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Construction of evaluation index system of water resources carrying capacity based on ecological civilization

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Ecological civilization construction is an important way to achieve sustainable development in China. To reconcile the contradictions between water resources and rapid economic growth in China, it is essential to establish a scientific and rational evaluation index system for water resources carrying capacity (WRCC) based on the concept of ecological civilization. This study first delves into the connotation of WRCC and constructs a theoretical framework for the WRCC evaluation index system under the guidance of ecological civilization. Then, correlation analysis and information contribution rate analysis are employed to optimize the index system. Finally, a comprehensive and representative evaluation index system for WRCC is formed. Taking the Henan section of the Yellow River Basin as an example, the results are as follows: (1) A WRCC evaluation index system with 4 target layers, 10 criterion layers, and 43 indicator layers is established; (2) The WRCC in the study area exhibits a general upward trend; (3) Key obstacles to WRCC development include water resources *per capita* (X_2), precipitation (X_1), groundwater resources per unit area (X_3), ecological water use rate (X_{19}) and forest coverage rate (X_{20}). Future efforts should prioritize mitigating water resource pressure and enhancing ecological environment protection. This study provides a reference for establishing an effective WRCC evaluation index system and holds significant practical implications for guiding the sustainable development of regional water resources.

KEYWORDS

water resources carrying capacity (WRCC), ecological civilization, evaluation index system, index screening, sustainable development

1 Introduction

With the rapid economic growth and urbanization in China, human exploitation of natural resources has reached an unprecedented level, leading to socio-environmental problems such as resource scarcity and environmental pollution (Dong et al., 2014; Li et al., 2017). These issues pose a serious threat to public health and sustainable societal development (Salehi, 2022). To achieve the sustainable development goals and to reconcile the contradictions among resource utilization, environmental protection and socioeconomic development, China has introduced the concept of ecological civilization within the framework of sustainable development. Subsequently, during the 18th National Congress of the Communist Party of China (CPC), considerable emphasis was placed on advancing ecological civilization construction, fully highlighting its importance, necessity and urgency. The report of the 18th National Congress also outlined the overall

requirements for vigorously promoting ecological civilization initiatives by integrating them into all aspects and the whole processes of economic, political, cultural and social development.

As the principles of environmental protection and sustainable development have become firmly established in public consciousness, the construction of ecological civilization has emerged as a shared mission and objective for all nations. Currently, examples of ecological civilization construction can be observed both domestically and internationally. For example, the city of Erfurt in Germany serves as a prime example of a circular economy industrial park in Europe. Adhering to the principles of resource recycling and environmental sustainability, the city has established multiple circular economy industrial parks. Within these parks, through the establishment of industrial chains and resource-sharing mechanisms, waste reduction, resource utilization, and harmless treatment have been successfully realized. Beijing, the capital of China, has achieved significant success in ecological city planning by enforcing stringent environmental protection regulations and implementing green development strategies, effectively integrating environmental governance with urban development. Therefore, the concept of ecological civilization, which is capable of addressing the complex challenges in China's development process, can be a viable pathway to achieve sustainable development (Gu et al., 2013; Xue et al., 2023).

To achieve efficient and sustainable economic growth, China's ecological civilization construction should strictly adhere to the top line of resource utilization, the bottom line of environmental quality and the red line of ecological protection. Therefore, it is imperative to restrict various development activities within the carrying capacity of resources and the environment (CPC Central Committee and State Council, 2015). The core of ecological civilization construction is to build a resource-saving and environment-friendly society based on the carrying capacity of resources and the environment, with the goals of realizing sustainable development governed by the objective laws of nature. Water resources carrying capacity (WRCC), as a specific area within resource and environment carrying capacity research, plays an essential role in advancing ecological civilization initiatives (Wang and Hu, 2018). In 2013, the Ministry of Water Resources emphasized that developing water ecological civilization is not only a crucial component but also a fundamental guarantee of ecological civilization. Furthermore, it serves as a significant initiative aimed at fostering human-water harmony and promoting the construction of ecological civilization (Ministry of Water Resources, 2013). At the same time, the Ministry of Water Resources clarified the core position of water ecological civilization construction and proposed to integrate the concept of ecological civilization into all aspects of the development, utilization, allocation and protection of water resources.

WRCC is a crucial metric for assessing the coordinated development of society, economy and ecology as supported by regional water resources (Chen et al., 2023; Chen et al., 2022). The concept of WRCC was first introduced by the Xinjiang Water Resources Soft Science Research Group in 1989 and has attracted significant attention and discussion among scholars. Due to the different understandings of scholars, a unified concept of WRCC

has not yet been formed. Currently, three predominant interpretations are widely used based on the connotations of the WRCC, namely, the maximum capacity of water resources for development, the maximum number of people it can support and the maximum scale or capacity for supporting economic and social development (Magri and Berezowska-Azzag, 2019; Naimi Ait-Aoudia and Berezowska-Azzag, 2016; Wang Y. F. et al., 2022). Despite these differing interpretations, it is important to note that WRCC represents a complex integrated system encompassing both natural and social dimensions. This complexity allows it to reflect the relationship between water resources and environmental conditions pertinent to human activities.

A scientific and reasonable evaluation index system is essential for accurately assessing the WRCC (Wang et al., 2019; Zuo et al., 2021). The constructed WRCC evaluation index system should not only reflect the current situation of regional water resources and ecological environment, but also determine whether human social and economic activities are within the carrying capacity of regional resources and environment. Currently, the construction of the WRCC evaluation index system primarily relies on a certain theoretical framework, followed by the selection of representative indicators. For example, Liao et al. (2020) developed a WRCC evaluation index system based on the carrier and load theory by selecting 33 indexes to assess the WRCC of 31 provinces in China. Fu et al. (2020) established an evaluation index system of resources and environmental carrying capacity comprising 26 indicators by using the pressure-state-response (PSR) model to conduct a comprehensive analysis of the Haihe River Basin. Bai et al. (2022) selected 15 evaluation indexes based on the support and pressure subsystems to evaluate the WRCC in Anhui province using both the cloud model and the coupling coordination degree model. Zhang et al. (2019) constructed an index system containing three subsystems of water resources, social economy and ecological environment with a total of 16 indicators and analyzed the changing trend of WRCC in Yuetang District.

Currently, there is a great number of research focused on the connotation interpretations and index system establishment of WRCC, which has significantly contributed to its development. However, further research is still needed considering that (1) during the new development period, WRCC has acquired richer connotations and new requirements due to its dynamic nature and timeliness; therefore, the establishment of the WRCC index system should incorporate the latest development concepts and requirements; (2) previous studies have seldom addressed the potential strong correlation between evaluation indicators and the relative importance of information contained within those indicators, which may reduce the accuracy of the evaluation results. Therefore, the primary objectives and contributions of this study are as follows: (1) to integrate the concept of ecological civilization throughout the construction of the WRCC evaluation index system, ensuring its dynamism and timeliness; (2) to optimize the evaluation index system by conducting correlation analysis and information contribution rate analysis, thereby eliminating redundant indicators and improving the system's efficiency. This study offers theoretical guidance for developing a carrying capacity index system and

FIGURE 1
Construction steps of the WRCC evaluation index system.
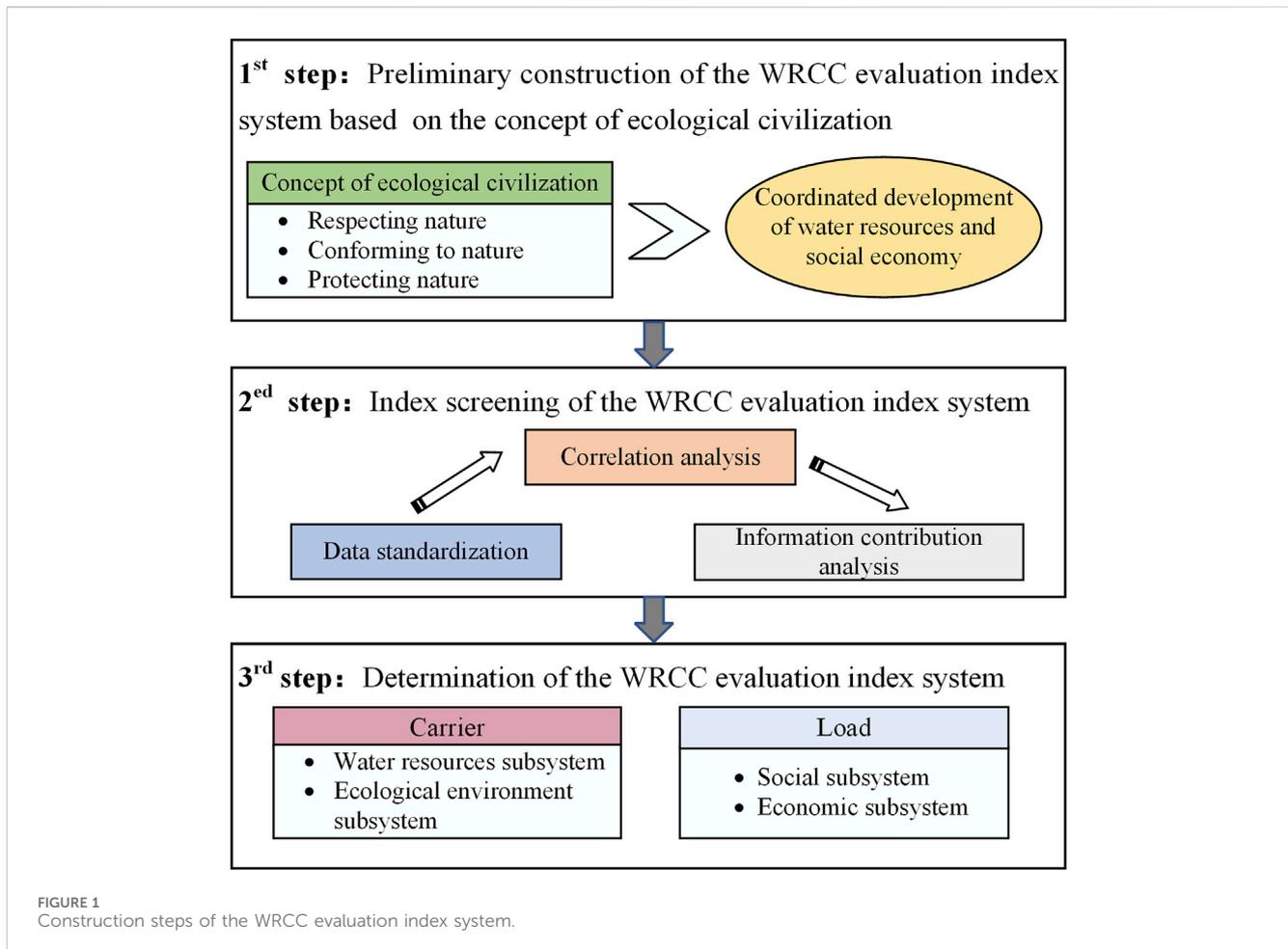
holds significant practical implications for promoting regional sustainable development.

2 Methodology

2.1 General idea for the construction of the WRCC index system

Based on the existing WRCC research theory, this study establishes a comprehensive evaluation index system stemming from the concept of ecological civilization and closely combining with the specific application of system theory within the domain of water resources. This system has great theoretical significance and effectively reflects the coordinated development of regional water resources, ecological environment and social economy. It provides both a theoretical framework and practical basis for the scientific planning and management of regional water resources. Specifically, the construction of the WRCC evaluation index system includes three main components: preliminary construction based on the concept of ecological civilization, screening of the evaluation indicators and final determination of the evaluation index system. The specific process is shown in Figure 1 below.

2.2 Screening methods for evaluation indicators

2.2.1 Data standardization

Since the evaluation indicators are featured in different attributes and magnitudes, they are not suitable for direct computational analysis (Gao et al., 2019; Peng and Deng, 2020; Zhang et al., 2014). Therefore, it is necessary to first standardize the original indicator data before conducting the analysis. Generally speaking, a larger original data value that exerts a stronger positive effect is classified as a positive indicator, whereas a smaller original data value with a stronger positive effect is categorized as a negative indicator. The standardization formulas for both the positive and negative indicators are shown in Equations 1, 2, respectively (Wang et al., 2021).

For positive indicator:

$$y_{ij} = \frac{x_{ij} - \min_j(x_{ij})}{\max_j(x_{ij}) - \min_j(x_{ij})} \tag{1}$$

for negative indicator:

$$y_{ij} = \frac{\max_j(x_{ij}) - x_{ij}}{\max_j(x_{ij}) - \min_j(x_{ij})} \tag{2}$$

where y_{ij} denotes the standardized value of x_{ij}; x_{ij} denotes the jth indicator of the ith evaluation object; and $\max_j(x_{ij})$ and $\min_j(x_{ij})$ denotes the maximum and minimum values of x_{ij}, respectively.

2.2.2 Correlation analysis

Correlation analysis involves the examination of two or more variables that exhibit correlation, primarily aimed at assessing the degree of correlation between these variables (Zhou et al., 2015). When constructing an evaluation index system, consideration should be given to the potential strong correlations among the selected evaluation indicators, which may lead to the duplication of indicator information and increase the complexity of the evaluation process. Therefore, it is necessary to conduct a correlation analysis in constructing an evaluation index system to identify and eliminate indicators that demonstrate multicollinearity and redundancy. In this study, correlation analysis is conducted by calculating the Pearson correlation coefficient using Equation 3 (Bermudez-Edo et al., 2018).

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \bullet \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (3)$$

where r is the correlation coefficient between index x and index y; n is the total number of indicator samples; $\bar{x}$ and $\bar{y}$ are the mean values of index x and index y, respectively.

2.2.3 Information contribution rate analysis

To construct a scientific and representative WRCC evaluation index system, the information contribution rate method is employed to further optimize the evaluation index system. This approach quantifies the proportion of information that each key factor contributes relative to the total information in the original indicator set. Specifically, it assesses how much of the original indicator set's information can be explained by each individual indicator. A higher information contribution rate indicates a greater explanatory power regarding the original indicator set. Therefore, indicators with a high information contribution rate should be retained in the screening process. The index screening method based on the information contribution rate can overcome the limitations of the factor analysis method by providing a comprehensive reflection of the information level of the evaluation indicators, rather than solely relying on a factor load of the index to explain the original index set. The specific calculation steps of this method are as follows (Chen H. H. et al., 2020).

2.2.3.1 Validity test of indicator data

The information contribution rate analysis method is derived from factor analysis. Therefore, it is essential to conduct the Kaiser-Meyer-Olkin (KMO) test and Bartlett sphericity test on the indicator data to ensure the structural validity of the indicator system. It is generally accepted that the applicability test is passed when the KMO statistic exceeds 0.5 and the significance probability of the Bartlett's sphericity test statistic is less than 0.05.

2.2.3.2 Determination of key factors

Principal component analysis is utilized to extract key factors that can effectively capture all the information contained in the original indicator set. In this study, key factors with eigenvalues exceeding 1 are extracted, and those with a cumulative variance contribution rate surpassing 70% are employed to represent all the information contained within the original indicator set. The mathematical computations for determining the eigenvalues of the indicator correlation matrix and calculating the cumulative variance contribution rate are detailed in Equations 4, 5, respectively.

$$\left|X^T X - \lambda_j E_n\right| = 0 \quad (4)$$

where X is the normalized index matrix; X^T is the transpose of the matrix X; λ_j is the eigenvalue; j is the number of factors; and E_n is the nth order unit matrix.

$$V_p = \sum_{j=1}^{p}\omega_j = \sum_{j=1}^{p}\left(\lambda_j/n\right) \quad (5)$$

where V_p is the cumulative variance contribution rate of the p factors; ω_j is the variance contribution of the jth factor.

2.2.3.3 Calculation of factor load matrix

The factor load matrix is formulated using the extracted key factors, and its calculation method is outlined in Equation 6.

$$A = \left(a_{ij}\right)_{n\times p} = \left[\lambda_1^{\frac{1}{2}}\xi_1, \lambda_2^{\frac{1}{2}}\xi_1, \ldots, \lambda_p^{\frac{1}{2}}\xi_p\right] \quad (6)$$

where A is the factor load matrix; a_{ij} is the jth factor load of the ith index; ξ_p is the standard orthogonalized eigenvector corresponding to the pth eigenvalue.

2.2.3.4 Calculation of information contribution rate

The indicator information contribution rate, which represents the interpretation proportion of the indicator to the original indicator set information, is calculated by Equation 7.

$$C_i = \sum_{j=1}^{p}\omega_j\left(a_{ij}^{2}\Big/\sum_{i=1}^{n}a_{ij}^{2}\right) \quad (7)$$

where C_i is the contribution rate of the ith index; a_{ij}^{2} is the magnitude of the information embedded in the jth factor by the ith indicator.

2.2.3.5 Screening of evaluation indicators

The relative importance ranking of each indicator can be determined by the magnitude of its information contribution rate. To ensure that the selected indicators adequately represent all the information contained within the original indicator set, the cumulative information contribution rate is introduced to further elucidate the proportion of information contributed by these indicators. The calculation method for determining the cumulative information contribution rate is presented in Equation 8.

$$R_s = \sum_{i=1}^{s}C_{ni}\Big/\sum_{i=1}^{n}C_i \quad (8)$$

where R_s is the cumulative information contribution of the s indicators; C_{ni} is the information contribution rate of the ith indicator among n indicators.

If the cumulative information contribution rate R_s of the indicators satisfies $R_{s-1} < R_0 \leq R_s$, then s indicators will be retained. R_0 is the threshold of cumulative information contribution rate, the larger its value, the more information is reflected in the original indicator set. In this study, a threshold of 0.7 is set for the cumulative information contribution rate.

2.2.3.6 Determination of evaluation index weight

The retained indicators after screening are $X_1, X_2, X_3, \ldots\ldots$, and X_k, with corresponding information contribution rates of $I_1, I_2, I_3, \ldots\ldots$, and I_k. The weights of the indicators X_i $(1 \leq i \leq k)$ are then calculated using Equation 9.

$$w_i = I_i \Big/ \sum_{i=1}^{k} I_i \tag{9}$$

2.3 Comprehensive evaluation method

2.3.1 WRCC evaluation model

This study utilizes an improved technique for order preference by similarity to ideal solution (TOPSIS) and gray correlation analysis model to accurately evaluate the WRCC and subsystem carrying capacity. The proposed model improves the TOPSIS method by assigning weights to the evaluation indicators and measures the dynamic development trend of the evaluation object through coupled gray correlation analysis. For detailed calculations, please refer to our previous research findings (Wang X. Y. et al., 2023). The values of the WRCC and subsystem carrying capacity range from 0 to 1, with a higher value indicating stronger carrying capacity. As WRCC serves as a characterization of relative carrying capacity, it can be used not only for comparing the carrying capacity among different subsystems but also for analyzing temporal trends in carrying capacity over time.

2.3.2 Obstacle degree model

The obstacle degree model is utilized in this study to identify the main obstacle factors hindering the improvement of WRCC. The indicators involved in the obstacle degree model primarily encompass factor contribution degree, indicator deviation degree and obstacle degree (Chen et al., 2021). The factor contribution degree signifies the weight of an individual indicator relative to the total target value; the indicator deviation degree represents the disparity between an individual indicator and the target value; whereas the obstacle degree denotes the impact level of a single indicator on the research object. Typically, the main obstacle factors are determined based on the magnitude of the obstacle degree, as detailed in Equation 10 (Wang X. Y. et al., 2022):

$$P_i = F_i S_i \Big/ \sum_{i=1}^{m} F_i S_i \tag{10}$$

where P_i denotes the index obstacle degree; F_i denotes the factor contribution degree, i.e., the weight of the ith index; S_i denotes the index deviation degree, $S_i = 1 - X_i$; and X_i denotes the standardized index value.

2.4 Study area and data resources

The Henan section of the Yellow River Basin, situated in the mid-lower reaches of the Yellow River Basin, comprises 10 municipal administrative districts within Henan Province, including Sanmenxia, Luoyang, Jiyuan, Jiaozuo, Zhengzhou, Xinxiang, Kaifeng, Hebi, Anyang and Puyang (Figure 2). Relying on the national strategy of the Yellow River and the construction of the Central Plains City Cluster, this area serves as a traditional agricultural region and a key grain production hub in China. The sustainable water resource management has becoming increasingly critical in this area to facilitate high-quality economic and social development while ensuring ecological security and promoting sustainable development (Wang S. S. et al., 2023). Consequently, due to its limited and uneven spatial-temporal distribution of water resources, the Henan section of the Yellow River Basin is selected as the focal point for relevant research studies.

The social, economic, water resources and ecological environmental statistics in the Henan section of the Yellow River Basin from 2010 to 2022 are used for this study. Statistics are primarily sourced from the Henan Statistical Yearbook (2010-2022), Henan Water Resources Bulletin (2010-2022), China Urban Statistical Yearbook (2010-2021), Henan Ecological and Environmental Status Bulletin (2009-2020), National Economic and Social Development Statistical Bulletin, as well as relevant statistics from each city within this region.

3 Results

3.1 Preliminary construction of the evaluation index system

The concept of ecological civilization presents higher demands on the models of economic and social development, aiming to realize the harmonious coexistence between human beings and nature through respecting, adapting to and protecting nature, rather than simply focusing on resource conservation and environmental protection. Therefore, the construction of a WRCC index system based on the concept of ecological civilization seeks to realize the harmonious development of human beings and nature by addressing the inherent contradiction between socioeconomic growth and resource-environmental protection. This means that the constructed WRCC index system not only reflects the regional water resources level and ecological environment condition but also assesses whether human activities remain within the carrying capacity of regional resources and environment. The WRCC represents the water resources conditions and environmental quality level related to human activities; thus, it is imperative to incorporate human activities into discussions regarding carrying capacity. Therefore, the construction of the WRCC index system should focus on four aspects: water resources support capacity, ecological environment level, social and economic development status. In addition, the requirements of the "three red lines" of China's strictest water resource management policies should also be considered when constructing the WRCC index system, with a focus on regional water resources utilization and environmental quality evaluation.

FIGURE 2
Geographical location of the study area.
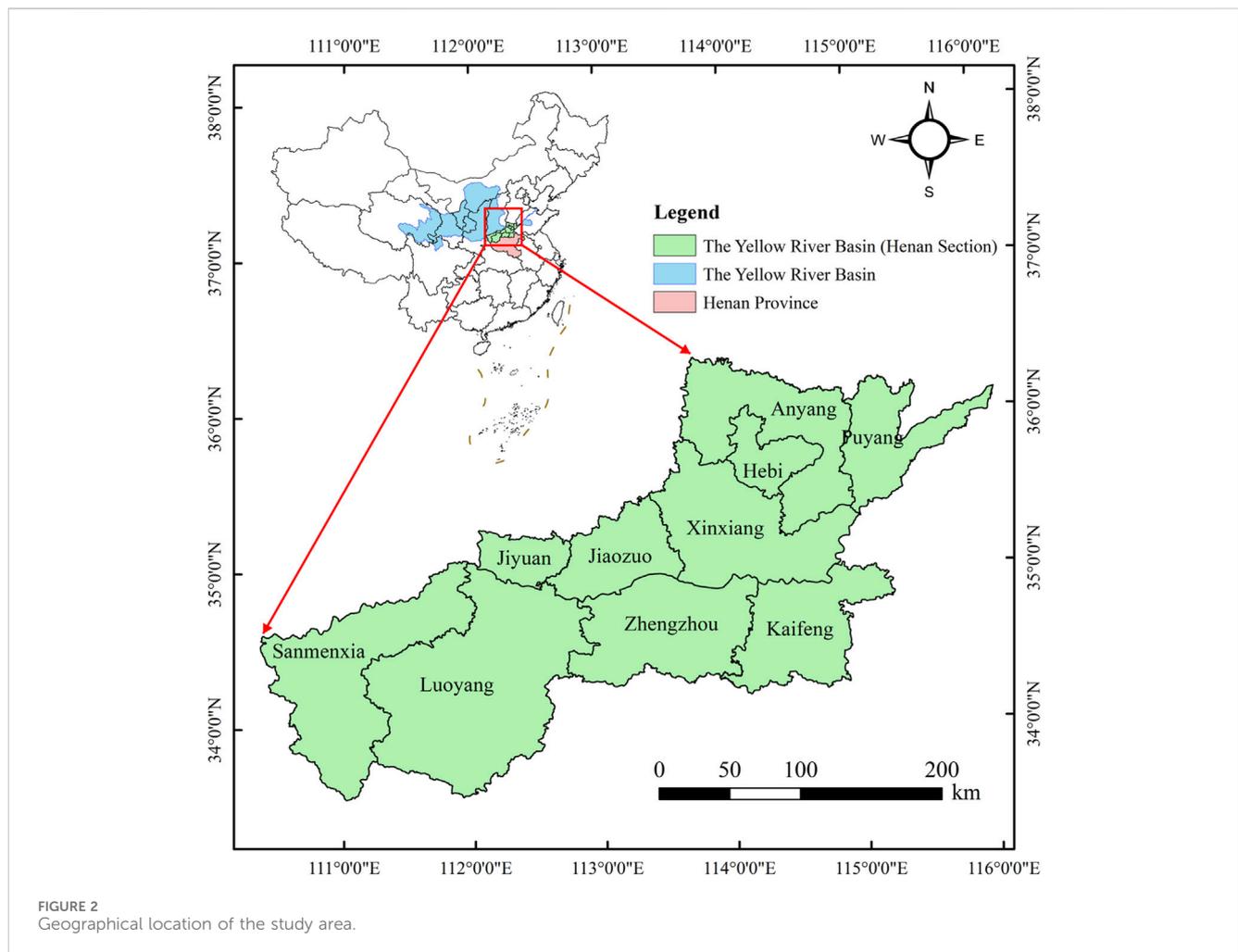
Against the backdrop of the concept of ecological civilization, this study initially identifies the four target layers of the WRCC evaluation index system, including the water resources, social, economic and ecological environment subsystems. Subsequently, through a systematic analysis of each target layer and in conjunction with the relevant contents of the "three red lines" of China's strictest water resource management policies, the criteria layers including water resources endowment, water resources development and utilization efficiency, water use efficiency and ecological and environmental pressure are established. Finally, representative evaluation indicators are selected based on the principles of scientific, systematic, dynamic, feasible and comparable with existing research results at home and abroad. Overall, the WRCC evaluation index system preliminarily constructed in this study consists of 4 target layers, 10 criterion layers and 43 index layers.

3.1.1 Water resources subsystem

The water resources subsystem is the primary focus of the WRCC research. As a fundamental natural resource essential for human survival and social production activities, water resources play a crucial role in supporting regional socioeconomic development and ecological environmental protection (Chen L. et al., 2020; Kummu et al., 2016). The water resources subsystem reflects the ability of regional water resources to support human

activities, that the extent of exploitation and utilization of regional water resources as well as the level of sustainable utilization are greatly determined by the quality and quantity of regional water resources (Yang et al., 2021). Therefore, in this study, water resource endowment, water production and supply capacity and water utilization status are used as criterion layers to measure the carrying capacity of regional water resources. Based on the existing research results, 5 indicators are chosen to represent the regional water resources endowment, namely, precipitation, total water resources, water resources *per capita*, surface water resources per unit area and groundwater resources per unit area. Then, 3 indicators are selected to reflect the water production and supply capacity, namely, water production modulus, water production coefficient and water supply modulus. Furthermore, 3 indicators are identified to depict the water utilization status, namely, utilization rate of water resources, utilization rate of surface water resources and utilization rate of groundwater resources. In brief, the water resources subsystem consists of 3 criterion layers and 11 index layers.

3.1.2 Social subsystem

The social subsystem is the main object of WRCC research, with the development of regional society being intricately linked to the water resources system (Zhang and Dong, 2022). Given that water

resources are indispensable to the daily life of the residents, the impact of the social dimension on the water resources system primarily stems from the population (Yang et al., 2019). Population serves as the core of the social subsystem; both its structure and size, along with residents' lifestyle and living standards, directly affect the sustainable utilization of regional water resources (Sinding, 2009). Therefore, this study utilizes regional population composition and domestic water use level as the criterion layers to assess the pressure exerted by human social activities on the water resources system. Specifically, 5 indicators, including population density, urbanization rate, Permanent population, population growth rate and the number of students enrolled in higher education, are chosen to represent the population composition of the region. Another 5 indicators, including *per capita* domestic water use, *per capita* water use, proportion of domestic water, urban water access rate and the *per capita* retail sales of consumer goods, are selected to reflect the domestic water use capacity of regional residents. In general, the social subsystem is composed of 2 criterion layers and 10 index layers.

3.1.3 Economic subsystem

The economic subsystem is an important link in the WRCC evaluation. Regional economic development is closely tied to water resource support, and both the development scale and industrial structure can directly influence the water resource demand (Zhang et al., 2019). Higher levels of economic development are associated with increased levels of water resources reuse, water resources protection and water pollution treatment. The development of the economic subsystem relies heavily on both the economic development scale and the water use efficiency within economic activities (Zhang et al., 2016). The economic development scale can be assessed by 7 indicators: GDP, proportion of secondary industry, proportion of tertiary industry, GDP *per capita*, *per capita* disposable income of urban residents, industrial water use ratio and R&D expenditure; while the water use efficiency of economic development is evaluated by 5 indicators: farmland irrigation water per mu, water use per 10^4 yuan industrial added value, water use per 10^4 yuan GDP, water consumption rate and irrigation rate of cultivated land. Overall, the economic subsystem is comprised of 2 criterion layers and 12 index layers.

3.1.4 Ecological environment subsystem

The ecological environment subsystem is the basis of human survival and development, closely intertwined with the social and economic progress, as well as the water resources and water environment of a given region (Kilkis, 2016). There is an interdependent relationship and mutual constraints between the regional ecological environment system and the water resources system. On the one hand, the ecological environment system plays a crucial role in water and soil conservation, providing strong support for regional WRCC; on the other hand, the expansion of urbanization, occupation of arable land and discharge of pollutants from agriculture, industry and life due to rapid socioeconomic development have exerted significant pressure on the ecological environment, thereby restricting the development of the WRCC. Therefore, this study selects the ecological environment status, ecological environmental management level and ecological environment pressure as the criterion layer to evaluate the ecological

environment subsystem. To assess the regional ecological environment status, 5 indicators, including ecological water use rate, forest coverage rate, proportion of cultivated land, green coverage rate and *per capita* green park area are selected. Additionally, 2 indicators, namely, sewage treatment rate and harmless treatment rate of household garbage, are chosen to demonstrate the regional ecological environment management level. Furthermore, 3 indicators, including wastewater discharge, sewage discharge per 10^4 yuan GDP and fertilizer application amount are used to reflect the regional ecological environment pressure. Briefly, the ecological environment subsystem comprises a total of 3 criterion layers and 10 indicator layers.

3.2 Screening of evaluation index system

3.2.1 Screening results of correlation analysis

The evaluation index data for the WRCC across 10 cities in the Henan section of the Yellow River Basin are standardized using the data standardization method. Subsequently, Pearson bivariate correlation analysis is conducted for each subsystem of WRCC, eliminating the indexes with multicollinearity within each subsystem based on the standardized index data. The principles for screening the evaluation indicators based on the correlation coefficient are as follows: (1) if the absolute value of the correlation coefficient between an indicator and multiple other indicators exceeds 0.8, those latter indicators are generally removed; (2) if the absolute value of the correlation coefficient between an indicator and other individual indicators does not exceed 0.8 but approaches a certain value, the former is considered for removal; (3) if the absolute value of the correlation coefficient between the two indicators exceeds 0.8, the indicator frequently used in the relevant reference is retained. Following these principles for indicator screening, a total of 9 WRCC indicators are deleted by analyzing their correlations within each WRCC subsystem, as shown in Table 1.

3.2.2 Screening results of information contribution rate analysis

In the analysis of information contribution rate, it is essential to conduct the KMO and Bartlett tests on each indicator data to confirm its validity. The results of the KMO and Bartlett tests for each subsystem indicator, following screening through correlation analysis, are shown in Table 2. It can be observed that the KMO values for all WRCC subsystems exceeds 0.5, while the significance probability of the Bartlett test statistical value is less than 0.05. This indicates that the screened evaluation indicators demonstrate structural validity and are suitable for factor analysis.

The cumulative information contribution rate is determined by calculating the information contribution rate of each indicator and arranging them in descending order. Taking the water resources subsystem as an example, the cumulative information contribution rate for each indicator is shown in Table 3. In accordance with relevant research and considering the specific requirements of this study, a threshold value of 0.7 is set for R_0. As a result, the top 6 indicators with the highest cumulative information contribution rate are retained for analysis within the water resources subsystem, and their weights are calculated using the weight calculation method.

TABLE 1 Indicator screening results based on the correlation coefficient analysis.

Subsystem	Indicator i	Indicator j (delete)	Correlation coefficient
Water resources	Precipitation	Water production modulus	0.9030
		Surface water resources per unit area	0.9090
	Utilization rate of water resources	Utilization rate of surface water resources	0.8790
Social	Permanent population	Number of students enrolled in higher education	−0.8420
	Urbanization rate	Per capita retail sales of consumer goods	0.8670
Economic	Irrigation rate of cultivated land	Industrial water use ratio	0.8010
	Proportion of tertiary industry	Proportion of secondary industry	0.8920
	R&D expenditure	GDP	0.9660
Ecological environment	Forest coverage rate	Proportion of cultivated land	−0.8930

TABLE 2 KMO and Bartlett's Test for WRCC subsystem.

Test type		Water resources	Social	Economic	Ecological environment
KMO measure of sampling adequacy		0.5920	0.5690	0.6570	0.5510
Bartlett's Test of Sphericity	Approx. Chi-Square	906	322	867	503
	df	28	28	36	36
	Sig	0.0000	0.0000	0.0000	0.0000

TABLE 3 Indicator screening and weighting of water resources subsystem.

Indicator	Rotated component matrix			Information contribution rate C_i	Indicators C_i in descending order	Cumulative information contribution rate R_0	Screening results	Weight
	ai_1	ai_2	ai_3					
Precipitation	0.5940	0.6510	0.2750	0.1246	Groundwater resources per unit area	0.1381	Retain	0.1798
Total water resources	0.4300	0.1290	0.7700	0.1162	Water supply modulus	0.2733	Retain	0.1759
Utilization rate of groundwater resources	0.7740	0.2930	0.3240	0.1155	Water resources *per capita*	0.4024	Retain	0.1680
Water production coefficient	−0.1320	0.6730	0.6100	0.1232	Precipitation	0.5270	Retain	0.1623
Groundwater resources per unit area	0.0450	0.9680	0.0720	0.1381	Water production coefficient	0.6503	Retain	0.1604
Water supply modulus	0.8430	−0.4440	0.1270	0.1351	Utilization rate of water resources	0.7683	Retain	0.1537
Utilization rate of water resources	0.8140	0.057	0.3760	0.1180	Total water resources	0.8845	Delete	—
Water resources *per capita*	0.9330	0.1070	−0.0290	0.1291	Utilization rate of groundwater resources	1.0000	Delete	—

Similarly, the indicators that need to be retained or eliminated from the other three subsystems are identified through the aforementioned calculation method. The weights of each retained indicator are also calculated and assigned, as presented in Table 4.

Overall, a total of 10 evaluation indicators are excluded based on the analysis of information contribution rate across the four subsystems, and there are 24 evaluation indicators are selected for further analysis.

TABLE 4 Indicator screening and weighting of social, economic and ecological environment subsystems.

Social subsystem			Economic subsystem			Ecological environment subsystem		
Indicator	Result	Weight	Indicator	Result	Weight	Indicator	Result	Weight
Urbanization rate	Retain	0.1838	Per capita disposable income of urban residents	Retain	0.1822	Fertilizer application amount	Retain	0.1803
Permanent population	Retain	0.1763	Water use per 10^4 yuan industrial added value	Retain	0.1770	Wastewater discharge	Retain	0.1756
Proportion of domestic water	Retain	0.1752	Water use per 10^4 yuan GDP	Retain	0.1746	Forest coverage rate	Retain	0.1742
Population density	Retain	0.1714	GDP *per capita*	Retain	0.1740	Ecological water use rate	Retain	0.1605
Per capita water use	Retain	0.1482	Proportion of tertiary industry	Retain	0.1554	Green coverage rate	Retain	0.1580
Per capita domestic water use	Retain	0.1451	Water consumption rate	Retain	0.1368	Sewage treatment rate	Retain	0.1513
Population growth rate	Delete	—	Irrigation rate of cultivated land	Delete	—	Per capita green park area	Retain	—
Urban water access rate	Delete	—	R&D expenditure	Delete	—	Sewage discharge per 10^4 yuan GDP	Delete	—
			Farmland irrigation water per mu	Delete	—	Harmless treatment rate of household garbage	Delete	—

3.3 Determination of the evaluation index system

After conducting the correlation analysis and information contribution rate analysis on the initially constructed WRCC evaluation index system, a total of 19 evaluation indicators are eliminated. This study ultimately establishes a WRCC evaluation index system consisting of 4 target layers, 10 criterion layers and 24 index layers, as presented in Table 5. The four WRCC subsystems are considered equally important, with their weight values set at 0.25. Consequently, the final weights of the 24 indicators within the entire WRCC system can be determined by multiplying the index weights of each subsystem by 0.25 (Table 5).

3.4 WRCC evolution

3.4.1 Temporal changes in the WRCC and subsystem carrying capacity

The WRCC and subsystem carrying capacity of the Henan section of the Yellow River Basin are assessed using the WRCC evaluation index system and the evaluation model constructed in this study. As illustrated in Figure 3, a notable increase in WRCC is observed in the Henan section of the Yellow River Basin, rising from 0.47 in 2010 to 0.59 in 2022, with a growth rate of 25.53%. The significant improvement in WRCC is closely linked to the effective improvement in both the ecological environment and the high-quality economic development. In 2021, the State Council issued the Outline of the Plan for Ecological Protection and High-Quality Development of the Yellow River Basin, which further promotes the ecological protection and high-quality development of the Yellow River Basin to a new level. This progress indicates that under the concept of ecological protection and high-quality development in the Yellow River Basin, there have been initial achievements in both the protection and rational utilization of water resources.

From the perspective of subsystems, the water resources subsystem carrying capacity fluctuates significantly from 2010 to 2022, ranging between 0.29 and 0.68. This variation demonstrates the substantial impact of natural precipitation on the basin's water resources status. Particularly in 2021, extreme precipitation events in Henan Province led to a notably higher water resources subsystem carrying capacity in this basin than other years. In contrast, the social subsystem carrying capacity exhibits a relatively minor variations, decreasing from 0.65 in 2010 to 0.61 in 2022 at a rate of 7.15%. This decline can primarily be attributed to the population growth and increased water consumption by residents. The economic subsystem carrying capacity and the ecological environment subsystem carrying capacity exhibit relatively consistent development trends, indicating a stable growth in both economy and ecological environment. However, it is worth noting that the economic subsystem carrying capacity experiences a significant increase, rising from 0.29 in 2010 to 0.67 in 2022, with a growth rate of 131.03%. This surge is largely due to the accelerated economic development within the basin over recent years and the continuous improvement of water consumption capacity. During this same period, the ecological environment subsystem carrying capacity grows from 0.49 to 0.69, at a rate of 40.82%, which underscores the ongoing enhancement of infrastructure in the Henan section of the Yellow River Basin and its notable improvement in sewage treatment capacity. Furthermore, with an increasing emphasis on the ecological environmental protection, a significant increasing trend is observed in both the ecological water use rate and the green coverage rate of built-up areas.

3.4.2 Identification of obstacle factors

The obstacle degree model is utilized to identify the main obstacle factors in the WRCC evolution in the Henan section of the Yellow River Basin. Statistical analysis of the top 5 obstacle factors for 10 cities in this region is conducted, and the results are shown in Figure 4. The predominant obstacle factors influencing the WRCC improvement in the Henan section of the Yellow River Basin are water resources *per capita* (X_2), precipitation (X_1), groundwater resources per unit area

TABLE 5 Evaluation index system of WRCC.

Target layer	Criterion layer	Indicator layer	Units	Weight
Water resources subsystem	Water resources endowment	Precipitation (X_1)	mm	0.0406
		Water resources *per capita* (X_2)	m^3/person	0.0420
		Groundwater resources per unit area (X_3)	10^4 m^3/km^2	0.0449
	Water production and supply capacity	Water production coefficient (X_4)	Dmnl	0.0401
		Water supply modulus (X_5)	10^4 m^3/km^2	0.0440
	Water utilization status	Utilization rate of water resources (X_6)	%	0.0384
Social Subsystem	Population composition	Population density (X_7)	person/km^2	0.0429
		Permanent population (X_8)	10^4 person	0.0441
		Urbanization rate (X_9)	%	0.0457
	Domestic water use level	Per capita domestic water use (X_{10})	L	0.0363
		Per capita water use (X_{11})	m^3	0.0372
		Proportion of domestic water (X_{12})	Dmnl	0.0438
Economic subsystem	Economic development scale	Proportion of tertiary industry (X_{13})	%	0.0389
		GDP *per capita* (X_{14})	yuan	0.0435
		Per capita disposable income of urban residents (X_{15})	yuan	0.0454
	Water use efficiency of economic development	Water use per 10^4 yuan industrial added value (X_{16})	m^3	0.0443
		Water use per 10^4 yuan GDP (X_{17})	m^3	0.0437
		Water consumption rate (X_{18})	%	0.0342
Ecological environment subsystem	Ecological environment status	Ecological water use rate (X_{19})	%	0.0401
		Forest coverage rate (X_{20})	%	0.0435
		Green coverage rate (X_{21})	%	0.0395
	Ecological environmental management level	Sewage treatment rate (X_{22})	%	0.0379
	Ecological environment pressure	Wastewater discharge (X_{23})	10^8 t	0.0439
		Fertilizer application amount (X_{24})	t	0.0451
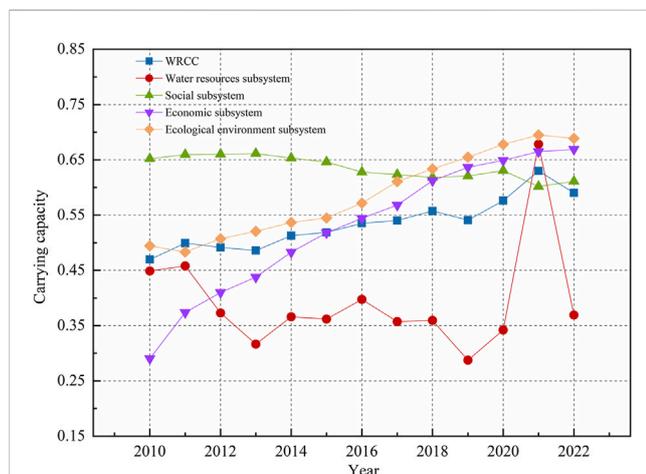
FIGURE 3
Changes of the WRCC and subsystem carrying capacity in the Henan section of the Yellow River Basin from 2010 to 2022.

(X_3), ecological water use rate (X_{19}) and forest coverage rate (X_{20}), with frequencies of 9, 7, 7, 6 and 5, respectively. It is evident that these obstacle factors are predominantly concentrated within the water resources subsystem and ecological environment subsystem. Although there has been a noticeable increasing trend in overall WRCC for the basin in recent years, the development within the Yellow River basin is still facing with resource and environmental pressure such as water resources scarcity and a fragile ecological environment. In future development, it is imperative to prioritize the protection of water resources and the ecological environment.

4 Discussion

This study proposes a method for constructing an evaluation index system of the WRCC based on the concept of ecological civilization. This method fully considers the development concepts and requirements associated with ecological civilization, rendering the index system developed in this study both dynamic and time-

FIGURE 4
Main obstacle factors of WRCC development in the Henan section of the Yellow River Basin.
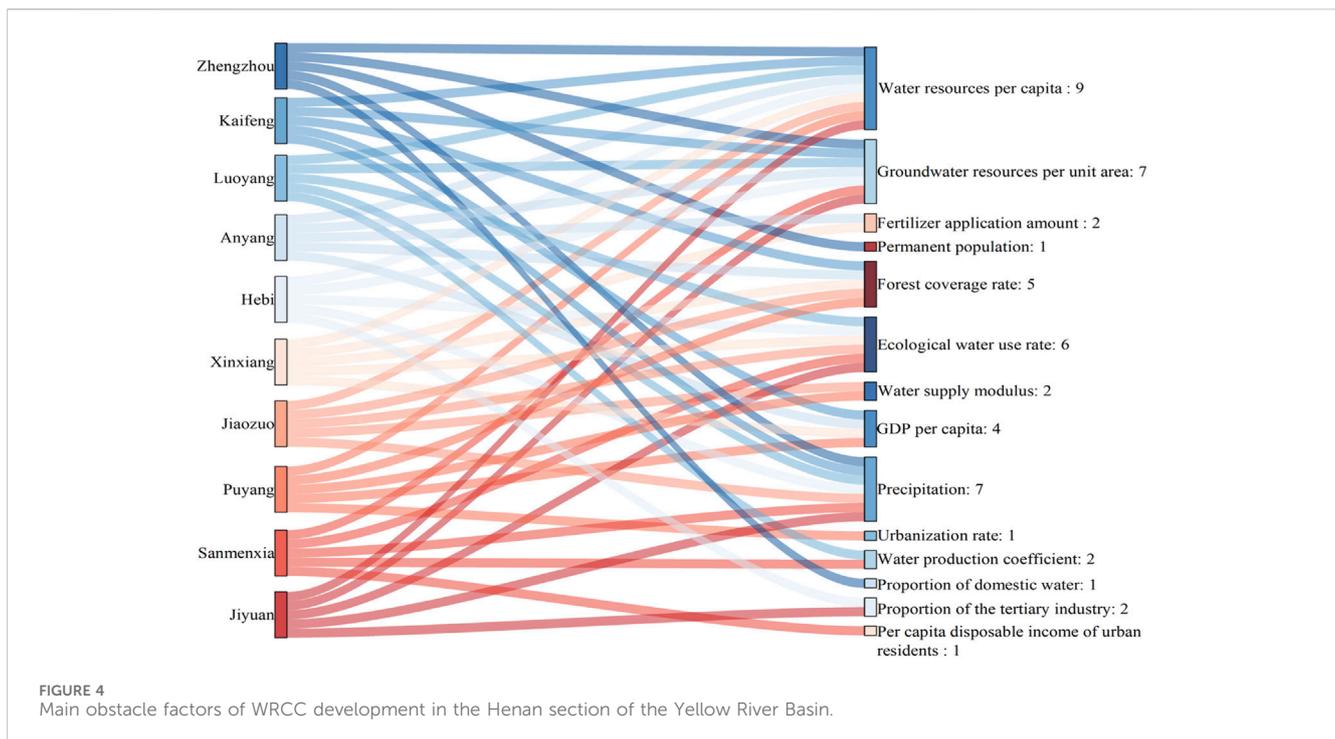
effective. Specifically, during the construction of the index system, this study incorporates the requirements of the "three red lines" of China's strictest water resource management policies. Consequently, indicators such as water resources development and utilization efficiency, socioeconomic water use levels and water pollution discharge are included. Although the study by Yang et al. (2019) considered indicators related to economic water use level and water pollution discharge, it overlooked crucial indicators such as water resource development and utilization efficiency, as well as domestic water use levels. Similarly, Zhang et al. (2019) also failed to incorporate these significant factors in their study. Furthermore, through conducting correlation and information contribution analysis, the construction process of the evaluation index system in this study is rendered more scientific and reasonable, thereby effectively reducing the redundancy of index information. For instance, Song et al. (2024) included both water resources and precipitation in the evaluation system of the water resources subsystem without conducting a rigorous screening and analysis of the indicators. This inclusion led to redundant information and unnecessarily complicated the computational process. The index system construction method employed in this study is both comprehensive and streamlined, effectively balancing the complexity of the WRCC system while ensuring the selection of representative evaluation indicators.

However, due to limitations in data acquisition, the selection of indicators in this study remains imperfect compared with existing relevant research. For instance, Zhang et al. (2018) included indicators such as river proportion worse than Grade V, seawater desalination volume and reclaimed water proportion in the assessment of resource and environmental carrying capacity. Hu et al. (2021) incorporated the guarantee rate of ecological water demand, as well as nitrogen and phosphorus pollutant discharge in the study of water environment carrying capacity. In future research, it is essential to implement appropriate measures to further improve these issues.

5 Conclusion

This study delves deeply into the connotation of WRCC based on the concept of ecological civilization and develops a preliminary WRCC evaluation index system centered around the coupled system of water resources, social, economic and ecological environment. Furthermore, correlation analysis and information contribution rate analysis are employed to screen and optimize the evaluation index system. This approach aims to construct a scientific and reasonable evaluation index system that can comprehensively reflect the current status of regional WRCC. Finally, using the constructed evaluation index system, an appropriate evaluation model is applied to determine the evolution trend of WRCC and identify its developmental weakness. This study plays a crucial role in guiding the sustainable utilization of regional water resources.

Taking the Henan section of the Yellow River Basin as the study area, the main findings are as follows: (1) Through a systematic analysis of the connotation of WRCC, 10 criterion layers and 43 indicator layers corresponding to the 4 target layers of the WRCC evaluation index system are initially determined. (2) By conducting the correlation analysis and information contribution rate analysis, a total of 19 indicators are removed, resulting in a final WRCC evaluation index system consisting of 4 target layers, 10 criterion layers and 24 index layers. (3) Empirical research indicates that the WRCC in the Henan section of the Yellow River Basin generally shows an increasing trend. The primary obstacle factors identified include water resources *per capita* (X_2), precipitation (X_1), groundwater resources per unit area (X_3), ecological water use rate (X_{19}) and forest coverage rate (X_{20}).

Through the analysis and summary of this study, to further promote the WRCC in the Henan section of the Yellow River Basin, it is recommended that relevant government departments prioritize alleviating water resource pressure and enhancing ecological

environment protection. Currently, the shortage of water resources *per capita* is the main obstacle factor restricting the improvement of the WRCC in the study area. To address this challenge, it is imperative to implement scientific and rational water resource management measures. This includes the optimal allocation of water resources, the establishment of water usage plans, and the enforcement of quantitative controls. A comprehensive water resource management system should be developed to ensure the sustainable utilization and protection of water resources. Furthermore, the ecological environment issue remains a significant constraint on the high-quality development of the study area. Future development should prioritize ecology and green growth by intensifying efforts in ecological restoration and protection, steadfastly promoting the development of green industries and circular economy, and fostering the sustainable utilization of ecosystems.

Data availability statement

The datasets presented in this article are not readily available because Data will be available from the corresponding author upon reasonable request. Requests to access the datasets should be directed to SL, lishq@igs-has.cn.

Author contributions

XW: Formal Analysis, Methodology, Writing–original draft. JG: Validation, Writing–review and editing. HJ: Writing–review and editing, Supervision. SL: Writing–review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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References

Bai, X., Jin, J. L., Zhou, R. X., Wu, C., Zhou, Y., Zhang, L., et al. (2022). Coordination evaluation and obstacle factors recognition analysis of water resource spatial equilibrium system. *Environ. Res.* 210, 112913. doi:10.1016/j.envres.2022.112913

Bermudez-Edo, M., Barnaghi, P., and Moessner, K. (2018). Analysing real world data streams with spatio-temporal correlations: entropy vs. Pearson correlation. *Constr.* 88, 87–100. doi:10.1016/j.autcon.2017.12.036

Chen, H. H., Wang, H., and Sui, X. (2020a). Evaluation indicator screening and weighting method based on information contribution ratio. *Sci. Res. Manag.* 41 (8), 240–247. doi:10.19571/j.cnki.1000-2995.2020.08.025

Chen, L., Huang, K. D., Zhou, J. Z., Duan, H. F., Zhang, J., Wang, D., et al. (2020b). Multiple-risk assessment of water supply, hydropower and environment nexus in the water resources system. *J. Clean. Prod.* 268, 122057. doi:10.1016/j.jclepro.2020.122057

Chen, Q. Y., Zhu, M. T., Zhang, C. J., and Zhou, Q. (2023). The driving effect of spatial-temporal difference of water resources carrying capacity in the Yellow River Basin. *J. Clean. Prod.* 388, 135709. doi:10.1016/j.jclepro.2022.135709

Chen, S. Y., He, Y. H., Tan, Q., Hu, K., Zhang, T., and Zhang, S. (2022). Comprehensive assessment of water environmental carrying capacity for sustainable watershed development. *J. Environ. Manag.* 303, 114065. doi:10.1016/j.jenvman.2021.114065

Chen, Y. Z., Lu, H. W., Li, J., Yang, Y., and Xia, J. (2021). Multi-criteria decision making and fairness evaluation of water ecological carrying capacity for inter-regional green development. *Environ. Sci. Pollut. R.* 28 (6), 6470–6490. doi:10.1007/s11356-020-10946-2

CPC Central Committee and State Council (2015). Opinions on accelerating the construction of ecological civilization.

Dong, H. J., Geng, Y., Fujita, T., Fujii, M., Hao, D., and Yu, X. (2014). Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. *Sci. Total Environ.* 500-501, 120–130. doi:10.1016/j.scitotenv.2014.08.094

Fu, J. Y., Zang, C. F., and Zhang, J. M. (2020). Economic and resource and environmental carrying capacity trade-off analysis in the Haihe River basin in China. *J. Clean. Prod.* 270, 122271. doi:10.1016/j.jclepro.2020.122271

Gao, S., Sun, H. H., Zhao, L., Wang, R., Xu, M., and Cao, G. (2019). Dynamic assessment of island ecological environment sustainability under urbanization based on rough set, synthetic index and catastrophe progression analysis theories. *Ocean. Coast. Manag.* 178, 104790. doi:10.1016/j.ocecoaman.2019.04.017

Gu, S. Z., Hu, Y. J., and Zhou, H. (2013). Ecological cvilization construction: scientific connotation and basic paths. *Resour. Sci.* 35 (1), 2–13.

Hu, G. Z., Zeng, W. H., Yao, R., Xie, Y., and Liang, S. (2021). An integrated assessment system for the carrying capacity of the water environment based on system dynamics. *J. Environ. Manag.* 295, 113045. doi:10.1016/j.jenvman.2021.113045

Kilkis, S. (2016). Sustainable development of energy, water and environment systems index for Southeast European cities. *J. Clean. Prod.* 130, 222–234. doi:10.1016/j.jclepro.2015.07.121

Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., et al. (2016). The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Sci. Rep.* 6 (1), 38495. doi:10.1038/srep38495

Li, J. W., Liu, Z. F., He, C. C., Yue, H., and Gou, S. (2017). Water shortages raised a legitimate concern over the sustainable development of the drylands of northern China: evidence from the water stress index. *Sci. Total Environ.* 590-591, 739–750. doi:10.1016/j.scitotenv.2017.03.037

Liao, X., Ren, Y. T., Shen, L. Y., Shu, T., He, H., and Wang, J. (2020). A "carrier-load" perspective method for investigating regional water resource carrying capacity. *J. Clean. Prod.* 269, 122043. doi:10.1016/j.jclepro.2020.122043

Magri, A., and Berezowska-Azzag, E. (2019). New tool for assessing urban water carrying capacity (WCC) in the planning of development programs in the region of Oran, Algeria. *Sustain. Cities Soc.* 48, 101316. doi:10.1016/j.scs.2018.10.040

Ministry of Water Resources (2013). Opinions of the Ministry of water resources on accelerating the construction of water ecological civilization. *Gazette Ministry Water Resour. People's Repub. China* (1), 22–25.

Naimi Ait-Aoudia, M., and Berezowska-Azzag, E. (2016). Water resources carrying capacity assessment: the case of Algeria's capital city. *Habitat Int.* 58, 51–58. doi:10.1016/j.habitatint.2016.09.006

Peng, T., and Deng, H. (2020). Comprehensive evaluation on water resource carrying capacity based on DPESBR framework: a case study in Guiyang, southwest China. *J. Clean. Prod.* 268, 122235. doi:10.1016/j.jclepro.2020.122235

Salehi, M. (2022). Global water shortage and potable water safety; Today's concern and tomorrow's crisis. *Environ. Int.* 158, 106936. doi:10.1016/j.envint.2021.106936

Sinding, S. W. (2009). Population, poverty and economic development. *Philosophical Trans. R. Soc. B-biological Sci.* 364 (1532), 3023–3030. doi:10.1098/rstb.2009.0145

Song, Q. R., Wang, Z. C., and Wu, T. H. (2024). Risk analysis and assessment of water resource carrying capacity based on weighted gray model with improved entropy weighting method in the central plains region of China. *Ecol. Indic.* 160, 111907. doi:10.1016/j.ecolind.2024.111907

Wang, J. H., and Hu, P. (2018). The connotation, evaluation criteria and experience model of water ecological civilization construction in China. *J. China Inst. Water Resour. Hydropower Res.* 16 (5), 430–436. doi:10.13244/j.cnki.jiwhr.2018.05.011

Wang, S. S., Yang, R. J., Shi, S., Wang, A., Liu, T., and Yang, J. (2023a). Characteristics and influencing factors of the spatial and temporal variability of the coupled water-energy-food nexus in the Yellow River Basin in henan province. *Sustainability* 15 (18), 13977. doi:10.3390/su151813977

Wang, X. Y., Liu, L., and Zhang, S. L. (2021). Integrated model framework for the evaluation and prediction of the water environmental carrying capacity in the Guangdong-Hong Kong-Macao Greater Bay Area. *Ecol. Indic.* 130, 108083. doi:10.1016/j.ecolind.2021.108083

Wang, X. Y., Zhang, S. L., Tang, X. P., and Gao, C. (2022a). Research on water resources environmental carrying capacity (WRECC) based on support-pressure coupling theory: a case study of the Guangdong-Hong Kong-Macao Greater Bay Area. *J. Environ. Manag.* 320, 115805. doi:10.1016/j.jenvman.2022.115805

Wang, X. Y., Zhang, S. L., Tang, X. P., and Gao, C. (2023b). Spatiotemporal heterogeneity and driving mechanisms of water resources carrying capacity for sustainable development of Guangdong Province in China. *J. Clean. Prod.* 412, 137398. doi:10.1016/j.jclepro.2023.137398

Wang, Y. F., Sun, K., Li, L., Lei, Y., Wu, S., Wang, F., et al. (2022b). The optimal allocation and the evaluation of water resources carrying capacity in Shendong mining area. *Res. Policy* 77. doi:10.1016/j.resourpol.2022.102738

Wang, Y. X., Wang, Y., Su, X. L., Qi, L., and Liu, M. (2019). Evaluation of the comprehensive carrying capacity of interprovincial water resources in China and the spatial effect. *J. Hydrol.* 575, 794–809. doi:10.1016/j.jhydrol.2019.05.076

Xue, B., Han, B., Li, H. Q., Gou, X., Yang, H., Thomas, H., et al. (2023). Understanding ecological civilization in China: from political context to science. *AMBIO* 52 (12), 1895–1909. doi:10.1007/s13280-023-01897-2

Yang, G., Dong, Z. C., Feng, S. N., Li, B., Sun, Y., and Chen, M. (2021). Early warning of water resource carrying status in Nanjing City based on coordinated development index. *J. Clean. Prod.* 284, 124696. doi:10.1016/j.jclepro.2020.124696

Yang, Z. Y., Song, J. X., Cheng, D. D., Xia, J., Li, Q., and Ahamad, M. I. (2019). Comprehensive evaluation and scenario simulation for the water resources carrying capacity in Xi'an city, China. *J. Environ. Manag.* 230, 221–233. doi:10.1016/j.jenvman.2018.09.085

Zhang, B., Chen, Z. M., Zeng, L., and Qiao, H. (2016). Demand-driven water withdrawals by Chinese industry: a multi-regional input-output analysis. *Front. Earth. Sci.* 10 (1), 13–28. doi:10.1007/s11707-015-0505-8

Zhang, J., Zhang, C. L., Shi, W. L., and Fu, Y. (2019). Quantitative evaluation and optimized utilization of water resources-water environment carrying capacity based on nature-based solutions. *J. Hydrol.* 568, 96–107. doi:10.1016/j.jhydrol.2018.10.059

Zhang, J. T., and Dong, Z. C. (2022). Assessment of coupling coordination degree and water resources carrying capacity of Hebei Province (China) based on WRESP2D2P framework and GTWR approach. *Sustain. Cities Soc.* 82, 103862. doi:10.1016/j.scs.2022.103862

Zhang, M., Liu, Y. M., Wu, J., and Wang, T. (2018). Index system of urban resource and environment carrying capacity based on ecological civilization. *Environ. Impact. Asses.* 68, 90–97. doi:10.1016/j.eiar.2017.11.002

Zhang, Z., Lu, W. X., Zhao, Y., and Song, W. (2014). Development tendency analysis and evaluation of the water ecological carrying capacity in the Siping area of Jilin Province in China based on system dynamics and analytic hierarchy process. *Ecol. Model.* 275, 9–21. doi:10.1016/j.ecolmodel.2013.11.031

Zhou, Y., Zhang, Q., Singh, V. P., and Xiao, M. (2015). General correlation analysis: a new algorithm and application. *Stoch. Env. Res. Risk A* 29 (3), 665–677. doi:10.1007/s00477-014-0970-8

Zuo, Q. T., Guo, J. H., Ma, J. X., Cui, G., Yang, R., and Yu, L. (2021). Assessment of regional-scale water resources carrying capacity based on fuzzy multiple attribute decision-making and scenario simulation. *Ecol. Indic.* 130, 108034. doi:10.1016/j.ecolind.2021.108034