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Original Research

Assessment of Water Resources Carrying Capacity of Yangtze River Basin and Its Driving Factors

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Abstract

The Yangtze River Basin (YRB) is an essential location for the development of eco-civilization in China, and the state of water environment in the watershed is still unsatisfactory at this stage. Therefore, 11 provinces (cities) of YRB were selected for the present study. The Water Resources Carrying Capacity (WRCC) indicator scheme is founded on the conceptual structure of Social-Economic-Natural Complex Ecosystem (SENCE), and 21 indicators in 3 aspects are con-structed. The entropy-weighted-TOPSIS method and grey relational analysis (GRA) were used to measure the WRCC of YRB from 2012 to 2021 and determine the driving factors. The results show that, first, there are large differences in WRCC levels in different regions, with an overall up-stream>midstream>downstream. The top three provinces (cities) in order are Szechwan (0.4721), Qinghai (0.4682) and Tibet (0.4655). Second, the trend of WRCC change is divided into three phases, fluctuating decline (2012-2015), recovery (2016-2018), and growth (2019-2021). Third, the subsystems of WRCC show stability, equilibrium, and variance, respectively. (4) The main drivers of WRCC are total fish production (0.8780), per capita daily domestic water consumption (0.8640), and total agricultural water consumption (0.8630).

Keywords: WRCC, SENCE conceptual framework, YRB, entropy-weight-TOPSIS method, GRA

Introduction

WRCC describes the extent to which a region's water supply can sustain harmonious socioeconomic and ecological growth. [1] Scholars have conducted many theoretical and empirical studies on water environment issues. It mainly includes WRCC, water resources characteristics [2], water security [3], and water safety [4]. WRCC evaluation is an important part of environmental carrying capacity, and a reasonable evaluation can reflect the water carrying capacity of a basin. Therefore, it is important to study the WRCC of YRB and analyze how to improve the carrying capacity of the basin under the limited water resources allocation.

The shortage of water substances in the basin and the deterioration of water environment and ecological functions pose a crisis to the development of the basin. China has tried to shift from single-factor environmental management to integrated management based on the Huaihe River Basin, Taihu Lake Basin and YRB. This is a strategic place for coordinated regional development and ecological civilization in China. [5] At this stage, the water, and ecological conditions of some cities in the YRB are still unsatisfactory, and it is difficult

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for WRCC to achieve sustainable support for socio-economic development. In the context of “protecting the Yangtze River”, how to achieve sustainable use of water resources while developing the economy has become an urgent issue for YRB.

At present, the more widely applied research methods on WRCC include AHP method [6, 7], cloud modeling method [8], principal component analysis [9, 10], TOPSIS method [11], and fuzzy comprehensive evaluation (FCE) method [12, 13]. To avoid the incomprehensiveness of single weight assignment, some scholars use the combination model [14] to evaluate WRCC. The above methods reduce the influence of human subjective factors though. However, the systematic nature of indicator selection and weight determination is neglected.

Scholars have developed the conceptual framework of the WRCC evaluation system and established different indicator systems. The first one is a model framework based on the “pressure-state-response” (PSR) [15, 16] and its variants [17, 18], which reveal the process. Second, a framework based on the SENCE conceptual framework [19] is used to establish a system of indicators from the components of the composite ecosystem. Third, ecosystem security was assessed by selecting indicators such as resilience and organization using the basic principles of ecosystems [20]. Fourth, the evaluation index system is constructed based on the connotation of ecological security.

In view of this, this study is based on the SENCE conceptual framework, and integrates the complexity and uncertainty of the system. The 11 provinces (municipalities) of YRB are studied, and the GRA judgment drivers are combined with the entropy-weight-TOPSIS method to conduct a comprehensive evaluation of the WRCC for 2012-2021. The results of the study aim to contribute to the stability and scientific management of the basin and promote the rapid development of ecological integration.

Materials and Methods

YRB Regional Scope

The regional scope of this study is YRB (Fig. 1), and the downstream area passes through Shanghai, Anhui, and Jiangsu provinces. In the middle reaches, it flows through Hubei (bounded by Yichang City in Hubei), Hunan, and Jiangxi. In the upstream region, it passes through Tibet, Qinghai, Yunnan, Sichuan, and Chongqing. The total volume of water in the Yangtze is 975.5 billion cubic meters. It has 20 times more water than the Yellow River and accounts for about 36% of the total runoff of the Yellow River in the country. YRB precipitation is mainly concentrated from April to October, with well-developed water systems and numerous lakes and reservoirs.

Research Process

The specific research process is as follows: Firstly, in conjunction with the SENCE conceptual framework, the water ecological assessment indicators system is established from economic, social and resource environment aspects. It can meet the scientific and systematic nature, but also objectively reflect the water ecological security situation and problems in the basin. Second, Data collection and collation. 21 indicators data from 11 provinces (cities) contain three categories: social, economic, and water environment. Third, Entropy weight - TOPSIS. A combined assessment of WRCC compares differences across regions and over time. The composite score value of all the components is calculated and the variability exhibited at the subsystem level is analyzed. Fourth, the GRA was applied to diagnose the driving factors. In this way, the major elements influencing the YRB WRCC are derived.

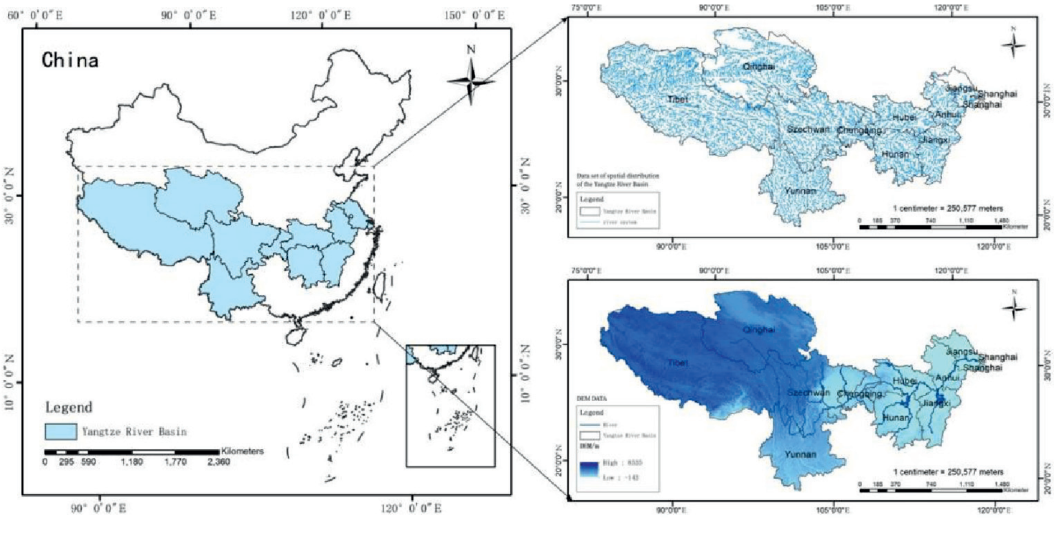

Fig. 1. YRB area location, water system distribution and DEM data.

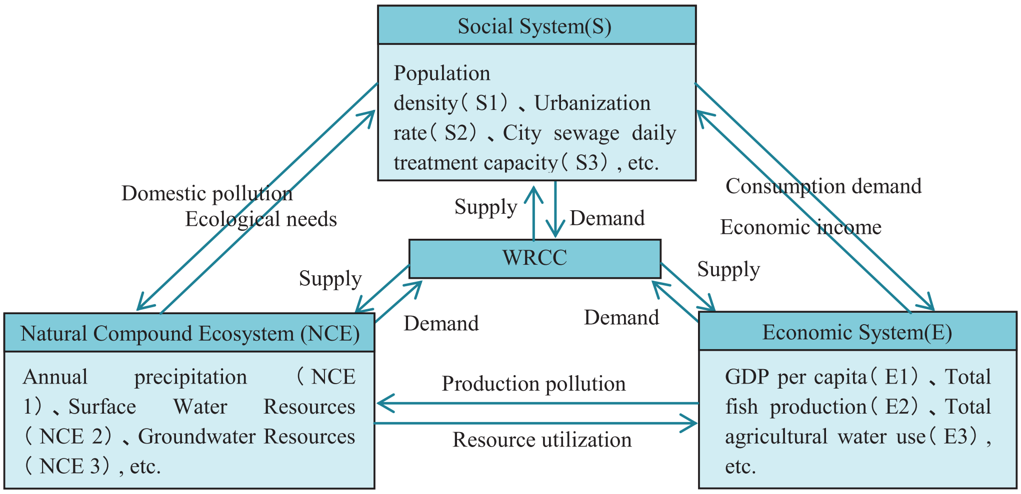

Fig. 2. SENCE Conceptual Framework.

Construction of Indicators

The SENCE conceptual framework [21] is a unity of ecological functions consisting of a combination of human social and economic activities and natural conditions, i.e., the SENCE complex ecosystem (Fig. 2). The framework is a unity formed by the interaction of the water ecosystem, water-related economic and social systems. It is the product of the interaction of environmental and human activities and historical development processes. [22, 23] The SENCE conceptual framework can objectively reflect the status and problems of regional WRCC while satisfying the scientific and systematic nature and has positive and practical guidance significance. The SENCE conceptual framework is based on the environmental and economic levels, and the indicator system is complete, effectively illustrating the interactions between human and nature. At the same time, it fully reflects the status and tendency of YRB resources, clearly showing the dynamic relationship between each level.

WRCC is influenced by various elements including water quantity, population, community, and economy, etc. A reasonable assessment indicator framework is the crucial to precisely evaluate the tolerance capacity of regional water environment. [24] Therefore, this study constructs a WRCC assessment system based on the SENCE conceptual framework, depending on the natural and socioeconomic status of the research area. Specifically, it is divided into three criterion layers: social, economic, and natural compound ecosystem, and 21 evaluation indicators are selected to evaluate the WRCC of YRB (Table 1). Among them, seven metrics were selected for the social subsystem, such as Population density (S1), Urbanization rate (S2) and City sewage daily treatment capacity (S3). Seven indicators such as GDP per capita (E1), Total fish production (E2) and Total agricultural water use (E3) were selected for the economic subsystem. The Natural Compound Ecosystem subsystem selected seven indicators, including Flood Damage Area (NCE5), Total wastewater discharge (NCE6), and Forest cover (NCE7).

Evaluation Methodology

WRCC is an essential proposition for measuring the renewable usage of natural resources, which has a high degree of ambiguity. The entropy weight-TOPSIS method is widely used because of the advantages of objective science and ease of operation. The TOPSIS method is a model for solving many-attribute determination issues. The calculation basis of this method is based on objective data reflecting the status and scarcity of regional water resources use. The entropy weighting method assigns rights to indicators with respect to the extent of the data dispersion. The entropy weight method combined with the TOPSIS model is more suitable for WRCC assessment in watersheds than evaluation methods such as the fuzzy integrated judgment method, AHP and FCE. Thus, the Entropy-TOPSIS methodology is the appropriate choice. The main parameters are calculated as follows:

The first step is to normalize the indicator data. Where, n, m is a positive integer.

The positivity metric (the greater the value, the more secure it is) is calculated by the formula:

$$x_{ij} = \frac{r_{ij} - \min_i(r_{ij})}{\max_i(r_{ij}) - \min_i(r_{ij})} \tag{1}$$

The minus metric (the lower the value, the safer it is) is calculated by the formula:

$$x_{ij} = \frac{\max_i(r_{ij}) - r_{ij}}{\max_i(r_{ij}) - \min_i(r_{ij})} \tag{2}$$

Table 1. China YRB's WRCC Assessment Indicator System.

Target Level	Guideline layer	Indicator layer	Unit	Characteristic
A: WRCC Index for China YRB	S: Social layer	S1: Population density	%	-
		S2: Urbanization rate	%	-
		S3: City sewage daily treatment capacity	Million Cubic Meters	+
		S4: Water resources per capita	Cubic meter/person	+
		S5: Urban water penetration rate	%	-
		S6: Per capita daily domestic water consumption	Liters	-
		S7: Effective irrigated area	Thousands of hectares	+
	E: Economic layer	E1: GDP per capita	Million yuan	+
		E2: Total fish production	Million tons	-
		E3: Total agricultural water use	BCM	-
		E4: Total industrial water use	BCM	-
		E5: Investment completed in wastewater treatment projects	Million yuan	+
		E6: Local financial expenditure on environmental protection	Billion	+
		E7: Secondary industry value added	Billion	+
	NCE: Natural Compound Ecosystem Layer	NCE1: Annual precipitation	Millimeter	+
		NCE2: Surface Water Resources	BCM	+
		NCE3: Groundwater Resources	BCM	+
		NCE4: Total Ecological Water Use	BCM	-
		NCE5: Flood Damage Area	Thousands of hectares	-
		NCE6: Total wastewater discharge	Million tons	-
		NCE7: Forest cover	%	+

In the second step, the entropy weighting method is applied to compute each indicator with objective weights. Entropy is a state function of a system and is a metric tool for the disorder of the system.

(1) Computing the weight of the value of item *j* in year *i*.

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{3}$$

(2) Computing the entropy value of each metric.

$$e_j = -k \sum_{i=1}^{n} \left(A_j Y_{ij}\right) p_{ij} \ln p_{ij} \tag{4}$$

In addition, add the definition: If $p_{ij} = 0$, then let $p_{ij} \ln p_{ij} = 0$.

(3) Calculate the weight coefficients of each indicator.

$$W_j = \frac{1 - e_j}{m - \sum_k^m \left(1 - e_j\right)} \tag{5}$$

The larger the entropy weight coefficient W_j, the more information the indicator represents. This indicates that the more the indicator contributes to the comprehensive evaluation.

The third step, TOPSIS method, is the superior-inferior solution distance method.

(1) Determine the weighted normalized decision matrix.

$$Z_{ij} = W_j X_{ij} \tag{6}$$

Among them, W_j is the index weight. X_{ij} is the indicator normalization matrix.

(2) Identify the negative and positive optimal answers.

$$Z_i^{\ +} = \{\max z_{ij}\} \tag{7}$$

$$Z_j^{\ -} = \{\min z_{ij}\} \tag{8}$$

(3) Calculate the distance of the indicator from the desired method of positive and negative aspects.

$$D_i^+ = \sqrt{\sum_{j=1}^{m}\left(z_{ij} - Z_j^{\ +}\right)} \tag{9}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m}\left(z_{ij} - Z_j^{\ -}\right)} \tag{10}$$

The lower value of D_i^+ indicates the closer the evaluation cell is to the correct desired solution. That is, the higher the level of WRCC. The lower the D_i^- value, the shorter the distance of the evaluation unit from the negative desired solution. That is, the lower the level of WRCC.

(4) Calculate the proximity of each evaluation object to the optimal solution of positive and negative.

$$C_i = \frac{D_i^-}{D_i^- - D_i^{\ +}} \tag{11}$$

Closer the distance of C_i from 1, it indicates that the superiority of the evaluation object.

In the fourth step, GRA analyzes the degree of influence of WRCC evaluation indicators. GRA determines how closely the parameter columns, and several data columns are geometrically similar and judges whether the connection is tight. This shows that an integrated research approach can effectively avoid subjectivity in measurement.

$$\gamma_{0ij}^{\ +} = \frac{\min_i\min_j\left|f_j^{\ +} - y_{ij}\right| + \rho\max_i\max_j\left|f_j^{\ +} - y_{ij}\right|}{\left|f_j^{\ +} - y_{ij}\right| + \rho\max_i\max_j\left|f_j^{\ +} - y_{ij}\right|} \tag{12}$$

$$\gamma_{0ij}^{\ -} = \frac{\min_i\min_j\left|f_j^{\ -} - y_{ij}\right| + \rho\max_i\max_j\left|f_j^{\ -} - y_{ij}\right|}{\left|f_j^{\ -} - y_{ij}\right| + \rho\max_i\max_j\left|f_j^{\ -} - y_{ij}\right|} \tag{13}$$

$$r_j^{\ +} = \frac{1}{n}\sum_{j=1}^{n}\gamma_{0ij}^{\ +} \tag{14}$$

Data Source

The data contain 11 provincial (municipal) decision-making units, 21 indicators, and a 10-year time span. Each year, the data set contains data on 21 indicators for 11 provinces (cities), with a sample size of 231. Therefore, the total sample size of WRCC evaluation indicators for YRB11 provinces (cities) from 2012-2021 is 2310.

The indicator data contain three aspects: social, economic and water environment: First, the data of social aspects such as Population density (S1), Urbanization rate (S2) and City sewage daily treatment capacity (S3) were collected from each province (city) Statistical Yearbook (2012-2022). Second, the numbers of economic aspects such as GDP per capita (E1), Total fish production (E2) and Total agricultural water use (E3) were derived from each province (city) Statistical Yearbook (2012-2022). Third, the data for the indicators of water environment such as Annual precipitation (NCE1), Surface Water Resources (NCE2) and Groundwater Resources (NCE3) are obtained through the Chinese Environmental Statistical Yearbook (2012-2022) and the Water Resources Department of each provincial (municipal) government public information and annual reports. Most of the indicator data were obtained through the above-mentioned databases. For the few missing data, linear interpolation was used to supplement the data.

In this study, the entropy weighted TOPSIS and GRA methods were used for comprehensive evaluation. Data were processed using Microsoft Excel and Stata MP software, and mapping was performed using ArcGIS10.8 and Microsoft Excel software. In addition, considering the regional variability of YRB, the three regions were divided into upstream, midstream， and downstream regions.

Results

Analyses of WRCC Comprehensive Assessment Results

Comparison between Different Regions

The combined distribution of WRCC indices was plotted by ArcGIS 10.8 software (Fig. 3). Tibet (0.471) is ranked first in the WRCC overall rating. It is also always in the first place in the year-by-year change of WRCC from 2012 to 2021. This indicates that Tibet attaches high importance to the problem of decreasing freshwater reserves in the Yangtze River headwaters area. Tibet actively responds to climate change and strengthens water environment monitoring, impact, and assessment. Facing the dual pressure of ecological environmental protection and economic development in upstream areas, Tibet promotes pollution prevention and focuses on economic construction.

Most of the cities at the bottom of the WRCC index composite evaluation are in up-stream areas. Upstream provinces (cities) are closer to the water sources of YRB and have higher water resources endowment. However, there are significant deficiencies in the ecological development level, technology level and social governance level in upstream areas compared to downstream provinces (cities). First, many mining and smelting enterprises are in more than 10 cities in Szechwan (0.264) and Chongqing (0.158) provinces. This has led to the formation of more than 200 tailings ponds in Szechwan and Chongqing, most of which are built along the tributaries of the Yangtze River. Once leaked, pollutants can quickly cause water pollution with the flow of water. In recent years, there have been successive cross-border input pollution incidents in YRB, with the antimony tailings pond spill in 2015 and the direct discharge of thallium-containing wastewater through the tailings pond in 2017. The two pollution events led to serious exceedances of antimony and thallium standards in Yangtze River water bodies, respectively, which seriously affected the safety of drinking water sources.

Secondly, Qinghai (0.099) is in the bottom rank of WRCC index. Qinghai is in alpine conditions, with harsh natural conditions and a single and fragile ecosystem structure. With the combined effects of climate variability and man-made events, once an ecosystem is destroyed, it will be extremely difficult to recover. The implementation of the Three Great Rivers Ecological Protection Project has had a beneficial influence on the reduction of human activity disturbances. The degradation of the alpine wetland ecosystem has been curbed, but the situation is still not optimistic.

The WRCC assessment results for 2012-2021 for each province (city) in the top and bottom of YRB were plotted by Microsoft Excel software (Fig. 4). From 2012 to 2021, the inter-provincial variation of WRCC in YRB is significant, specifically upstream>mid-stream>downstream. This is because WRCC is a comprehensive indicator presented by the interaction between society, economy, and environment. The natural environment is not a sufficient condition to determine the level of WRCC. In addition to the physical environment, WRCC is modulated by the degree of economy and the level of community governance and is characterized by dynamic changes. For example, Israel has a world-leading desalination technology despite its extreme water scarcity and has developed dry crop agriculture to achieve large exports of agricultural products. From the results presented by the data, we know that the midstream region has better WRCC levels than the downstream region, showing a steady improvement trend. The economic and technological level and social governance level of the downstream provinces (cities) are at a huge disadvantage compared to the middle and downstream provinces (cities), which makes the final presentation of the above results.

The top three load carrying capacity means are Szechwan (0.4721), Qinghai (0.4682) and Tibet (0.4655). The three provinces maintained good WRCC levels over the years, with a gradual upward trend over the research duration. Specifically, there is a high level of economic growth in Szechwan. Szechwan uses water competently in its manufacturing and invests in the development of green and creative technologies and ecological management. The WRCC provided by natural water systems in Sichuan Province is gradually being reconciled with the pressures brought about by urban economic and social growth. Thus, the level of WRCC in Szechwan is spatially distributed in a high-quality posture. Tibet is close to the water source of YRB and has a higher water endowment. Local ecological and environmental protection work has been carried out in an orderly manner, with increasing attention paid to the safety of the water environment. Tibet has carried out work to rectify excessive outfalls, improve the drainage network, increase the rate of sewage treatment, increase vegetation cover, conserve water, and strengthen river cross-section monitoring.

The top three lowest load carrying capacity averages are Jiangxi (0.3018), Jiangsu (0.3043) and

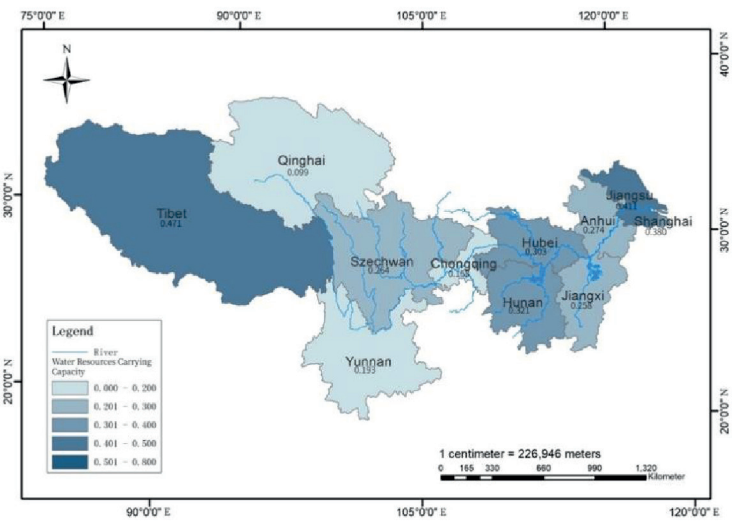

Fig. 3. YRB WRCC Composite Index for Different Regions.

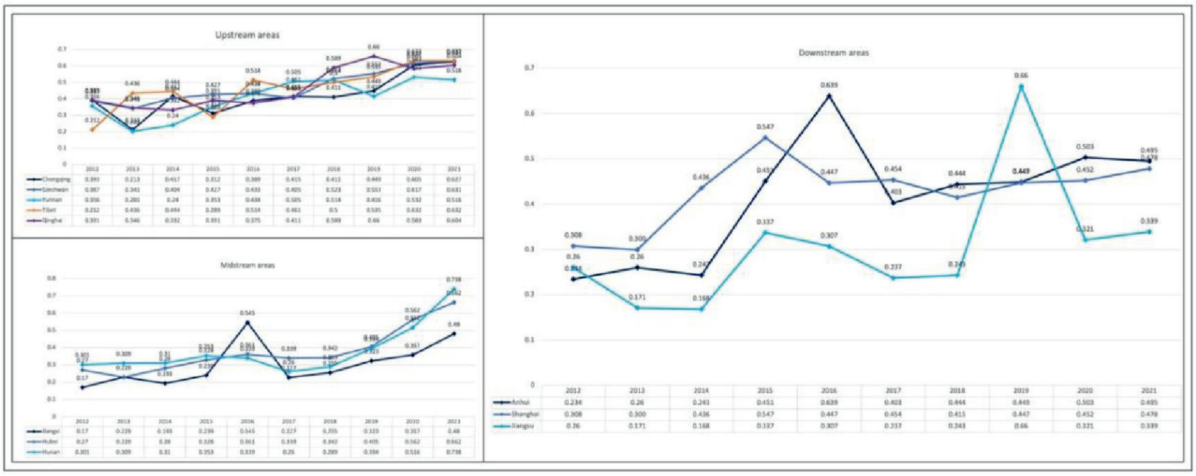

Fig. 4. Combined changes in WRCC in downstream, midstream, and upstream areas of YRB.

Hubei (0.3778) in that order. The average load carrying capacity is around 0.35, which is in the alert level of water environment. Jiangsu is the only province in the downstream region where the WRCC average is at the bottom. The areas represented by Suzhou, Wuxi and Changzhou have taken over many secondary industries from Shanghai. Jiangsu's rapid economic development is accompanied by a large amount of water pollution and industrial water consumption. At the same time, Jiangsu's water conservation and pollution control is not significant, resulting in a significantly lower level of WRCC than other regions. Although the midstream area is rich in water resources, both the environmental and socioeconomic subsystems have the lowest scores in the YRB. Among the midstream regions, Jiangxi (0.3018) and Hubei (0.3778) have been on the verge of the low-level line in WRCC.

Comparison between Different Times

The trend of WRCC in YRB (Fig. 5) is divided into three main phases: fluctuating decline (2012-2015), recovery (2016-2018), and growth (2019-2021). First, from 2012 to 2015, the WRCC in all regions of the basin showed a small fluctuating downward trend. Except for Tibet, Shanghai, and Jiangsu, the WRCC levels in the rest of the provinces (cities) are decreasing. Years of "economic first" of the rough development of the water ecology caused serious damage, it is hard to repair soon. This is an essential reason for the stagnation of WRCC from 2012-2015.

Second, the WRCC level of YRB showed a small recovery trend in 2016-2018. The main reason is that in January 2015, the State Council issued the "Opinions on the Implementation of the Toughest Water Resources Control System". The policy's rigorous assessment

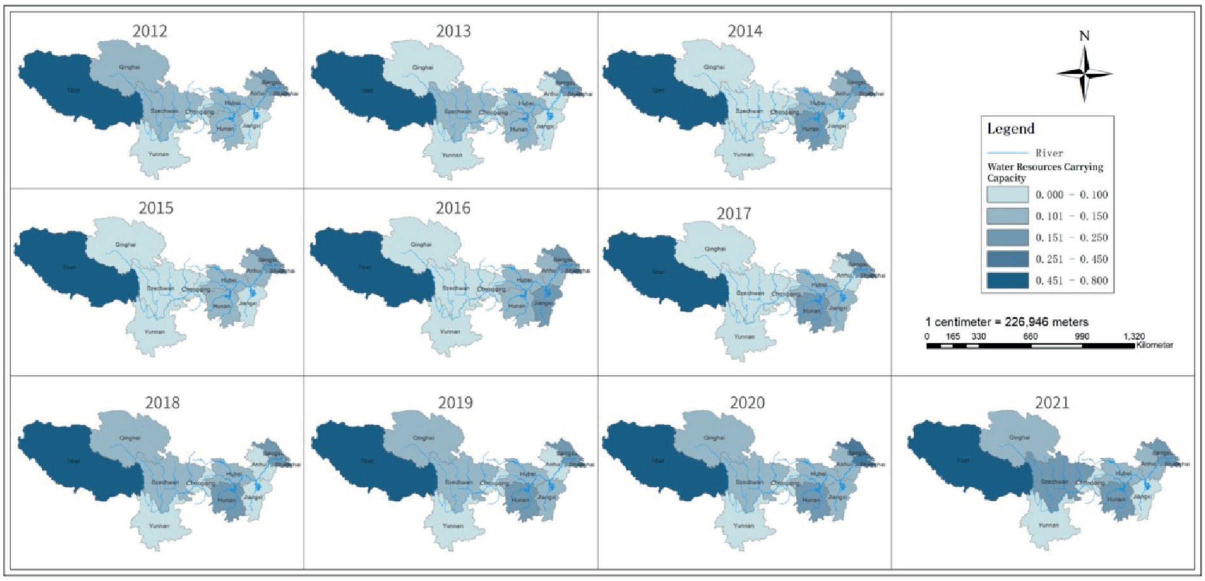

Fig. 5. Year-to-year change in WRCC levels from 2012-2021.

has prompted localities to actively reduce the stresses placed on aquatic systems by human activities. The actions implemented in each region have led to different degrees of improvement in WRCC levels.

Third, in 2019-2021, WRCC levels in all YRB11 provinces (cities) show a relatively large rebound, basically reaching the maximum in a decade. The reason is that water resources have been strictly managed in recent years, and the upstream and midstream areas have been able to promote economic growth and coordinate the balance of water resources by virtue of their late-stage advantages. And the downstream areas have been optimized through industrial structure, water use structure and water pollution management have been greatly optimized. Thus, the level of WRCC in the whole basin can be rapidly improved. In addition, the "Law of the PRC on the Conservation of the Yangtze (2020)" was passed on December 26, 2020. Further strengthen the protection and supervision of YRB.

Analysis of Subsystem Evaluation Results

Limited by natural water availability and affected by man-made strategies, there are differences in water resources, socio-economic growth patterns and ecological conditions among YRB provinces (cities). Therefore, the WRCCs of 11 localities and municipalities show some spatial heterogeneity. To more clearly reflect the variability exhibited by regions at the subsystem level. This research performs entropy-weight-TOPSIS synthesis calculations on the social subsystem, economic subsystem, and Natural Compound Ecosystem subsystem affecting WRCC. This results in a composite score value for each subsystem for the period 2012-2021.

Social Subsystem

The distribution of social subsystems in YRB is relatively stable (Table 2). First, the degree of social subsystem development in downstream regions is positive and shows a gradual increase. From 2012-2016, most of the economic subsystem scores of Anhui, Shanghai and Jiangsu varied between 0.15-0.35. from 2016-2021, the economic subsystem scores of the three provinces were higher, with the best development in the Anhui region. during 2016-2021, Shanghai's scores were lower than those of Anhui and Jiangsu, but the overall level was stable, with no years of significant decline. Second, within the mid-stream region, the social subsystem score in Jiangxi is an exceptional case. The rest of the time except for 2016 shows a relative decrease in the degree of development. Overall, the degree of economic progress is polarized between the downstream and upstream areas of the YRB.

Economic Subsystem

The Economic subsystem of YRB is more evenly distributed (Table 3). First, the WRCC scores for the Economic subsystem in both the midstream and downstream regions are located near 0.50 for the years 2012-2021. The scores of individual years are around 0.20. Second, Yunnan has the lowest Economic subsystem score among the upstream regions. The Yunnan Economic system index has been around 0.35 for many years, and even dropped to about 0.25 in individual years. This indicates a comparatively weak economic subsystem in the region. This is mainly due to the fluctuating downward trend of the data for the indicators of completed investment in wastewater treatment projects (E5) and local financial expenditure on environmental protection (E6) in the Economic sub-system of Yunnan. Third, the carrying capacity scores of the Economic subsystem in YRB regions are high during 2016-2021, mostly around 0.55. This indicates that the YRB is strengthening the treatment of pollution in the Yangtze River waterway environment to form the mainstream compensation system. Regional

Table 2. Social subsystem evaluation score 2012-2021.

Areas	Upstream areas					Midstream areas			Downstream areas		
Year	Chongqing	Szechwan	Yunnan	Tibet	Qinghai	Jiangxi	Hubei	Hunan	Anhui	Shanghai	Jiangsu
2012	0.231	0.338	0.091	0.260	0.490	0.209	0.365	0.349	0.086	0.353	0.275
2013	0.181	0.263	0.167	0.350	0.253	0.133	0.378	0.358	0.182	0.366	0.240
2014	0.344	0.306	0.192	0.354	0.388	0.186	0.398	0.416	0.250	0.429	0.173
2015	0.248	0.349	0.272	0.311	0.297	0.224	0.415	0.491	0.341	0.515	0.330
2016	0.405	0.445	0.361	0.608	0.441	0.580	0.530	0.371	0.455	0.645	0.509
2017	0.493	0.543	0.420	0.713	0.483	0.249	0.501	0.309	0.491	0.521	0.533
2018	0.548	0.620	0.457	0.694	0.583	0.256	0.496	0.348	0.609	0.580	0.558
2019	0.572	0.643	0.552	0.769	0.613	0.329	0.457	0.594	0.653	0.692	0.607
2020	0.819	0.698	0.693	0.753	0.606	0.355	0.583	0.675	0.934	0.615	0.755
2021	0.890	0.837	0.786	0.699	0.609	0.483	0.594	0.690	0.801	0.647	0.799

Table 3. Economic subsystem evaluation score 2012-2021.

Areas	Upstream areas					Midstream areas			Downstream areas		
Year	Chongqing	Szechwan	Yunnan	Tibet	Qinghai	Jiangxi	Hubei	Hunan	Anhui	Shanghai	Jiangsu
2012	0.513	0.443	0.502	0.213	0.314	0.139	0.372	0.428	0.304	0.322	0.277
2013	0.330	0.334	0.265	0.535	0.529	0.449	0.236	0.500	0.342	0.326	0.401
2014	0.296	0.495	0.266	0.520	0.358	0.338	0.264	0.401	0.216	0.396	0.457
2015	0.515	0.552	0.343	0.275	0.626	0.404	0.385	0.502	0.345	0.241	0.532
2016	0.362	0.432	0.299	0.414	0.431	0.324	0.438	0.531	0.582	0.471	0.575
2017	0.386	0.450	0.380	0.295	0.392	0.362	0.434	0.407	0.401	0.649	0.545
2018	0.433	0.464	0.371	0.315	0.474	0.512	0.543	0.461	0.446	0.44	0.529
2019	0.480	0.561	0.441	0.363	0.625	0.676	0.697	0.515	0.503	0.417	0.540
2020	0.495	0.511	0.478	0.571	0.408	0.535	0.449	0.497	0.368	0.408	0.597
2021	0.537	0.576	0.456	0.536	0.473	0.573	0.550	0.571	0.458	0.462	0.572

governments maintain the water environment of tributaries. Mainly in the form of financial subsidies, industrial support, and talent training.

Natural Compound Ecosystem Subsystem

The Natural Compound Ecosystem subsystem scores of the YRB are highly variable and have a more complex variability (Table 4). First, this variability in scores is specific to downstream regions. In Shanghai and Jiangsu, for example, economic development, population load and urbanization rate growth, high water-consuming industry enterprises still exist in large numbers. This leaves the aquatic environment still facing pressure and the ecology facing grave threats. Second, ratings in the midstream region tend to be in good shape, peaking in 2021. The Natural Compound Ecosystem subsystem scores in Jiangxi, Hubei and Hunan provinces gradually improved during the period 2012-2021. Third, the scoring change in the upstream region is split into two stages. On the one hand, most of the WRCC scores for the Natural Compound Ecosystem subsystem in the upstream region were around 0.35 in 2012-2015. On the other hand, most of the scores for the Natural Compound Ecosystem subsystem in the upstream region lie around 0.55 for the years 2016-2021. This suggests that the overall water quality in the upper areas is good, but some of the tributaries are heavily polluted.

WRCC Evaluation Index Impact Level Analysis

In this study, GRA was applied to rank the correlations of 21 indicators of the WRCC appraisal metric framework of YRB. This yields the extent to which each indicator affects the WRCC. Based on

Table 4. Natural Compound Ecosystem Subsystem Evaluation Score 2012-2021.

Areas	Upstream areas					Midstream areas			Downstream areas		
Year	Chongqing	Szechwan	Yunnan	Tibet	Qinghai	Jiangxi	Hubei	Hunan	Anhui	Shanghai	Jiangsu
2012	0.400	0.369	0.276	0.136	0.354	0.263	0.139	0.210	0.223	0.101	0.256
2013	0.152	0.415	0.142	0.313	0.163	0.259	0.125	0.175	0.212	0.088	0.103
2014	0.498	0.411	0.249	0.367	0.256	0.218	0.241	0.229	0.257	0.497	0.099
2015	0.244	0.377	0.421	0.291	0.208	0.304	0.289	0.248	0.577	0.893	0.322
2016	0.393	0.427	0.623	0.705	0.300	0.366	0.281	0.267	0.807	0.210	0.250
2017	0.383	0.265	0.703	0.528	0.376	0.244	0.252	0.176	0.364	0.14	0.132
2018	0.316	0.496	0.704	0.706	0.674	0.197	0.199	0.161	0.373	0.147	0.120
2019	0.367	0.478	0.280	0.668	0.733	0.264	0.278	0.252	0.320	0.186	0.678
2020	0.584	0.641	0.476	0.650	0.737	0.462	0.604	0.441	0.453	0.226	0.220
2021	0.593	0.545	0.402	0.760	0.730	0.670	0.744	0.877	0.404	0.228	0.228

the YRB scores for the 21 indicators, it was found that the top 5 drivers of the WRCC for the watershed were primarily the social and economic subsystems. The driving degrees are, in descending order, E2 total fish production (0.8780), S6 per capita daily domestic water consumption (0.8640), E3 total agricultural water consumption (0.8630), E4 total industrial water consumption (0.8630) and S7 effective irrigated area (0.8610). Of these five indicators, all are related to people's behavior. This demonstrates that a primary element influencing WRCC in the watershed is man's actions. Among them, three indicators are from the Economic subsystem. It is thus clear that improving the area's economy and strengthening the eco-environment is the keyway to enhance the WRCC level in the basin.

In recent years, YRB has increased its systematic and comprehensive management efforts. The ecological situation has achieved a historic change from severe deterioration in the past to an overall improvement. The forest coverage rate (NCE7) continues to improve, the desertified and sandy land area continues to decrease, and the desert treatment area accounts for 25% of the total area. This phenomenon has effectively improved the ecological conditions of the watershed and improved the regional water resources carrying capacity.

Discussion

(1) The WRCC of YRB showed an overall improvement in the assessment of the bearing level. WRCC comprehensive evaluation index is at 0.099-0.471. Among them, Qinghai (0.099) is in a weak carrying state, while Tibet (0.471) has a relatively high carrying degree of water resources and a large development potential. From 2012 to 2021, the combined level of WRCC shows upstream>midstream>downstream. inter-provincial differences in WRCC are significant, and the top three mean values are Szechwan (0.4721), Qinghai (0.4682) and Tibet (0.4655) in the upstream. The bottom three are Jiangxi (0.3018), downstream Jiangsu (0.3043) and downstream Hubei (0.3778), in that order. The YRB was managed by zoning according to the high and low WRCC. First, the upstream area gives play to the advantages of the water environment and adheres to sustainable development. Second, the midstream region through the orderly transfer of industries, industrial chain extension and optimization of industrial layout. Thirdly, the downstream regions take advantage of economic development to increase pollution control and efficient use of water resources.

(2) In the spatiotemporal pattern evolution, the WRCC level of YRB shows a steady increase in general, and there are disparities between regions. The level of WRCC development from 2012-2021 is specified as a period of fluctuation and decline (2012-2015), recovery (2016-2018), and growth (2019-2021). Although the WRCC in the basin provinces (cities) has been upgraded, the level is not high overall. This indicates that the governance synergy of YRB has not yet been formed, and the level of WRCC is low, with more room for improvement. In recent years, although it has been improved under the promotion of green development concept and water ecological civilization construction, it is still on the verge of serious overload. We are determined to implement a reasonable water resources management policy, promote inter-provincial cooperation and improve horizontal ecological compensation.

(3) In the subsystem division, the bearing power of the 3 subsystems tended to in-crease in general. Social subsystem scores are stable. Economic subsystem scores were balanced. However, the Natural Compound Ecosystem subsystem has a large difference in ratings. It shows that with similar water availability, there are differences in the way of socioeconomic progress and ecological environment construction efforts. This leads to the difference in WRCC grade. YRB should take measures to strengthen water management, strictly control waste sewage discharge and ensure water supply safety. In addition, improve water conservancy projects and establish a water supply guarantee system.

(4) Among the driver associations, E2 total fish production (0.8780) was the most important driver of WRCC. social subsystem, S6 per capita daily domestic water consumption (0.8640) and S7 effective irrigated area (0.8610) also played a strong role in influencing WRCC in YRB. Total agricultural water uses in the Economic subsystem E3 (0.8630), and total industrial water use in E4 (0.8630) similarly had an impact effect. Rajaram et al. showed that anthropogenic factors do influence ecological changes [25].

Conclusions

Water resources are strategic economic resources for basin development and an important guarantee for sustainable development of the basin. Objectively assess the basin WRCC and facilitate the harmonious growth of water sources and economic communities. Although the state of the water conditions in YRB has been on a volatile increase in recent years, the rate of growth has been slow. Therefore, corresponding corrective measures must be actively taken to realize the harmonious growth of water and social economy. The following measures are recommended for the future.

(1) Enhance the agricultural water conservancy project construction and tap the potential of water exploitation. With the growth of residents' consumption level, the demand for water resources has gradually increased. Therefore, YRB must deal with the issue of oversupply of resources at the source. For one thing, the government should increase the financial expenditure on water conservancy infrastructure construction. Strengthen the irrigation project construction. The aim is to ensure a balance between the demand for and provision of water resources and to achieve harmonious

ecological and socio-economic development. On the other hand, the unified management of the water environment is strengthened through the formulation of laws and regulations. Different regions adopt different laws and regulations according to their own characteristics and focus on cooperation in ecological and environmental protection.

(2) Raise consciousness of water saving and strengthen the rational use of natural resources. First, YRB must start with conservation and protection, development and improvement of water-saving processes, and development of high-tech water-saving technologies. In the meantime, government departments develop strategic measures for water conservation and rational configuration of water resources. Second, the total amount of water used in different areas is controlled and rainwater resources are fully utilized. The water environment department coordinates the reuse of sewage treatment to enhance the water ecology of YRB. Third, through the media to promote news about water resources protection, strengthen the awareness of water conservation and environmental protection in the whole society.

(3) Strengthen the planning and management of water sources to realize the best allocation of water sources. First, in terms of economic environment, set appropriate water prices. The establishment of sub-regional, sub-industry water allocation program. Second, in terms of social environment, the adjustment of industrial structure should be increased. For example, to ensure a sustainable supply of water resources for industries with high utilization rate, high added value, low water consumption and low pollution, and to achieve the optimal configuration of water sources. Third, in terms of ecological environment, an ecological protection system is established. The aim is to achieve the integrity of the watershed's water ecosystem to nourish the entire region of the YRB.

Conflict of Interest

The authors declare no conflict of interest.

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