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Study on Water Resource Carrying Capacity of Huaihe River Basin Based on SENCE Framework

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Article

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Abstract

The Huaihe River Basin (HRB) is a key area for water resources management and ecological protection in China, and there are regional differences and pressures in the current water resources carrying capacity (WRCC) of the basin. Therefore, this study selects five provinces (cities) in HRB as the research object, and constructs a WRCC evaluation system covering three aspects and 18 indicators based on the conceptual framework of socio-economic-natural composite ecosystem (SENCE). Through the entropy weight-TOPSIS method and grey correlation analysis (GRA), the WRCC of HRB during the period of 2013–2022 was measured and the main driving factors were analysed. The results show that (1) there are significant differences in WRCC levels in different regions, with the overall performance of downstream > upstream > midstream, and the province with the highest score is Jiangsu (0.576). (2) The trend of WRCC changes experienced a period of fluctuating decline (2013–2015), a period of slow growth (2016–2019) and a period of stability (2020–2022). (3) The social subsystem of WRCC is stable, the economic subsystem has large regional differences, and the pressure on the natural composite ecosystem increases. (4) The main drivers of the WRCC are urbanisation rate (0.8957), GDP per capita (0.8632) and daily domestic water consumption per capita (0.8547).

1. Introduction

Amid the continuous and swift progression of the worldwide economic and societal landscape, the pace of industrialization and urbanization is quickening. Presently, there is an unchecked inclination toward the exploitation of the ecological sphere and resources that are vital for human sustenance, resulting in the rise of numerous issues. These encompass a multitude of obstacles such as the discharge of pollutants, inefficient utilization of energy and resources, and the ongoing degradation of the ecological habitat. Water resources, however, are fundamental resources for maintaining regional economic development and ecosystem balance, and they play an important role in supporting economic activities and protecting natural ecology [1]. The United Nations Water (UN Water) states that about 15% of energy production uses water resources, and this trend is on the increase.Global water use in 2019 was 4.6× 10^{15} litres per year, and it is expected to increase to5.5× 10^{15} litres to6× 10^{15} litres in 2030 or 2050, and nearly 6 billion people will face a shortage of clean water resources in 2050 [2].

As one of the largest developing nations, China holds 6% of the world's freshwater resources. Yet, its per capita water consumption stands at just 2,200 cubic meters, roughly 25% of the global average[3]. This status places China among the 13 countries with the most limited freshwater resources per capita. [4, 5]. The HRB is vital for food production in China, significantly contributing to agricultural output and ensuring food security, energy and minerals, and manufacturing industries due to its advantages of fertile land, abundant resources, and convenient transportation, Consequently, it has emerged as a pivotal area for advancing the nation's strategic plan, which aims to foster the premature growth in the eastern regions and to bolster the ascent of the central territories [6]. However, the HRB is situated in China's north-south climate transition zone, an important geo-ecological boundary that is ecologically fragile and highly sensitive to global climate change [7]. Rainfall patterns in the basin vary both spatially

and temporally, with frequent natural calamities like droughts and floods causing significant clashes between water availability and consumption [8, 9]. Consequently, researching HRB holds considerable importance. The absence of scientific direction for distributing water resources and reducing the strain on socio-economic systems and the capacity of water resource supply.

WRCC denotes the maximum sustainable development level that water ecosystems in a specific region can support when water resource management and socio-economic factors are optimized over a designated period and technological capabilities. Creating a suitable model for assessing the carrying capacity of regional water resources holds significant theoretical and practical importance for the region's economic growth, environmental conservation, and sustainable water resource utilization [10]. Currently, water resources carrying capacity assessment methods mainly include hierarchical analysis [11], fuzzy analysis [12], principal component analysis [13], and system dynamics [14]. To mitigate the undue impact of individual subjectivity and prevent the partial distribution of weights, certain academics have employed the combined model method for assessing WRCC [15–18]. For example, Ren,L et al. Developed fifteen metrics for assessing the capacity of Guiyang city's water resources, utilizing a hierarchical analysis and entropy weighting approach, focusing on three key elements of water resources: carrying support and contr ol and the pressure on water resources, along with a mix of weights, indicated an annual enhancement in Guiyang city's water resources carrying capacity from 2009 to 2018 [19].Ge,W et al. Employed methods like fuzzy synthesis analysis, grey correlation analysis, and multiple linear regression model for both quantitative and qualitative evaluation of water resource carrying capacity (WRCC) in various social development strategies. The results h emphasized the significance of enhancing wastewater management and the efficient utilization of transit water resources, which are expected to positively influence the swift growth of the Changji Economic Circle [20].Gulishengmu, A et al. Utilized the GRA-TOPSIS method for an in-depth evaluation of the WRCC, managing the interaction between water resources, ecological contexts, and socio-economic capacity through the analysis of the indicator's data. s to ren the results of the evaluations become more genuine and rational [21].

The current research of scholars on the connotation of WRCC, evaluation index system and evaluation method provides a solid foundation for this paper. The solution to the fundamental issue lies in developing a scientifically sound evaluation index system and utilizing methods to assess the carrying capacity of water resources. [22]. Dai Wenyuan et al. Chosen 17 segments of streams in Gansu for study, grounded in the 'social-economic-natural composite ecosystem' (SENCE) theory, to develop a water ecological security assessment index encompassing four economic dimensions. growth, societal advancement, natural assets, and the ecological setting [23]. (1) Economic level: This primarily concerns the balance between sustainable water resource use and economic development, the rising demand for water from economic activities, resource shortages hindering growth, and the intricate relationship between regional economic development and water resource utilization [24]. (2) Social level: This focuses on aligning population growth, urban and rural development with water resources. As population density rises and urbanization accelerates, the supply-demand gap for water resources widens, making integrated water resource management and allocation to vulnerable groups a priority [25, 26]. Natural

resources: This study centers on the distribution and circulation of water and other natural resources, examining their effects on the ecological environment. Key areas of focus include water sources, water ecosystems, water pollution, and the natural regulation of water resources [27, 28]. (4) Ecosystems: The study focuses on the impacts of water resources on biodiversity, wetland ecology, river ecosystems, and climate change, as well as its key role in maintaining ecological balance [29, 30].

Based on this, researchers around the world are gradually enriching their studies related to WRCC, but in general, it seems that there are still some problems and shortcomings that need to be solved: firstly, there are more WRCC assessments studying a certain city, and there is a lack of comprehensive cross-regional assessments. Second, most of the studies only analysed from a single temporal or spatial dimension and lacked temporal and spatial difference analysis. Finally, the HRB's WRCC evaluation index system is not sufficiently developed, and few have explored its driving factors in depth. This research utilizes the SENCE theoretical model as a basis for a comprehensive evaluation of a basin's water resource capacity and to explore correlations among evaluation metrics. Acknowledging the complex and unpredictable nature of water resource systems, the aim is to enhance the scientific rigor of the assessment outcomes. Focusing on the five provinces (cities) of the HRB, the conceptual framework promotes effective water resource management and sustainable societal development. The SENCE framework, integrated with GRA, is employed to identify key influencing factors. Furthermore, the entropy weight-TOPSIS method facilitates a comprehensive analysis of HRB's WRCC from 2013 to 2022, serving as an important reference point.

The remainder of the paper is structured as follows: the second section presents an analysis of the current situation in the study area and establishes the evaluation index system based on relevant requirements and data collection. The third section analyzes and discusses the data results. The fourth section summarizes the conclusions.

2. Materials and Methods

2.1. Study Area

Located in eastern China, the HRB is bordered by the Yellow Sea to the east, the Tongbai and Funiu Mountains to the west, and the Dabie Mountains, Tongyang Grand Canal, and the southern bank of the Rutai Canal, which separates it from the Yangtze River to the south. The Yellow River Basin lies to the north (as shown in Fig. 1). The geographic coordinates range from 111°55'E to 121°25'E and 30°55'N to 36°36'N, covering an area of 270,000 square kilometers. Covering 40 cities at the prefecture level in five provinces—Hubei, Henan, Anhui, Jiangsu, and Shandong—it includes 178 counties, housing around 166 million people. Among all areas, the basin's average population density stands out as the highest. basins of rivers, surpassing the national average by 4.5 times [31].

The HRB is primarily composed of extensive plains, making up roughly 70% of its total landmass, with the remainder being mountainous and hilly. The division of the Huaihe River Basin into the u is

determined by the regional distribution patterns of water resources. The upper stretches (situated over Wangjiaba Lock), the central segments (stretching from Wangjiaba Lock to Lake Hongze's exit), the lower segments (beneath Lake Hongze's exit), and the Yishu-Si River Basin.The upper reaches of the Huaihe River Basin have undulating hills on both sides, developing waterways and many tributaries; the middle reaches are gentle, with many lakes and depressions; and the lower reaches are low-lying, with an intertwined water network and channels. The recent surge in pesticide usage in agriculture, coupled with the swift growth of industries that consume a lot of water and pollute significantly, has resulted in a yearly rise in wastewater emissions, severely contaminating the wat er entities within the basin [32]. The ecological balance in the Huaihe Baxin region has been severely strained due to pollution and acute water scarcity issues, severely disrupting water resources [33, 34].

2.2. Research Processes

This study develops a comprehensive index system for WRCC based on the SENCE conceptual framework and employs entropy weight-TOPSIS and GRA methods to assess the WRCC development level in HRB. The specific research process (Fig. 2) is as follows: First, WRCC Index System Framework: Using the social-economic-natural ecosystem concept from SENCE and existing related index research, a scientifically sound evaluation framework is constructed. Second, data collection and organization: Data for 20 indicators across 5 provinces (cities) are categorized into four types: social, economic, natural resources, and ecological environment. Social and economic data are sourced from the Statistical Yearbooks (2013–2022) of each province (city); ecological environment data are taken from the China Environmental Statistical Yearbook (2013–2022); and water resources data are derived from the China Water Resources Statistical Yearbook (2013–2022). Third, the entropy weight-TOPSIS method compares WRCC disparities across different regions and timeframes, calculating the composite score for each subsystem to analyze variability at the subsystem level. Fourth, GRA is used to identify the driving factors affecting WRCC in HRB, aiming to provide a basis for the rational development and utilization of water resources in the basin.

2.3. Indicator construction

The SENCE conceptual framework is an interdisciplinary, systemic approach to understanding and managing complex social, economic, natural and ecosystem interactions [35]. The framework is based on integrative thinking and emphasises the dynamic relationships and interdependencies between different systems [36]. Its core theoretical foundation lies in the integration of systems science and ecology, which emphasise wholeness, hierarchy and dynamics, arguing that the behaviour of complex systems cannot be understood through the study of a single component alone, but requires an integrated consideration of the various levels and elements of the system. Ecology, on the other hand, focuses on the interactions between organisms and their environment, emphasising the balance and health of ecosystems.The SENCE framework combines the two, proposing an integrated perspective to study and manage environmental issues [37].The SENCE conceptual framework is built on the basis of the environmental and economic dimensions, with a more complete system of indicators, effectively

describing the interactions between human beings and nature, and fully reflecting the current situation and development trends of HRB water resources. The SENCE conceptual framework integrates environmental, economic, and other levels, offering a comprehensive indicator system that effectively illustrates the interaction between humans and nature. It thoroughly reflects the current status and development trends of water resources in HRB, clearly demonstrating the dynamic relationships among these levels (Fig. 3).

The research categorizes the water resource carrying capacity system into three distinct subsystems: social, economic, and natural composite ecology. It establishes an assessment index system comprising a target layer, guideline layer, and indicator layer. The target layer serves as a comprehensive assessment index for the water resource carrying capacity of the Huaihe River Basin, reflecting the capacities of the five provinces (municipalities). The indicator layer includes 18 evaluation indicators: the social subsystem features five indicators that highlight the pressure on water resources due to population growth and the demand for a higher quality of life, while the economic subsystem also contains five indicators that assess the contribution to and constraints on water resources carrying capacity through industrial and regional water use efficiency. The economic subsystem contains five evaluation indicators, reflecting the promotion and constraints on the carrying capacity of water resources through industrial water use efficiency and regional economy; the natural composite ecological subsystem selects 8 evaluation indicators, reflecting the supportive and constraining effects of the ecological environment on water resources through analysing the current status of pollutant discharge and ecological environment management, and the supportive effects of water resources on the social, economic and ecological environment through water resources endowment and development and utilisation levels.

Table 1
WRCC Evaluation Indicator System for HRB in China.

Objective Level	Criteria Level	Indicator layer	Unit	Attributes	References
A:WRCC index of HRB China	S: Social layer	S1:Population density	Persons/km2	-	[38] [39]
		S2:Urbanisation rate	%	-	
		S3:Daily domestic water consumption per capita	Litres/person	-	
		S4:Daily urban wastewater treatment capacity	Million cubic metres	□	
		S5:Effective irrigation area	Thousand hectares	□	
	E: Economic layer	E1:GDP per capita	million	□	[40] [41]
		E2:Percentage of secondary economy	%	+	
		E3:Completed investment in industrial pollution control	million	□	
		E4:Total industrial water consumption	billion cubic metres	-	
		E5:Expenditure of local finance on environmental protection	billion	□	
	NCE: Natural Complex Ecosystem Layer	NCE1:Surface Water Resources	billion cubic metres	□	[42] [43] [21] [44]
		NCE2:Volume of underground water resources	billion cubic metres	□	
		NCE3:Flood-affected area	thousand hectares	-	
		NCE4:Total ecological water consumption	billion cubic metres	-	
		NCE5:Greening area per capita	square metres	□	
		NCE6:Water resources per capita	m^3/person	□	

Objective Level	Criteria Level	Indicator layer	Unit	Attributes	References
		NCE7:Average Annual Precipitation	mm	□	
		NCE8:Total aquatic products output	million tonnes	□	

('-' represents negative indicators and '+' represents positive indicators)

2.4. Evaluation methodology

WRCC is a significant topic for evaluating the sustainable use of water resources, characterized by its complexity due to factors like quantity, quality, and extent of exploitation. To ensure reliable assessment results, it is essential to determine the weights of the indicators accurately. The entropy weight-TOPSIS method is a widely adopted approach for this purpose, known for its scientific rigor and operational simplicity [45]. The TOPSIS method effectively addresses multi-attribute decision-making problems, relying on objective data that reflects the current state of water resource utilization and regional scarcity [46]. The entropy weight method assigns weights to each indicator by analysing the degree of discrete data, and determines the weights based on the differences in the degree of order of the information of each indicator, so as to achieve the objectivity of weight allocation [47]. When the entropy weight method is used in combination with the TOPSIS model, its advantages are particularly significant. In contrast to conventional fuzzy comprehensive judgment, hierarchical analysis, and fuzzy comprehensive evaluation methods, the entropy weight-TOPSIS approach demonstrates greater effectiveness in evaluating watershed WRCC [48]. By combining the objectivity of the entropy-rights method and the systematic nature of the TOPSIS model, it provides decision makers with a comprehensive and effective tool to better address complex water resource management challenges. Its application not only helps to accurately assess the carrying capacity of water resources, but also provides strong support for the development of sustainable water resources management strategies. Consequently, the entropy weighting-TOPSIS technique is broadly acknowledged as the optimal approach for evaluating the carrying capacity of water resources in river basins. Below is the formula for calculating its primary parameters:

In the first step, the indicator data are normalised.

The positive indicator (the larger the value, the safer it is) is calculated as:

$$x_{ij} = \frac{r_{ij} - \min_i \left(r_{ij}\right)}{\max_i \left(r_{ij}\right) - \min_i \left(r_{ij}\right)}$$

1

The negative indicator (the smaller the value the safer) is calculated as::

$$x_{ij} = \frac{\max\limits_{i}\left(r_{ij}\right) - \mathrm{r_{ij}}}{\max\limits_{i}\left(r_{ij}\right) - \min\limits_{i}\left(r_{ij}\right)}$$

2

Where, $\mathrm{r_{ij}}\ (i = 1,2,\cdots,n; j = 1,2,\cdots,m)$ is the original value of the jth indicator in year i. n m are positive integers.

In the next phase, the entropy weighting technique was utilized to establish the objective weights for the indicators. Entropy acts as a measure of a system's disorder and serves as a tool for assessing the level of uncertainty within the system [49].

(1) Calculate the weight of the jth value in year i

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum\limits_{i=1}^{n} x_{ij}^{2}}}$$

3

(2) Determine the entropy figure for every indicator

$$e_j = -k\sum\limits_{i=1}^{n}\left(A_j Y_{ij}\right) p_{ij}\ln p_{ij}\ j = 1,2,\cdots,m$$

4

Where, k is related to the number of samples, often take $k = \frac{1}{\ln n}$ In addition, add the definition: if $p_{\mathrm{ij}} = 0$, then let $p_{\mathrm{ij}}\ln p_{\mathrm{ij}} = 0$

(3) Calculation of the weighting factor for each indicator

$$W_j = \frac{1-e_j}{m-\sum\limits_{k}^{m}\left(1-e_j\right)},\ j = 1,2,\cdots,m \quad (5)$$

The larger the entropy weight coefficient W_j, the more information the index represents, indicating its greater role in comprehensive evaluation [50].

In the third step, TOPSIS model, i.e., the distance between superior and inferior solution method.TOPSIS method is a commonly used and effective method in multi-objective decision analysis. The fundamental procedure involves: initially, utilizing the normalized original data matrix, employing the cosine method to identify the best and poorest solutions among the restricted options. Next, consider the spacing separating each object under evaluation. and the most effective program and the least effective one are computed accordingly. Ultimately, the closeness of each assessed item to the ideal program is determined, and the nearer the object is to 1, the superior the evaluation.

(1) Determine the weighted normalised decision matrix

$$Z_{ij} = W_j X_{ij}$$

6

Where, W_j is the indicator weights. X_{ij} is the indicator normalisation matrix.

(2) Identify the positive ideal solution and the negative ideal solution.

The positive ideal solution Z^+ and the negative ideal solution Z^- are the maximum and minimum values of the weighted normalised decision matrix Z_{ij} respectively:

$$Z_i{}^+ = \left\{\max z_{ij}\right\}, \forall j = 1,2,\cdots,n \quad (7)$$

$$Z_j{}^- = \left\{\min z_{ij}\right\}, \forall j = 1,2,\cdots,n \quad (8)$$

(3) Determine how far each assessed object is from the positive ideal solution and the distance to the negative ideal solution:

$$D_i^+ = \sqrt{\sum_{j=1}^{m}\left(z_{ij} - Z_j{}^+\right)}, \forall i = 1,2,\cdots,n \quad (9)$$

$$D_i^- = \sqrt{\sum_{j=1}^{m}\left(z_{ij} - Z_j{}^-\right)}, \forall i = 1,2,\cdots,n \quad (10)$$

The smaller the D_i^+ value, the closer the evaluation unit is to the positive ideal solution, indicating a higher WRCC level. Conversely, the smaller the D_i^- value, the closer the evaluation unit is to the negative ideal solution, indicating a lower WRCC level.

(4) Evaluate how closely each assessed item corresponds to both the positive and negative ideal outcomes:

$$C_i = \frac{D_i^-}{D_i^- - D_i{}^+}$$

11

The closer C_i is to 1, the better the evaluator is.

In the fourth phase, GRA is used to evaluate the impact of the WRCC assessment metrics. The core concept of GRA involves measuring the geometric similarity between the parameter data columns and various comparative data columns to assess the strength of their connections. This method examines the correlation among indicators by analyzing the level of dependence in their developmental

dynamics.It can be seen that an integrated approach to research is effective in avoiding subjectivity in measurement.

$$\gamma_{0\mathrm{ij}}^{+} = \frac{\min_{i}\min_{j}\left|f_{\mathrm{j}}^{+} - y_{\mathrm{ij}}\right| + \rho\max_{i}\max_{j}\left|f_{\mathrm{j}}^{+} - y_{\mathrm{ij}}\right|}{\left|f_{\mathrm{j}}^{+} - y_{\mathrm{ij}}\right| + \rho\max_{i}\max_{j}\left|f_{\mathrm{j}}^{+} - y_{\mathrm{ij}}\right|}$$

12

$$\gamma_{0\mathrm{ij}}^{-} = \frac{\min_{i}\min_{j}\left|f_{\mathrm{j}}^{-} - y_{\mathrm{ij}}\right| + \rho\max_{i}\max_{j}\left|f_{\mathrm{j}}^{-} - y_{\mathrm{ij}}\right|}{\left|f_{\mathrm{j}}^{-} - y_{\mathrm{ij}}\right| + \rho\max_{i}\max_{j}\left|f_{\mathrm{j}}^{-} - y_{\mathrm{ij}}\right|}$$

13

$$r_{j}^{+} = \frac{1}{n}\sum_{j=1}^{n}\gamma_{0ij}^{+}$$

14

$$r_{j}^{-} = \frac{1}{n}\sum_{j=1}^{n}\gamma_{0ij}^{-}$$

15

2.5. Data sources

The dataset comprises five provincial (municipal) units for decision-making, 18 indicators, and spans over a decade. Annually, the dataset comprises information on 18 metrics across 5 provinces (cities), encompassing a total sample size of 90. Consequently, the overall sample size for WRCC The assessment metrics for HRB5 provinces (municipalities) during 2013–2022 stand at 900.

The data for the indicator covers three domains: the social, economic, and aquatic environment. Initially, data on social aspects such as population density (S1), urbanization rate (S2), and daily sewage treatment capacity (S3) were obtained from the Statistical Yearbooks. spanning every province (city) from 2013 to 2022. Second, economic indicators such as GDP per capita (E1), the proportion of secondary industry (E2), and completed industrial pollution control investments (E3) were also obtained from the same yearbooks. Lastly, data related to the water environment, including surface water resources (NCE1), groundwater resources (NCE2), and flood-affected areas (NCE3), were gathered from the China Environmental Statistics Yearbook (2013–2022) and annual reports from provincial water resource departments. Most indicators were readily available from these sources, and for the few missing data points, linear interpolation was employed to fill in the gaps..

The data needed for this study were filtered and organized for a comprehensive evaluation using both the entropy weight-TOPSIS method and GRA. Data processing and statistical analyses were carried out using Microsoft Excel and Stata MP software, while mapping was done with ArcGIS 10.8 and Microsoft Excel. Furthermore, to account for the regional variability within the HRB, the area was divided into upstream, midstream, and downstream regions. This study assessed the combined changes in WRCC and the regional variability of the HRB.

3. Results and analyses

3.1. Analysis of WRCC's comprehensive evaluation results

3.1.1. Analyzing the differences across various regions

The composite distribution of the WRCC index was plotted by ArcGIS10.8 software (Fig. 4).The WRCC composite indexes of HRB provinces (municipalities) in descending order are: Jiangsu (0.576), Hubei (0.449), Shandong (0.405), Anhui (0.385), and Henan (0.310).In the WRCC composite evaluation, Jiangsu (0.576) ranked in the first place. It consistently ranks first in the annual changes of WRCC from 2013 to 2022, indicating a strong connection between water resources carrying capacity and the level of economic and social development. As one of China's economic centres, Jiangsu Province, with the introduction of a series of policies such as the 2013 Jiangsu Sheng Ecological Civilization Construction Plan, has carried out a scientific assessment of water resource use so as to ensure the benign and sustainable development of urbanisation, which ultimately increased the carrying capacity of water resources by a relatively large margin during the decade.

The cities at the bottom in the comprehensive evaluation of the WRCC index are in the midstream region, and there are significant deficiencies in the level of ecological development, technology and social governance in the upstream region of Henan (0.310) and the midstream region of Anhui (0.385) in comparison with the downstream provinces (cities). Henan Province is China's most populous province, with a high proportion of agricultural population, and the overuse of chemical agricultural materials such as pesticides, fertilisers, and mulch films has largely contributed to the decline of ecological functions, and some of the cities have also suffered from particularly serious problems of over-exploitation of groundwater and industrial pollution discharges, which have led to a decline in the groundwater level and deterioration of water quality. In particular, some local chemical enterprises do not strictly comply with environmental regulations in the production process and discharge untreated industrial wastewater into the Huai River, further exacerbating the water pollution problem. On the other hand, the Henan Province suffered more natural disasters in a decade, such as the worst drought in the last five years in 2019, with only 529.1 mm of precipitation, and heavy rainfall in the summer of 2021, with 1,127.7 mm of precipitation.The cities of Huainan and Huaibei, which are located in the Anhui section of the HRB, took advantage of their rich mineral resources during the early period of economic development to vigorously develop heavy industries, such as coal and electricity. In the short term, the two cities made significant progress in economic construction, however, because heavy industries such as coal and electricity have

the disadvantages of high energy consumption and serious environmental pollution. Problems such as land subsidence, destruction of vegetation, atmospheric pollution and wastewater discharge brought about by mineral exploitation have seriously threatened the carrying capacity of the city's water resources.

The WRCC assessment results of HRB upstream, midstream and downstream provinces (municipalities) from 2013 to 2022 were plotted by Microsoft Excel software (Fig. 5).The inter-provincial differences in WRCC of HRB from 2013 to 2022 are significant, which is shown as downstream>upstream>midstream. WRCC serves as a comprehensive indicator reflecting the interplay of the social, economic, and water environment systems. The natural environment alone does not determine WRCC levels; instead, economic development and social governance also play crucial roles, contributing to its dynamic nature. For instance, Israel, despite its limited water resources, excels in desalination technology and dry-crop agriculture, leading to significant agricultural exports. Data indicate that the WRCC in the downstream region surpasses that of the midstream region, indicating a steady improvement. However, the downstream provinces face significant challenges regarding economic, technological, and governance levels compared to those in the mid and upper reaches, which influences these outcomes.

Leading in average carrying capacity are Jiangsu (0.5569), Hubei (0.4582), and Shandong (0.4073). For an extended duration, the trio of provinces has consistently upheld a high standard of WRCC, achieving a steady state throughout the decade. First, the water resources allocation system continues to improve. Jiangsu and Shandong provinces have implemented three major inter-basin water transfer projects, namely, the northward transfer of river water, the eastward diversion of river water, and the diversion of river water to Huaihuai, to realise the mutual transfer of water resources between river basins and regions. The Shandong section of the South-to-North Water Diversion Project started operation in 2013, greatly alleviating the water shortage in Shandong Province and improving the province's ability to guarantee water supply. Secondly, the management of water resources protection is becoming more and more perfect. Jiangsu Province has taken the lead in the country in realising the three full coverage of standard construction, dual-source water supply and long-term management and care of water sources in cities above the county level. It has organised and completed the construction of 96 centralised surface drinking water sources above the county level, and completed the consolidation and upgrading project of rural drinking water safety. Hubei Province has implemented a fishery resources breeding and releasing programme, making full use of biological measures to purify water and improve water quality. Vigorous efforts have been made to carry out stocking and releasing, giving full play to the purifying effect of organisms and achieving good ecological, economic and social benefits. Thirdly, the capacity of water resources supervision has been gradually improved. Jiangsu Province has carried out water resource quality monitoring of Hongze Lake and other major lakes, strengthened water abstraction measurement and monitoring, online monitoring of water users, and established a mechanism for verification and calibration of water abstraction measurement facilities. Hubei Province's Department of Ecology and Environment has established automated digital stations for monitoring water quality at various sources, conducting online assessments of nine key metrics such as water temperature, pH level, and dissolved oxen. Index of ygen and potassium permanganate.

The bottom two values of the average value of carrying capacity are Henan (0.3204) and Anhui (0.3808). The average value of carrying capacity is around 0.35, which is in the alert level of water environment. The arable land area of Henan Province is twice as large as that of Jiangsu Province, and Henan and Anhui Provinces are rich in arable land resources, with large populations but limited quantities of various types of resources, and relatively weak supply security capacity. Economic and social development, ecological and economic industries accounted for a low proportion also makes the pressure on water resources, energy and food production is increasing, in a state of overstretch. The province is actively promoting the construction of an eco-province, but because of the weak ecological foundation, environmental quality is still at the stage of accumulation of quantitative changes, and the mechanism of good collaboration between the economy and ecology has not yet been fundamentally formed, which ultimately leads to a lower level of water resources carrying capacity in the middle and upper reaches of the Huaihe River basin than in other regions.

3.1.2. Comparison between different times

The WRCC trends in the HRB (Fig. 6) are divided into three main phases: a period of fluctuating decline (2013–2015), a period of slow growth (2016–2019), and a period of stabilisation (2020–2022). Initially, from 2013 to 2015, the WRCC throughout the basin showed a slight and fluctuating decline, with the exception of Henan, which had a small increase, the WRCC ratings of the rest of the provinces (cities) had a decreasing trend. During this period, a large number of rural and agricultural residents migrated to cities, the level of regional urbanisation gradually increased, and the demand for industrial and agricultural water increased significantly, resulting in an imbalance between water supply and demand. From 2016 to 2019, the WRCC level of the HRB exhibited a slight recovery trend. This improvement can be attributed to the joint issuance of the "Key Basin Water Pollution Prevention and Control Plan (2016–2020)" by China's Ministry of Environmental Protection (MEP), the National Development and Reform Commission (NDRC), and the Ministry of Water Resources (MWR). This document divides the Huaihe River Basin into 20 water ecological control zones (WECZs) and 188 water environmental control units (WECUs), providing clear directions for enhancing WRCC in the region. The measures taken in each area have resulted in varying levels of enhancement in WRCC levels. Third, WRCC levels remain consistent over the 2020–2022 period.The reason for this is that the upstream areas have strengthened ecological protection and the construction of water source conservation areas, and strictly controlled water resources development and pollution discharge. Meanwhile, the middle reaches have effectively alleviated water use pressure by optimising water use structure and improving water use efficiency. In the downstream region, wastewater treatment and recycled water utilisation have been strengthened to improve the quality of the water environment, and the combined measures have contributed to the stabilisation of the WRCC level.

3.2. Analysis of evaluation results of WRCC subsystems

Variations in water resource availability, socio-economic growth trends, and ecological conditions among the provinces (cities) of the YRB stem from the limited natural water resources and the influence of human policies. As a result, the WRCCs among the 11 municipalities show significant spatial

differences. To better capture the diversity within these areas, this research incorporates entropy weight-TOPSIS across different social subsystems.

3.2.1. Social subsystem

The Social subsystem score of HRB is more stable (Table 2). The cities of Jiangsu in the downstream region differed greatly from the other cities in the Huaihe River Basin, but the other cities showed a gradual increase in the degree of development to the better. Hubei has a better state of social development in the two years 2016–2017, with the score peaking at 0.421 in 2017. Henan has a steady development with a better score year by year from 2016–2022, except for an obvious fluctuation in 2015. Anhui in the midstream region presents a rating pattern of two years of development followed by one year of decline in the third year from 2013–2021, overall in a state of fluctuation, but the fluctuation will not exceed 0.05.Jiangsu's social development is not only at the highest level in the Huaihe River Basin, but also second only to Guangdong in the development of all provinces in China.The level of ratings from 2013–2019 are all above 0.88, but in the three years after 2019, the ratings tend to be on a downward trend. Shandong's Social subsystem score is the most stable province in the Huaihe River Basin, with the score increasing year by year, achieving the highest score of 0.503 in 2022.

Table 2
Social Subsystem Evaluation Score 2013–2022

Areas	**Upstream areas**		**Midstream area**	**Downstream areas**	
Year	Hubei	Henan	Anhui	Jiangsu	Shandong
2013	0.338	0.239	0.252	0.881	0.333
2014	0.337	0.243	0.250	0.882	0.350
2015	0.277	0.217	0.207	0.894	0.350
2016	0.402	0.270	0.290	0.881	0.344
2017	0.421	0.279	0.347	0.887	0.344
2018	0.374	0.285	0.329	0.890	0.368
2019	0.366	0.310	0.347	0.881	0.392
2020	0.359	0.331	0.368	0.860	0.424
2021	0.335	0.350	0.332	0.850	0.499
2022	0.377	0.379	0.367	0.768	0.503

3.2.2. Economic subsystem

The HRB Economic subsystem scores are highly variable and the picture of change is more complex (Table 3). First, this rating variability is specifically reflected in the regional comparison between

upstream, midstream, and downstream, with most of the ratings in the mid- and upstream regions being in the range of 0.15–0.35, and most of the economic ratings in the downstream regions being located in the range of 0.35–0.85, a difference of more than two times. Second, this difference reflects the imbalance of economic development within the Huaihe River Basin. Upstream and midstream regions have lower and more fluctuating economic ratings due to their weak economic base and homogeneous industrial structure, while downstream regions such as Jiangsu and Shandong have significantly higher ratings due to their better economic base. Third, despite the overall better downstream economy, Shandong's economic ratings have fallen since 2019, while Jiangsu remains robust. In the future, the economic gap between the middle and upper reaches and the lower reaches should be narrowed through industrial upgrading and policy support to promote the coordinated development of the basin.

Table 3
Economic subsystem evaluation score, 2013–2022

Areas	**Upstream areas**	**Midstream area**		**Downstream areas**	
Year	Hubei	Henan	Anhui	Jiangsu	Shandong
2013	0.157	0.239	0.222	0.854	0.611
2014	0.156	0.315	0.246	0.693	0.487
2015	0.177	0.393	0.155	0.744	0.473
2016	0.162	0.474	0.129	0.670	0.418
2017	0.166	0.441	0.177	0.701	0.433
2018	0.167	0.458	0.126	0.738	0.376
2019	0.256	0.347	0.206	0.851	0.335
2020	0.213	0.214	0.227	1.000	0.396
2021	0.217	0.141	0.247	0.656	0.434
2022	0.340	0.150	0.257	0.721	0.381

3.2.3. Natural Compound Ecosystem subsystem

HRB's Natural Compound Ecosystem subsystem scores varied over the decade (Table 4), with Hubei and Shandong having more favourable ecosystems, while the scores for Jiangsu and Anhui showed some fluctuation and stress. Among the upstream regions, Hubei's score is generally more stable, especially reaching a high of 0.691 in 2014, and then fluctuates slightly but performs relatively well overall, with a score of 0.656 in 2022, maintaining a high level. In contrast, Henan's score is relatively low, initially at 0.193 in 2013, but after reaching a peak of 0.470 in 2019, the score falls slightly to 0.254 in 2022, showing a trend of greater fluctuations. Anhui in the midstream region has a relatively stable score, reaching a peak of 0.607 in 2014, after which the score declines to 0.459 in 2022, indicating some fluctuations in the region's ecosystems, but the overall trend remains relatively stable. Among the

downstream regions, Jiangsu's score fluctuates more, reaching a maximum value of 0.416 in 2015, and then decreasing year by year to 0.206 in 2022, indicating greater ecosystem pressure. Shandong, on the other hand, had a more robust performance, initially at 0.505 in 2013 and rising to 0.548 in 2022, suggesting that the condition of its ecosystems improved over the period.

Table 4
Natural Compound Ecosystem Subsystem Evaluation Score 2013–2022

Areas	**Upstream areas**		**Midstream area**	**Downstream areas**	
Year	Hubei	Henan	Anhui	Jiangsu	Shandong
2013	0.651	0.193	0.516	0.283	0.505
2014	0.691	0.255	0.607	0.315	0.386
2015	0.625	0.296	0.594	0.416	0.400
2016	0.665	0.271	0.541	0.287	0.323
2017	0.589	0.470	0.425	0.260	0.381
2018	0.575	0.364	0.643	0.255	0.378
2019	0.648	0.330	0.588	0.258	0.344
2020	0.678	0.289	0.547	0.238	0.336
2021	0.525	0.482	0.341	0.211	0.406
2022	0.656	0.254	0.459	0.206	0.548

3.3. Analysis of the level of impact of the WRCC evaluation indicators

GRA's decision-making is influenced by the resemblance in geometric configurations among assessment units and the presence of both positive and negative 'ideal solutions'. This research utilized GRA to assess the significance of 18 metrics within HRB's WRCC evaluation index system. Th results in the extent to which each indicator impacts WRCC (Fig. 7). The analysis of HRB's 18 indicators revealed that the primary five factors influencing WRCC in the watershed were predominantly social and economic levels. The drivers, in descending order, were S2 urbanisation rate (0.8957), E1 GDP per capita (0.8632), S3 daily domestic water use per capita (0.8547), E2 share of secondary industry in the economy (0.8180), and E5 local financial expenditure on environmental protection (0.8115). Among these five indicators, all of them are related to social development and economic activities, and three of them are from the economic subsystem. This indicates that the adjustment and optimisation of economic factors in the development planning of HRB plays a key role in the sustainable management of water resources; therefore, the promotion of the organic integration of economic development and water resources management is an important means of upgrading the regional WRCC.

4. Discussion

(1) Regional variability of WRCC: The results of the WRCC assessment of the Huaihe River Basin (HRB) show that there are significant differences in the carrying capacity of water resources among the regions in the basin. Downstream regions, such as Jiangsu and Shandong, benefit from a higher level of economic development and a better water resources management system, and have significantly higher WRCC scores than upstream and midstream regions. The upstream and midstream regions, especially Hubei, Henan and Anhui, on the other hand, have low WRCC scores due to a relatively weak economic base, a single industrial structure and greater ecological and environmental pressures. For example, Henan Province has a large population and large arable land, but the overuse of chemical fertilisers and pesticides in agriculture, coupled with over-exploitation of groundwater, has led to a weakening of the ecosystem's carrying capacity and greater difficulty in managing water resources. The midstream regions, such as some cities in Anhui, have long relied on resource-based industries, such as coal and electricity, and other heavy industries, which have achieved some success in economic development but have also brought about serious environmental problems, especially the pollution and over-consumption of water resources. In the future, zoning management strategies should be implemented to address the characteristics of different regions. The upstream areas should give full play to their advantages in natural resources, develop water resources moderately, and promote economic development under the premise of protecting the ecology; the midstream areas should achieve cleaner production and green transformation of industries through optimisation and adjustment of the industrial structure; and the downstream areas should continue to give full play to their economic advantages, strengthen the improvement of the efficiency of water resources utilisation, intensify the efforts in pollution control, and enhance the synergy and cooperation with the mid- and upstream areas, in order to promote the overall coordinated development.

(2) Temporal trends: from the data of 2013–2022, it can be seen that the WRCC of the HRB has experienced three significant development stages: a period of fluctuating decline (2013–2015), a period of slow recovery (2016–2019), and a period of stabilisation (2020–2022). During the period of fluctuating decline, the decline in water resources carrying capacity is mainly related to the increase in regional urbanisation and the rapid growth in industrial and agricultural water demand, which leads to an imbalance between water resources supply and demand. At the same time, poor water resource management in some areas exacerbated the decline in water resources carrying capacity. With the introduction of water pollution prevention and control policies at the national level, especially the implementation of the Key Basin Water Pollution Prevention and Control Plan (2016–2020) in 2016, the water resources carrying capacity of the HRB started to recover during 2016–2019. During this period, the efficiency of water resources utilisation has been significantly improved by strengthening water resources protection and ecological restoration projects in all provinces and cities.The overall level of WRCC tends to stabilise in 2020–2022, and the enhancement of water resources management in the upstream and midstream areas, and the reinforcement of wastewater treatment and reclaimed water utilisation in the downstream areas have jointly promoted the improvement of the basin's water resources carrying capacity.

(3) Subsystem variability: Among the three sub-systems of the Huaihe River Basin WRCC, the social sub-system scores are relatively stable, while the economic sub-system scores show large differences between regions. Downstream regions, such as Jiangsu and Shandong, have a stronger economic base and consistently higher scores, while upstream and midstream regions, such as Hubei, Henan, and Anhui, have more fluctuating scores due to slower economic development. This indicates that economic development has a significant impact on WRCC. The scores of the natural composite ecosystem subsystems also differed considerably, especially in Jiangsu in the downstream and Anhui in the midstream, where the ecosystems were under increasing pressure as economic development accelerated and the scores showed a decreasing trend. This indicates that in the process of upgrading the WRCC, it is not only necessary to focus on economic development, but also to take effective measures to protect and restore the ecosystem. Only by maintaining the coordinated development of economy, society and ecology can the long-term enhancement of water resources carrying capacity be achieved.

(4) Analysis of Driving Factors: The GRA analysis of HRB WRCC evaluation indicators highlights that economic and social factors, such as urbanization rate, GDP per capita, and the proportion of the secondary industry, significantly contribute to enhancing water resources carrying capacity. Notably, the urbanization rate (S2) and per capita GDP (E1) exert a particularly strong influence on WRCC, emphasizing the growing importance of water demand and management as the economy grows and urbanization accelerates. Additionally, local financial investments in environmental protection (E5) and per capita daily domestic water consumption (S3) are also key factors affecting WRCC. This underscores the need for optimal adjustments in economic strategies and improvements in water resource management capabilities for effective basin development planning. Consequently, future water resource management should strive for a balance between economic growth and ecological sustainability, promoting coordinated development of the regional economy and water resources.

5. Conclusions

The water resources carrying capacity (WRCC) of the Huaihe River Basin has shown a certain upward trend over the past decade, but the differences between regions are still obvious. The downstream regions of Jiangsu and Shandong, with their well-developed economies and well-established water resources management systems, have high WRCC scores and show good coordination between water resources use and economic development. However, the upstream and midstream regions, such as Hubei, Henan and Anhui, have lower WRCC scores due to their relatively lagging economic development and low water use efficiency. These differences suggest that the level of economic development and social governance capacity play an important role in determining the carrying capacity of water resources in each region. Therefore, it is recommended to enhance the regional water resources carrying capacity through targeted measures in the future to reduce regional disparities and achieve sustainable development within the basin.

(1) Strengthen the rational allocation and efficient use of water resources within the basin, especially in the upstream and midstream areas. Introduce advanced water-saving technologies and promote water-saving production methods, especially in agriculture and industry, in order to reduce the waste of water resources. Agricultural water consumption is high in the upstream and midstream areas and can be significantly reduced through modernised irrigation systems, such as precision drip and sprinkler irrigation technologies. The industrial sector should enhance water recycling and encourage the development of water-saving enterprises, thereby reducing dependence on water resources and improving the overall water resources carrying capacity (WRCC).

(2) For regions with a weak economic base and limited governance capacity, policy and financial support needs to be increased to promote economic structure optimisation and industrial upgrading. Priority should be given to the development of high value-added and low water-consuming industries, and the reliance on traditional high water-consuming industries should be gradually reduced. At the same time, ecological protection should be promoted simultaneously, and the impact of water resources development on the ecosystem should be mitigated through the restoration of the natural water cycle and the implementation of ecological restoration projects for rivers and lakes, so as to ensure that the development of water resources goes hand in hand with ecological balance. The government should also strengthen infrastructure construction, especially in the fields of sewage treatment and water resource monitoring, in order to achieve coordination and unity between water resources development and environmental protection.

(3) Downstream areas should give full play to their economic advantages and focus on strengthening pollution control and sewage treatment capacity. With the rapid development of economy and industry, the pressure of water pollution is increasing, so it is necessary to upgrade sewage treatment facilities, increase investment in sewage treatment technology, and promote the use of reclaimed water to enhance the recycling rate of water resources. At the same time, a stricter water resource management system should be established to ensure that enterprises and residents use water reasonably in accordance with the law and avoid wastage and pollution. In addition, downstream areas should strengthen cooperation with upstream and midstream areas, and through financial support, technology transfer and ecological compensation, help upstream and midstream areas to improve their water resources management level, so as to promote synergistic management and sustainable development of the basin as a whole.

Declarations

Conflicts of Interest:

The authors declare no conflicts of interest.

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Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Data Availability

All data generated or analysed during this study are included in this published.

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Figures

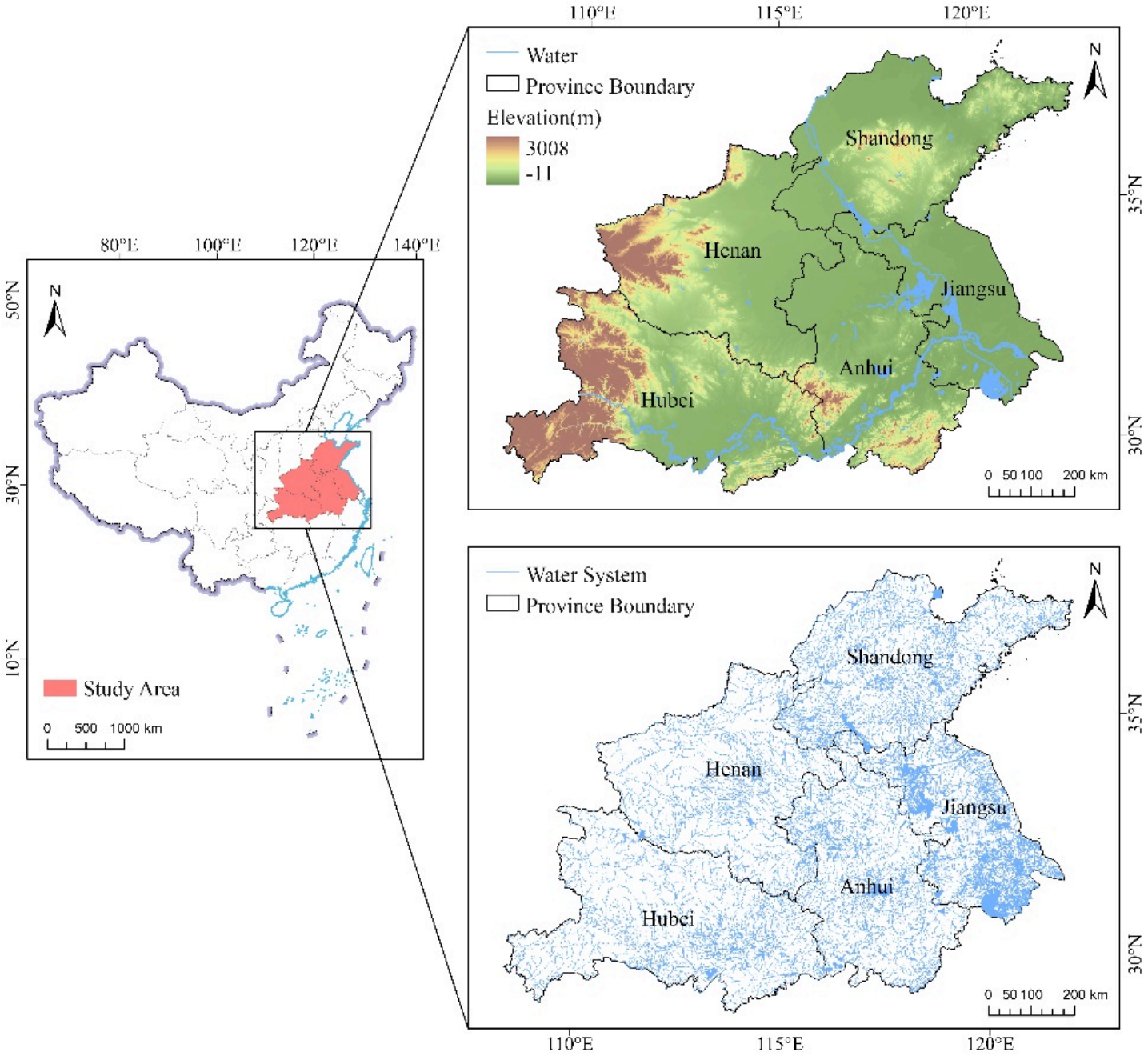


Figure 1

Location of HRB region, allocation of water systems, and DEM information.

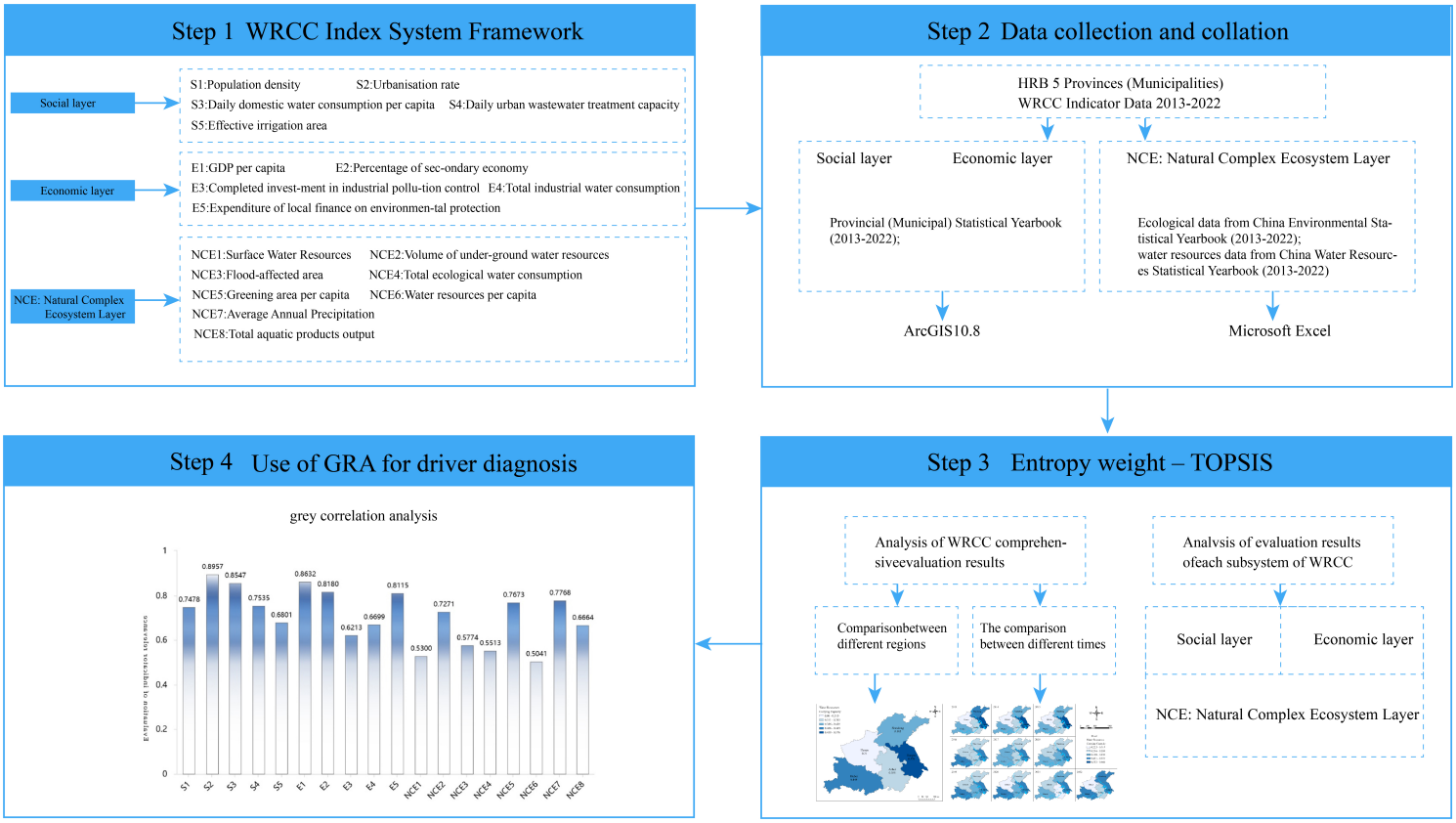


Figure 2

SENCE conceptual framework

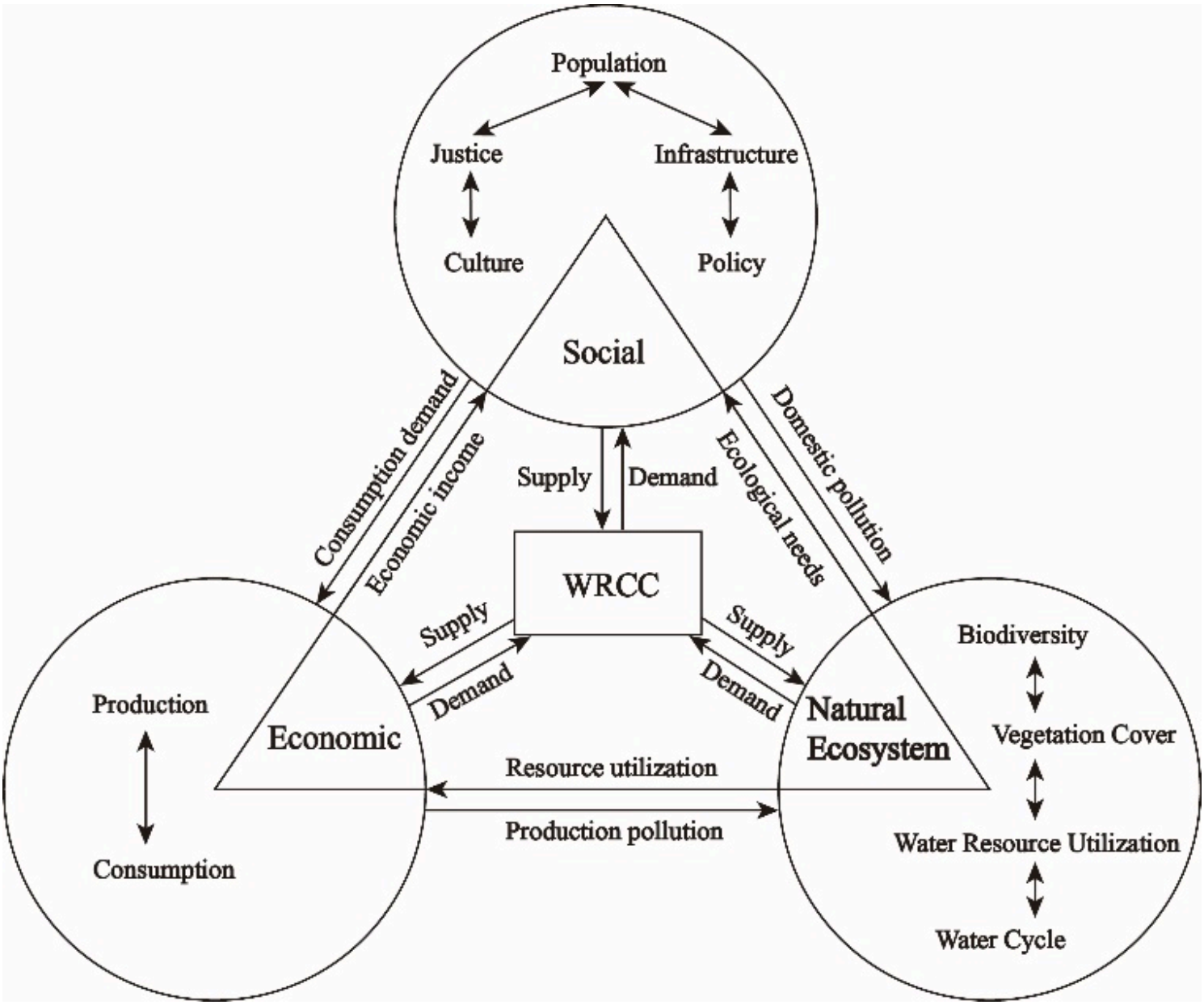


Figure 3

SENCE conceptual framework

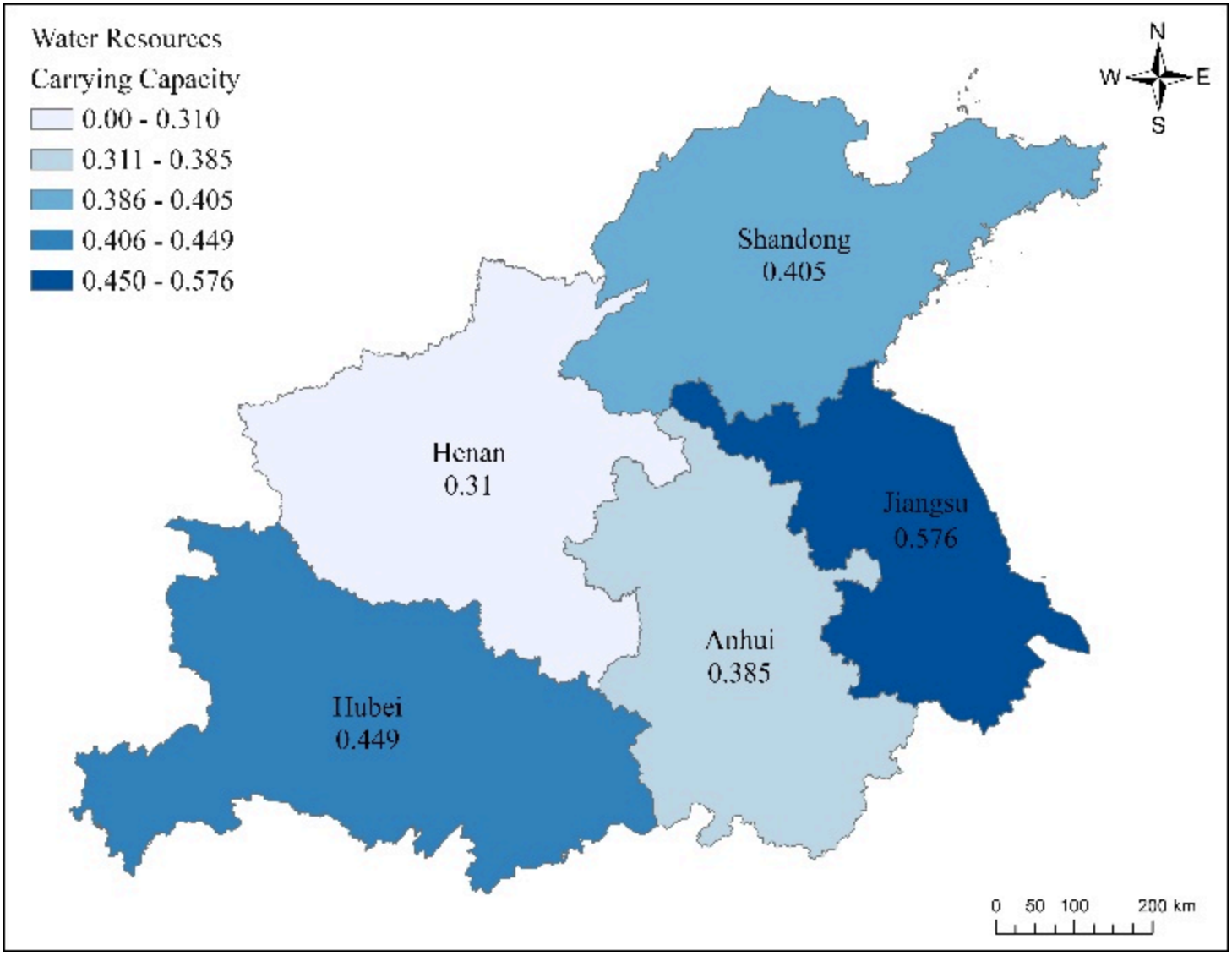
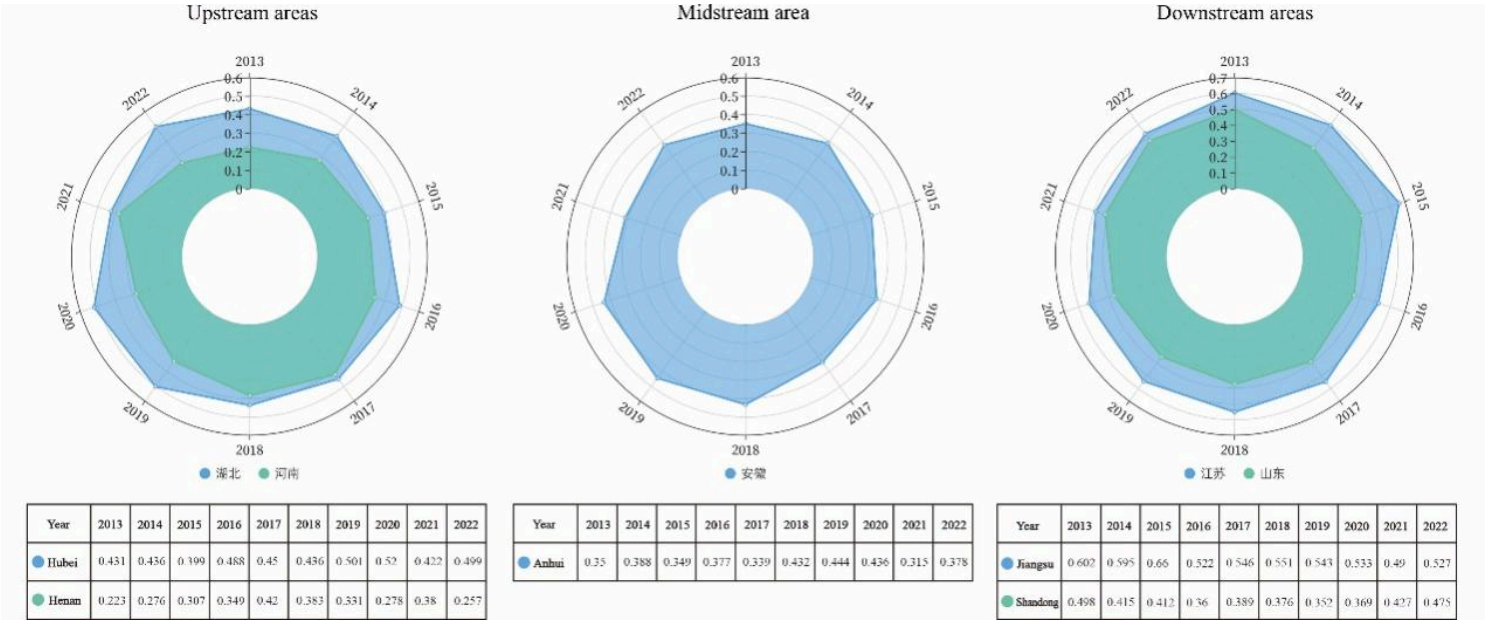


Figure 4

Composite index of HRB WRCC for various areas.



Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Hubei	0.431	0.436	0.399	0.488	0.45	0.436	0.501	0.52	0.422	0.499
Henan	0.223	0.276	0.307	0.349	0.42	0.383	0.331	0.278	0.38	0.257

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Anhui	0.35	0.388	0.349	0.377	0.339	0.432	0.444	0.436	0.315	0.378

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jiangsu	0.602	0.595	0.66	0.522	0.546	0.551	0.543	0.533	0.49	0.527
Shandong	0.498	0.415	0.412	0.36	0.389	0.376	0.352	0.369	0.427	0.475

Figure 5

Joint changes in WRCC take place across the downstream, midstream, and upstream regions of the HRB.

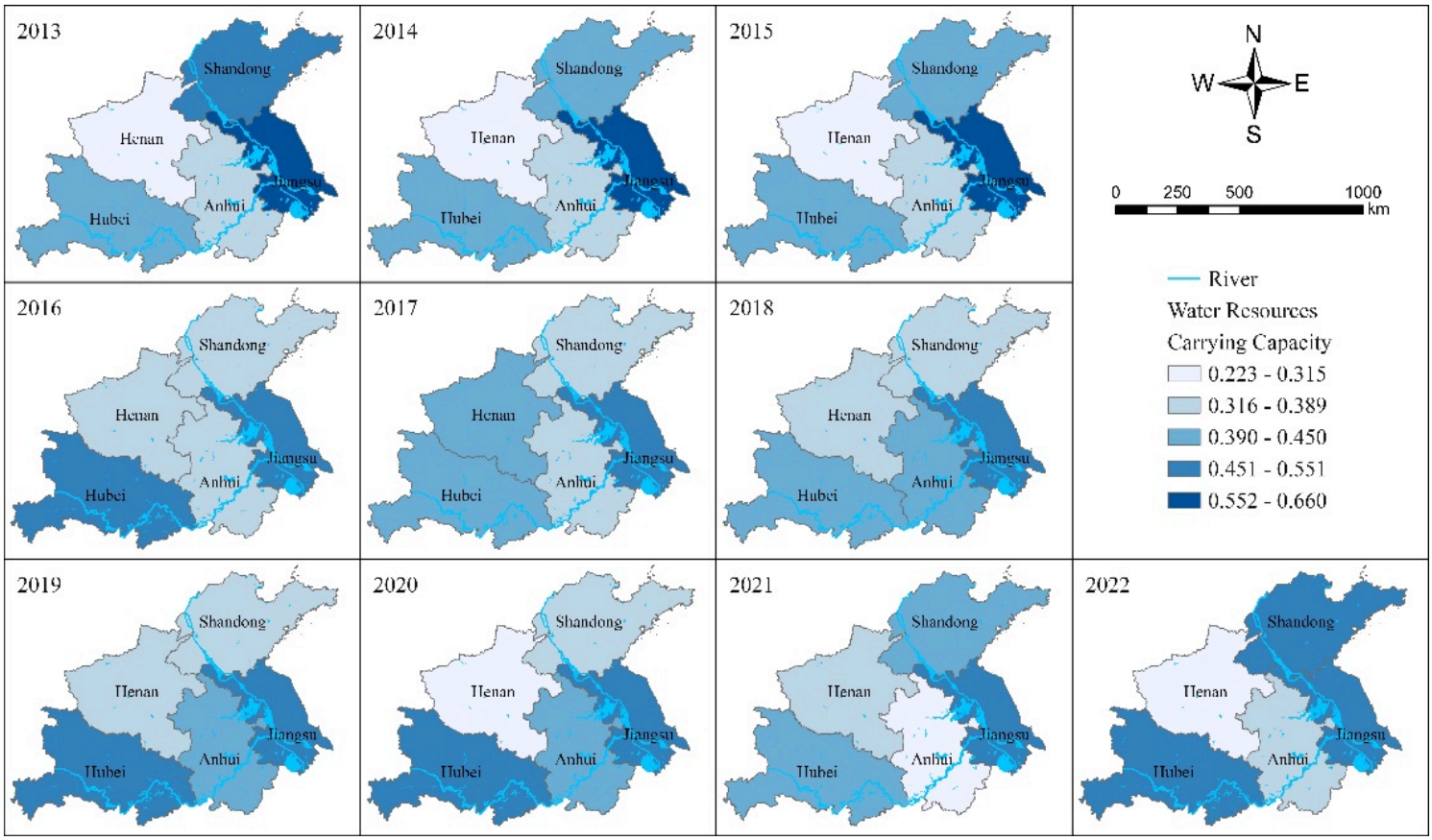


Figure 6

Year-on-year change in WRCC, 2012-2021

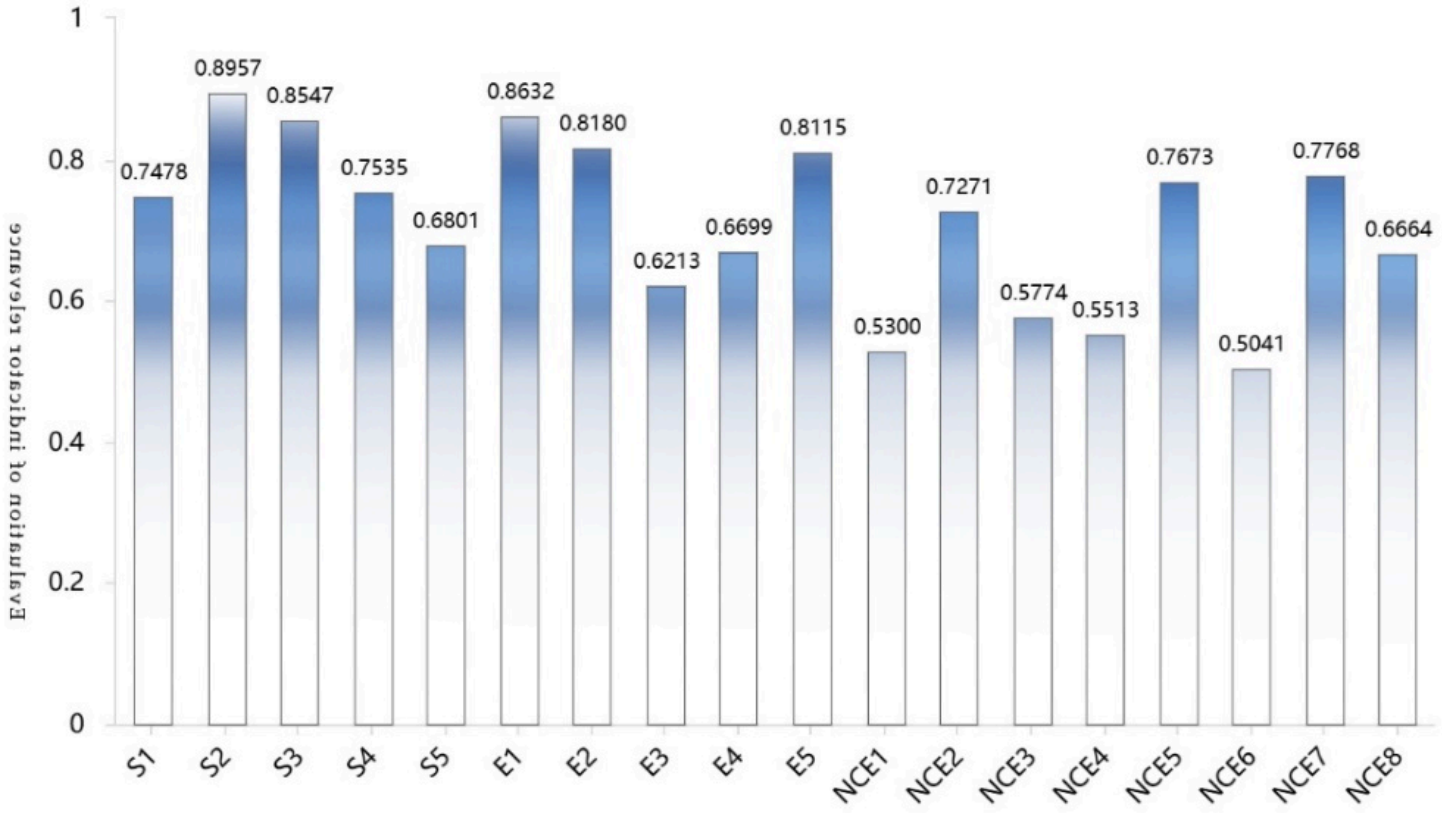


Figure 7

Ranking of WRCC evaluation indicators by level of impact.