle degree of the surface water resource development and usage rate comprises more than one third, which is the main obstacle factor. This means that these seven provinces have deficiencies in water resource development and usage, and regional water resources must be further optimized for development and usage. In Sichuan and Shanxi especially, Fig. 8b indicates that the obstacle degrees reach 64.6433% and 70.0601%, respectively. Although Sichuan’s total water resources are among the highest in China, its water resources are unevenly distributed, and the usage rate is low. In 2020, Sichuan’s surface water resources amount to 323.62 billion m³, but its surface water supply is only 22.78 billion m³, and the usage rate of surface water resources development is only 7.04%. Ningxia, Inner Mongolia, Shaanxi, and Shanxi lack water resources. Henan and Shandong are large-population provinces, and population pressure has increased pressure on WRCC.

In the socioeconomic system, Fig. 8a reveals that regions with higher obstacles to the industrial water consumption rate and water consumption worth 10,000 yuan of industrial added value are both in Qinghai, with obstacle degrees of 12.4343% and 18.9259%, respectively. This suggests that Qinghai’s industrial structure is underdeveloped, the level of industrial modernization is low, and the industrial structure and level need to be adjusted. The irrigated area rate is 0% in Ningxia, Shaanxi, Henan, and Shandong. This means that these provinces have developed agriculture and high levels of irrigated arable land. In Henan and Shandong in particular, Fig. 8b reveals that the irrigated area rate is more than 50%, and Shandong reaches 81.92% of the irrigated area rate in 2020. However, this indicator reaches 73.0238% for Gansu’s obstacle degree. This implies that Gansu’s agriculture is underdeveloped, that the level of irrigated arable land is somewhat low, and the level of agricultural modernization is insufficient. Gansu is located at the intersection of three major plateaus—the Loess Plateau, the Qinghai-Tibet

(a) Major obstacle factors and obstacle degrees of water resources carrying capacity in nine provinces of the Yellow River Basin in 2020



(b) Obstacle degree of main obstacle factors of water resources carrying capacity in nine provinces of the Yellow River Basin in 2020 (%)

Province	x1	x2	x3	x4	x5	x10	x11	x12
Qinghai	0.0000	26.7633	0.0000	0.0000	0.0000	12.4343	18.9259	27.0714
Sichuan	3.4546	10.0307	0.0000	64.6433	0.0000	0.0000	0.0000	16.9800
Gansu	0.0000	26.9762	0.0000	0.0000	0.0000	0.0000	0.0000	73.0238
Ningxia	20.0247	0.5724	12.5951	39.0483	15.6794	5.7824	0.0000	0.0000
Henan	19.7982	0.0000	13.6942	47.5703	14.2211	0.0000	0.0341	4.5901
Shaanxi	21.5527	0.3954	14.8056	44.1647	18.0488	0.0000	0.0000	0.0000
Shanxi	10.5921	0.7440	10.0929	70.0601	7.4450	0.0000	0.0000	0.0417
Inner Mongolia	19.3549	0.1303	9.8146	57.5932	12.3441	0.0000	0.0000	0.0000
Shandong	12.5397	0.2265	6.2228	52.4545	12.5918	8.5920	5.0683	0.0000

Fig. 8 Obstacle degree of the main obstacle factors of WRCC in the YRB’s nine provinces in 2020

Plateau, and the Inner Mongolia Plateau—with complex and diverse landscapes that are not beneficial for the expansion of agriculture. In 2020, Gansu’s irrigated area rate is only 25.7%; the surface of Gansu’s agricultural development is seriously inadequate.

In the eco-environmental system, Fig. 8b demonstrates that for the obstacle factors of the ecological water usage rate, the forest coverage rate, and the urban wastewater treatment rate, the cumulative obstacle degree in all nine provinces is less than 5%. This suggests that the eco-environmental system is not the main system layer hindering the improvement of WRCC in the YRB. This means that the ecological environment in the YRB’s nine provinces is well-developed.

Discussion

Compared to previous studies, we explored WRCC in the YRB from different dimensions. The results indicate that the WRCC in the entire YRB and the upper and middle reaches

experienced gradual improvement from 2005 to 2020, while the WRCC in the lower reaches of the Yellow River fluctuated more, all rising to level II in 2020. The WRCC of the YRB’s nine provinces improved overall but with significant regional differences. This is consistent with the findings of prior studies (Wang et al. 2021b).

Unlike past research, from an analytical perspective, we explored regional variability among the three spatial dimensions of WRCC in the YRB from different spatial dimensions. In terms of time selection, we analyzed the long-term trends of WRCC in the YRB from 2005 to 2020. In addition, we chose to build an RBF neural network model for the analysis to avoid the disadvantage of artificially determined weights of indicators to obtain more scientific outcomes. Table 5 presents the similarities and differences between our study and past literature.

Our findings indicate that the sediment accumulation and soil erosion of the lower Yellow River make the improvement of WRCC in this region slow, causing it to fluctuate greatly. This has implications for the country’s 14th Five-Year Plan regarding the construction of silt dams and the comprehensive

management of soil erosion on sloping land in the YRB. The conclusion that the overall improvement of WRCC in the YRB's nine provinces has significant regional differences provides some insight into China's Action Plan of the Yellow River Ecological Protection and Management Campaign.

This study has some limitations, however. The period chosen for this study is 2005–2020. The COVID-19 outbreak began at the end of 2019. Epidemic prevention and control had different degrees of impact on agricultural development, industrial production, water resource development, and ecological construction. However, we did not include the impact of the COVID-19 pandemic on WRCC. We hope that the impact of the COVID-19 epidemic on WRCC in the YRB can be studied in the future to obtain richer conclusions.

Conclusions

We analyzed WRCC in three spatial dimensions: (1) the YRB as a whole; (2) the upper, middle, and lower reaches; and (3) provincial areas. For a long time, regional WRCC has received considerable attention, but few studies have examined regional differences between WRCC from

different spatial dimensions. Our study fills this gap in the literature. In contrast to other studies, we chose 2005–2020 as the research period to determine the long-term development trends of WRCC in the YRB. In addition, to avoid artificially determining the weights of the indicators and obtaining more accurate outcomes, we established an RBF neural network model to study WRCC in the YRB.

We found that from 2005 to 2020, the WRCC in the entire YRB and the upper and middle reaches of the Yellow River gradually improved from level IV to level II. WRCC in the downstream region was poor, showing spatial differences. The WRCC index dropped below 2 in 2018 and 2020, reaching level II, and the sediment problem was serious. Overall improvement of the WRCC in the YRB's nine provinces was good, but the WRCC in Inner Mongolia and Henan was poor. In 2020, the WRCC index remained above 2, and the spatial difference was large. From the perspective of obstacle factors, the development and usage rate of surface water resources are the main obstacles. In 2020, the obstacle degree of the YRB reached 87.4871%, indicating that water resource development and usage need to be optimized. The irrigated area rate in Gansu was the primary obstacle factor, with an obstacle degree of 73.0238%, indicating that the

Table 5 Comparison of this study with previous research

Study	Area	Time	Method	Results and findings
Cui et al. (2022)	Yellow River irrigation area	2010–2017	Dynamic differential degree coefficient	Overall WRCC improved in five counties in the Yellow River irrigation area
Wang et al. (2021b)	The YRB's nine provinces	2008–2017	Fuzzy set pair analysis	The overall improvement trend of WRCC is obvious over the past 10 years, but there are regional differences
Hu et al. (2022)	Inner Mongolia, China	2000–2019	Supply and demand analysis and S-curve threshold analysis	The provincial WRCC is 0.25 (out of 1.00)
Zhang et al. (2019)	YRB	2015	Normal cloud model	The characteristic value of the WRCC index is 2.70, which is in the critical state of level III
Qiao et al. (2021)	The YRB's nine provinces	2008–2017	Population-economic-society-spatial (PESS) framework and pressure-state-response (PSR) model	There is an imbalance between WRCC and urbanization
Xu et al. (2022)	Zhuanglang River basin	2016	Fuzzy comprehensive evaluation model	WRCC in the Zhuanglang Basin can basically meet the needs of towns
This study	The entire YRB, its upper, middle, and lower reaches, and its nine provinces	2005–2020	RBF neural network model	The WRCC of the entire YRB and the upper and middle reaches of the Yellow River show gradual improvement. The WRCC in the lower reaches of the Yellow River fluctuates greatly. Overall, WRCC improves in the YRB's nine provinces, but with significant regional differences

agricultural level is underdeveloped. Qinghai's industrial factors mostly hindered the improvement of its WRCC, with an obstacle degree of 31.36%, suggesting a low level of industrialization.

Given the above, we have specific practical suggestions: Water resource conservation and intensive use should be promoted. Water resources in the YRB are limited; as such, water should be allocated for the city, the land, the people, and production. Water resources should be viewed as the biggest rigid constraint for reasonable planning of water demands. Water and sand control should be strengthened. The YRB has been highlighted by the problem of less water and more sand and the uncoordinated relationship between water and sand. We should reinforce the comprehensive management of soil erosion, make full use of the YRB step reservoir, and carry out scientific management and joint regulation of water and sand. In addition, the pace of industrial modernization needs to be accelerated. The YRB should maintain the basic stability of the industry, especially the proportion of manufacturing. We should also adhere to the main position of the national manufacturing economy. Furthermore, attention should be paid to the development of industrial modernization technology. This will improve the level of industrial modernization.

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Author contribution Xinrui Sun: conceptualization, writing — original draft, writing — review and editing. Zixuan Zhou: methodology, software, data curation. Yong Wang: writing — original draft, writing — review and editing, visualization, funding acquisition.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate The manuscript was reviewed and ethical approved for publication by all authors.

Consent for publication The manuscript was reviewed and consents to publish by all authors.

Competing interests The authors declare no competing interests.

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