Comprehensive evaluation of water ecological environment in watersheds: a case study of the Yangtze River Economic Belt, China

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Comprehensive evaluation of water ecological environment in watersheds: a case study of the Yangtze River Economic Belt, China

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Abstract

The Yangtze River Economic Belt, as an inland economic zone with global influence, has shown a trend of prosperous economic development in recent years. In 2020, the total population of the Yangtze River Economic Belt accounted for nearly 50% of China's total population, and the GDP has reached 471,580 billion yuan. With economy developing, water pollution, resource depletion and many other environmental problems continue to emerge. Steady state of water ecological environment is an important part of ecological security. In order to investigate the regional water ecological security state, this study constructs a comprehensive evaluation indicator system with the framework of "Driving force-Carrying source-State-Management" (DCSM). The entropy weight method is used to determine the weight of each indicator, and then the weighted rank sum ratio model is introduced to classify the water ecological environment of Yangtze River Economic Belt from 2010 to 2019. Finally, the adversarial interpretative structure model is used to refine the ranking of each region. The results show that (1) The overall state of water ecology in the Yangtze River Economic Belt is at a medium level, with different regional divergent shortcomings in the upper, middle and lower basins. (2) Regional differences are obvious. The overall performance of the upper reaches is stronger than the middle and lower reaches and it can also founded that Zhejiang and Jiangsu present certain particularities which can be concluded as follow: the regions which consider traditional industrialization as the main development path perform worse. (3) It can be seen that from the sub-system level, the carrying state and water ecological management sub-system is highly correlated with the quality of water ecological environment. Therefore, in the future, it is necessary to pay attention to the overall water ecological safety in the basin and promote the sustainable development of water ecology.

Keywords Water ecological environment · The entropy weight method · The weighted rank sum ratio model · The adversarial interpretative structure model · Evaluation · The Yangtze River Economic Belt

Introduction

Water ecology is closely related to human production and life. Besides, the state of water ecological environment can reflect the state of ecological security in many aspects, such as society, economy and nature. Water ecology is regarded as an environmental carrier bearing the pressure of human daily activities. As an environmental carrier bearing the pressure of human daily activities. Its stability and security are vulnerable to external interference and threat, which are concretely showed in the increase of population density, resource consumption and pollutant discharge and other environmental problems. The capacity of water resources must be taken into consideration to maintain the sustainable development of economy and society as well as ecological environment. It can be concluded that a reasonable and reliable regional water ecological evaluation plays an important role in improving the

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quality of water ecological environment.

After the Second World War, the western industrial economy developed rapidly, as a result of which, the industry needed more water and the impact of human beings on the water ecological environment is increasing day by day. In the 1960s, Britain and the United States took the lead in putting forward corresponding requirements for water ecology in environmental law, which is considered to be the beginning of people's attention to water environmental problems. In 1991, Kay and Schneider proposed that the stability of water ecological environment should include two aspects, which were structure and function. In the meantime, they also clarified the source and converging role of water ecological environment in the whole earth ecosystem (Kay and Schneider 1991).

At present, there are many researches on water ecological environment in academia, which are mainly divided into the following aspects: The first aspect are the researches of water ecological environment, which mainly focuses on water ecological protection, carrying capacity calculation, water ecological risk identification and so on. Based on Constanza's theory of ecosystem health (Constanza et al. 1992), Eisela introduced hydrological parameters into water eco-environment assessment and explored the importance of hydrological criteria in river water environment assessment (Eisela et al. 2003). Ghazavi used 7 environmental parameters to characterize the hydrogeological environment in Iran and identified the risk of water pollution in different areas (Ghazavic and Ebrahimi 2015). Leeuwen considered the sustainability of the development of urban water cycle services and carried out water resources management to create space for the optimizing of urban water environment (Leeuwen 2013). Milner monitored the combined effects of glacier changes on rivers and coastal oceans, proving that the shrinking of glaciers has aggravated the ecological pollution of global water environment to a certain extent (Milner et al. 2017). Tian established a water resources carrying system to quantitatively evaluate the spatial and temporal changes of water resources carrying capacity of urban agglomerations in the middle reaches of the Yangtze River from 2012 to 2018, and calculated the coupling coordination degree among various subsystems (Tian et al. 2021).

The second aspect is the construction and application of evaluation index of water ecological environment. The purpose is to establish a reasonable model framework and provide an effective indicator reference for the comprehensive evaluation of water ecological environment in the region. At present, The comprehensive evaluation index system of water ecological environment mainly includes "pressure-state-response" (PSR) framework (Cheng et al. 2013) and "drive-pressure-state-response" (DPSR) framework (Shi et al. 2018), "drive-pressure-state-influence-response" (DPSIR) framework, etc. (Newton et al. 2013). For example, Wang constructed the evaluation index system of water ecological sustainability in Beijing based on PSR model from four aspects of water resources, economy, society and environment (Wang et al. 2018). Huang combined sustainability theory and DPSR framework to construct a water ecology evaluation index system in Yangtze River basin (Huang et al. 2020). Christos used the GIS approach and DPSIR framework to explore the main causes and sources of water ecological stress in the Gallikos Basin in northern Greece from socio-economic and water environmental factors (Christos et al. 2014).

The third aspect researches the choice of water ecological environment evolution methods. At present, the evaluation methods of water ecological security are mainly divided into the following 4 types: water ecological pressure model, spatial statistical model, hierarchical evaluation model and geographic digital model. Among them, the representative methods are fuzzy comprehensive evaluation method, ecological footprint method, gray correlation model, analytic hierarchy process, etc. For example, Lin used TOPSIS model and Monte Carlo simulation method to assess the eutrophication of Erhai Lake Basin in China (Lin et al. 2020). Chen introduced water and carbon indicators into the ecological footprint model, developed a three-dimensional ecological footprint model, and calculated the carbon footprint and water ecological carrying capacity of the Central China Delta from 2000 to 2015 (Chen et al. 2021). Mu established a spatial econometric model to quantitatively study the level of water resources utilization in Northwest China (Mu et al. 2021). Based on system dynamics theory and analytic hierarchy process (AHP), Wang established an index system for water environment assessment of Bosten Lake Basin, which included industry, agriculture, population and other factors (Wang et al. 2018). Based on the analytic hierarchy process (AHP) and geographic remote sensing images, Qiao established a surface water environmental risk index assessment model (Qiao et al. 2021). Zhao used spatial data analysis and geographic and time-weighted regression methods to measure the coupled coordination degree between urbanization and water environment in the Hanjiang River Basin of China (Zhao et al. 2021). Wang introduced fuzzy comprehensive evaluation method, grey correlation analysis and multiple linear regression model into the prediction and evaluation of urban water environment (Wang et al. 2020). Gao introduced the single factor index evaluation method, the fuzzy comprehensive evaluation method and the cloud model, and established the normal cloud-fuzzy evaluation model to study the environmental pollution characteristics of the Qinhuai River in Nanjing (Gao et al. 2019). According to the water environment characteristics of the Three Gorges Reservoir, Li established a grey prediction model (GM) with improved initial index to predict the trend of water environment pollution risk (Li et al. 2017).

Based on the existing research, the combination of ecological models and mathematical methods enriches the content of water ecological environment evaluation, but there are still some deficiencies which can be concluded as follows: first, the water ecological environment evaluation index system is not perfect enough, most of which select mainly social and economic factors, ignoring the indicators of water ecological environment; Second, there is a lack of research on the classification and regional differences of water eco-environment. In order to improve the scientific and reliable evaluation results of the water ecological environment in the basin, it is necessary to seek a more objective and comprehensive evaluation method that takes the actual situation of the region into account. The weighted rank sum ratio model is an evaluation grading model, which uses the transformation of rank to classify the research objects according to the nature of the index. Combined with the adversarial interpretative structure model, the ranking of evaluation objects can be refined, and the influence of the intrinsic correlation of indicators on the evaluation results can be explored. Therefore, this paper takes the Yangtze River Economic Belt as the research object, comprehensively measures the impact of industrial, agricultural and domestic pollution emissions on the water ecological environment, and constructs a comprehensive evaluation index system of water ecological environment based on the framework of “driving force-carrying source-carrying state-management” (DCSM).Then, the classification results of water ecological status in the Yangtze River Economic Belt from 2010 to 2019 are calculated by using the entropy weight method, the weighted rank sum ratio model, and the adversarial interpretative structure model, and identifies the differences between regions . It is hoped to provide a scientific basis for promoting the sustainable utilization of water resources, the coordination of economic and social development with ecological environmental protection in the Yangtze River Economic Belt.

Research methods and models

Entropy weight method

Entropy weight method is an objective assignment method, which obtains weights based on the information entropy of each indicator. Generally, the smaller the information entropy of an indicator means the greater its indicator variability and the greater the weight is. Otherwise, it is smaller (Zhang et al. 2021; Zheng et al. 2018; Lv et al. 2020). The calculation steps are as follows.

Assume that the original evaluation indicators matrix is as below:

$$\begin{bmatrix} o_{11} & o_{12} & \cdots & o_{1m} \\ o_{21} & o_{22} & \cdots & o_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ o_{n1} & o_{n2} & \cdots & o_{nm} \end{bmatrix} \tag{1}$$

The dimensions of each evaluation indicators are different, and the original matrix is standardized:

Positive indicators:

$$u_{ij} = \frac{o_{ij} - min(o_j)}{max(o_j) - min(o_j)} \tag{2}$$

Negative indicators:

$$u_{ij} = \frac{max(o_j) - o_{ij}}{max(o_j) - min(o_j)} \tag{3}$$

The normalized matrix is as follows:

$$\mathrm{U} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1m} \\ u_{21} & u_{22} & \cdots & u_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ u_{n1} & u_{n2} & \cdots & u_{nm} \end{bmatrix} \tag{4}$$

The weight matrix is calculated as shown in formula (5):

$$\omega_j = \frac{1 - e_j}{m - \sum_{j=1}^{m} e_j} \tag{5}$$

In this formula, $e_j = -\frac{1}{\ln(n)} \sum_{j=1}^{m} p_{ij} \ln p_{ij}$, $p_{ij} = \frac{u_{ij}}{\sum_{j=1}^{m} u_{ij}}$,and ln0=0.The entropy weight method is used to calculate the weight matrix W = (ω_1 ω_2 $\cdots$ ω_m).

Weighted rank sum ratio model

The rank sum ratio (RSR) model is mainly applied to the comprehensive rating of statistical analysis, which was proposed by Chinese statistician Tian Fengdiao in 1988. The basic idea is to obtain a dimensionless statistic RSR through rank transformation in the data matrix, and then classify the evaluation object based on the result. The larger the RSR value indicates the better comprehensive evaluation (Li et al. 2010; Chen et al. 2015). The weighted rank sum ratio model (WRSR) fully considers the indicators weights on the basis of RSR and is more sensitive to small changes within the indicators. Compared with TOPSIS, DEA, AHP, etc. , the weighted rank sum ratio model can avoid the influence of subjective opinions and make the evaluation results more objective (Tan et al. 2017). The weighted rank sum ratio model contains three elements: rank, indicator weights, and Probit. Among them, the rank means the ranking of the sample under the indicator. Under positive indicators, the smaller the rank is, the better the performance is, which is opposite to negative indicators. The indicator weight indicates the importance of the indicator, and Probit is the probability unit corresponding to the weighted rank sum ratio result, which can reflect the fitting degree of the model. The calculation process of the weighted RSR model is as follows:

(1) In the matrix of indicators, the evaluation indicators are composed of positive indicators and negative indicators, the positive indicators are positively correlated with the evaluation results and ranked from smallest to largest, while the negative indicators are on the contrary.

(2) WRSR is obtained by combining rank and weight, which is shown in below formula (6):

$$WRSR_i = \frac{1}{n}\sum_{j=1}^{m} \omega_j \cdot R_{ij} \tag{6}$$

In the formula, n and m respectively represent the number of evaluation objects and the number of indicators. ω_j is the weight of the j-th indicator denoting the rank order of the sample in the i-th row under the j-th column of indicators.

(3) Calculating the WRSR of objects and ranking them from the smallest to the largest. The downward cumulative frequency is calculated, and the corresponding Probit is solved. Finally, it is necessary to carry out regression analysis, and calculate the corresponding regression equation according to the least square method.

(4) Based on the classification standard and linear image, the classification threshold can be determined, and the grade of each evaluation object also can be obtained.

Adversarial interpretative structure model

The adversarial interpretative structure model (AISM) is proposed based on the interpretative structure model (ISM) and can be used to analyze the relationship of factors in complex systems (Tan et al. 2019), which integrates the game adversarial idea in the traditional ISM, establishes the simplest hierarchical directed topological hierarchical graph with adversarial idea based on the reachable matrix obtained from the relational matrix and the principle of opposite level extraction. Due to the complexity of the extraction method, the analysis result is a set of opposite level topological graphs, which can achieve a more detailed hierarchical division of the research samples (Zhang et al. 2021). The specific calculation process is as follows:

(1) In a decision matrix D with m columns, there are m different indicator dimensions. The positive indicators are recorded as $p1$, $p2 \cdots pm$; the negative indicators are recorded as $q1$, $q2 \cdots qm$. For any two rows x, y satisfy:

Positive indicators: $d_{(x,p1)} \geq d_{(y,p1)}$ and $d_{(x,p2)} \geq d_{(y,p2)}$ and $\cdots$ and $d_{(x,pm)} \geq d_{(y,pm)}$.

Negative indicators: $d_{(x,q1)} \leq d_{(y,q1)}$ and $d_{(x,q2)} \leq d_{(y,q2)}$ and $\cdots$ and $d_{(x,qm)} \leq d_{(y,qm)}$.

(2) The partial order relation between x and y is written as: $x \prec y$, which means that the element y is superior to the element x. That is, given the partial order set (D, $\prec$), $\forall d_i, d_j \in$ D, if $d_j \prec d_i$, then $a_{ij} = 1$, if $d_i \prec d_j$, then $a_{ij} = 0$. The relationship matrix A = $(a)_{n\times n}$ is obtained.

(3) Calculating the reachable matrix of the relation matrix A, which is shown in formulas (7) and (8):

$$\mathrm{B} = \mathrm{A} + \mathrm{I} \tag{7}$$

$$\mathrm{B}^k = \mathrm{B}^{k+1} = \mathrm{R} \tag{8}$$

In these formulas, B is a multiplication matrix, I is an m-order Boolean square matrix with a diagonal of 1. The reachable matrix R can be obtained by multiplying B. It can be concluded matrix R = A.

(4) The result of the hierarchical graph is determined by the antecedent set Q, the common set T and the reachable set R. In the relational matrix A, its elements meet the following requirements: the

antecedent set $Q(e_i)$ is all elements corresponding to column 1; The reachable set $R(e_i)$ is all the elements corresponding to line 1. The common set $T(e_i)$ is the intersection of both.

(5) Divide the hierarchy according to the priority of the results, let $R(e_i) = T(e_i)$, and place the extracted samples in the order from top to bottom to obtain the UP type hierarchical graph. Divide the hierarchy according to the priority of causes, let $Q(e_i) = T(e_i)$, and place the extracted samples in the order from bottom to top to obtain the DOWN type hierarchy graph. Up type and DOWN type are a set of opposite extraction results, the Pareto optimal sample is at the top level, and the worst sample is at the bottom level. The order of study objects can be determined according to the results.

Steps of regional water ecological environment assessment based on WRSR and AISM

(1) Construct a regional water ecological environment evaluation indicator matrix $O = [o_{ij}]_{n\times m}$, n represents the number of samples, m represents the number of water ecological environment indicators, and the matrix $U = [u_{ij}]_{n\times m}$ is obtained by normalization operation.

(2) Based on the entropy weight method to determine the weight of each indicator, the weight matrix is $W = \{ \omega_1, \omega_2, \cdots \omega_m \}$.

(3) The WRSR and the cumulative frequency corresponding to the n samples are obtained according to the formula (6). With the Probit value as the independent variable and WRSR as the dependent variable, n groups of (Probit, WRSR) data are linearly fitted, and the partial differential of error is calculated. The general formula of the linear fitting is $y=a+bx$, which can be expressed as:

$$\overline{WRSR} = a + b \cdot Probit \tag{9}$$

(4) Consistency testing of the fitted results. Based on previous experience, the Kendall test in discrete data context is generally used as shown in formula (10) (Betensky et al. 1999). W_k is the Kendall concordance coefficient.

$$W_k = \frac{12 \cdot n\left(\sum_{i=1}^{n} WRSR_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} WRSR_i\right)^2\right)}{n^2 - 1} \tag{10}$$

(5) The linear images are classified according to the Probit, and the evaluation results are tested by hypothesis.

(6) WRSR and Probit are combined to form a decision matrix and the corresponding reachable matrix is calculated according to the partial order rule, formulas (7) and (8), the antecedent set and the reachable set are extracted.

(7) The samples are placed according to the result priority rule and cause priority rule, respectively, and a set of UP type, DOWN type directed topological hierarchical graphs with adversarial properties are obtained. Considering the adversarial structure and Pareto optimality principle, the highest level element intersection set is taken as the optimal sample and the lowest level element intersection set is taken as the worst sample. Each level determines the ranking of evaluation samples, from which the final comprehensive evaluation results can be obtained.

Research materials

Research area

The Yangtze River Economic Belt is an extremely large economic development area dominated by the urban agglomerations of Yangtze River Delta , the middle reaches of the Yangtze River and Chengdu-Chongqing, covering Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan and Guizhou. Recently, the Yangtze River Economic Belt has developed rapidly, with its total population accounting for nearly 50% of China's total population. Besides, its GDP exceeds 4.7 billion yuan, accounting for 46.4% of China's overall GDP. The Yangtze River Economic Belt is an inland river economic zone with global influence because of its developed water system and abundant resources. However, in recent years, it has faced with problems such as excessive concentration of heavy chemical industry and inefficient utilization of water resources which leads to the water ecological environment in poor condition. Thus, carrying out water ecology protection work is of great urgency.

Evaluation indicator system construction

Due to the particularity of water ecological environment and the availability of indicator data, a comprehensive evaluation indicator system of water ecological environment in Yangtze River Economic Belt is constructed based on the DCSM framework of "Driving force - Carrying source - State - Management". In this framework, D is the support effect of water environment on human production activities and regional development driving factors, C is the pollution source of water ecological environment brought by social production activities, S is the state of water ecological environment under pressure, and M reflects the water ecological management measures and the ability of society to regulate water pollution. The evaluation indicator system is divided into 4 standard layers, including 21 evaluation indicators, as shown in Table 1.

Result

The analysis of indicator weights

The evaluation indicator matrix is formed by weighted average of the original data over the years. The weights of each indicator are calculated by the entropy weight method, and the calculation results are shown in Table 1. In the indicator layer, Wastewater discharge of industrial added value of 10,000 yuan > Water consumption per 10,000 yuan of industrial gross product > Water consumption per 10,000 yuan of tertiary gross domestic product > GDP per capita > Investment in treatment of " three wastes " > Industrial wastewater reuse rate > Water resources development and utilization rate > Proportion of environmental protection investment in regional GDP > Output of industrial solid waste > Regional green coverage rate > Regional forest coverage > Water resources per capita > Current water quality compliance rate > Average water consumption per acre of regional farmland > Domestic waste pollution per capita > Park area per capita > Urbanization rate > Proportion of environmental infrastructure investment to fixed asset investment > Urban per capita water consumption > Water consumption per 10,000 yuan of agricultural gross product > Average agricultural pollution discharge of gross agricultural output. In the criteria layer, the indicator weights are ordered as follows: Driving force > State > Carrying source > Management.

Table 1 Comprehensive evaluation indicator system of water ecological environment in Yangtze River Economic Belt

Target layer	Criterion layer	Indicator layer	Type	Weight
Regional water ecological environment evaluation	Driving force	Water consumption per 10,000 yuan of agricultural gross product (D1)	−	0.0206
		Water consumption per 10,000 yuan of industrial gross product (D2)	−	0.0926
		Water consumption per 10,000 yuan of tertiary gross domestic product (D3)	−	0.0856
		GDP per capita (D4)	+	0.0816
		Urbanization rate (D5)	−	0.0251
	Carrying source	Wastewater discharge of industrial added value of 10,000 yuan (C1)	−	0.0969
		Output of industrial solid waste (C2)	+	0.0486
		Average water consumption per acre of regional farmland(C3)	−	0.0285
		Average agricultural pollution discharge of gross agricultural output(C4)	−	0.0181
		Urban per capita water consumption (C5)	−	0.0243
		Domestic waste pollution per capita (C6)	−	0.0277
	State	Water resources development and utilization rate (S1)	−	0.0559
		Water resources per capita (S2)	+	0.0320
		Industrial wastewater reuse rate (S3)	+	0.0756
		Current water quality compliance rate (S4)	+	0.0307
		Regional green coverage rate(S5)	+	0.0433
		Regional forest coverage (S6)	+	0.0343
		Park area per capita (S7)	+	0.0269
	Management	Proportion of environmental protection investment in regional GDP (M1)	+	0.0504
		Proportion of environmental infrastructure investment to fixed asset investment (M2)	+	0.0249
		Investment in treatment of "three wastes" (M3)	+	0.0764

The analysis of regional classifications

According to the weighted rank sum ratio model and the least square method, the downward cumulative frequency and the corresponding standard normal deviation μ are calculated by using MATLAB, and the unit probability value (Probit) is obtained. The regression analysis is performed with WRSR as the dependent variable and Probit as the independent variable. The regression equation is obtained as follows:

$$\overline{WRSR} = 0.044 + 0.097 \cdot Probit \tag{11}$$

The regression equation is tested by parameters and the correlation coefficient r^2=0.58968, with a linear positive correlation between $\overline{\text{WRSR}}$ and Probit. F=78.19, $P < 0.01$, which prove that the regression equation is statistically significant.

Based on previous researches (Wang et al. 2021; Sun et al. 2017; Du 2020), the water ecological environment evaluation results can be classified into the following 4 levels: level I (poor), level II (medium), level III (good), and level IV (excellent). Hypothesis test on the results of classification:

Original hypothesis is H_0: The evaluation results are not correlated, and each evaluation indicator and the classification results are independent of each other.

Alternative hypothesis is H_1: The evaluation results are correlated, and each evaluation indicator is not independent from the classification results.

Formula (10) is used to calculate W_k= 0.1137, which satisfies $D(n-1)\cdot W_k \sim \chi^2(n-1)$ and $p >$ 0.1137. The original hypothesis is accepted. The classification results are independent of each other. The linear model is statistically significant. The results of each parameter are shown in Table 2. The classification results of water ecological environment in the Yangtze River Economic Belt are shown in Table 3, and the linear regression image is shown in Figure 1.

Table 2 Results of WRSR, Probit and other parameters

Province	*WRSR*	Downward cumulative frequency	*Probit*	$\overline{WRSR}$
Shanghai	0.4015	9.09	3.6592	0.3989
Hunan	0.4387	18.18	4.0884	0.4406
Hubei	0.4826	27.27	4.3932	0.4701
Chongqing	0.4890	36.36	4.6495	0.4950
Sichuan	0.5296	45.45	4.8844	0.5178
Jiangxi	0.5614	54.55	5.1130	0.5400
Anhui	0.5635	63.64	5.3478	0.5627
Guizhou	0.5717	72.73	5.6038	0.5876
Yunnan	0.5767	81.82	5.9078	0.6171
Jiangsu	0.5975	90.91	6.3346	0.6585
Zhejiang	0.7879	97.73	6.9954	0.7226

Table 3 Classification results of water ecological environment in the Yangtze River Economic Belt

Level	Probit	$\overline{WRSR}$	Classification results
I (poor)	(-∞,4]	(-∞,0.432]	Shanghai
II (medium)	(4,5]	(0.432,0.529]	Hunan, Hubei , Chongqing, Sichuan
III (good)	(5,6]	(0.529,0.626]	Jiangxi, Anhui, Guizhou, Yunnan
IV (excellent)	(6,+∞)	(0.626,+∞)	Jiangsu, Zhejiang

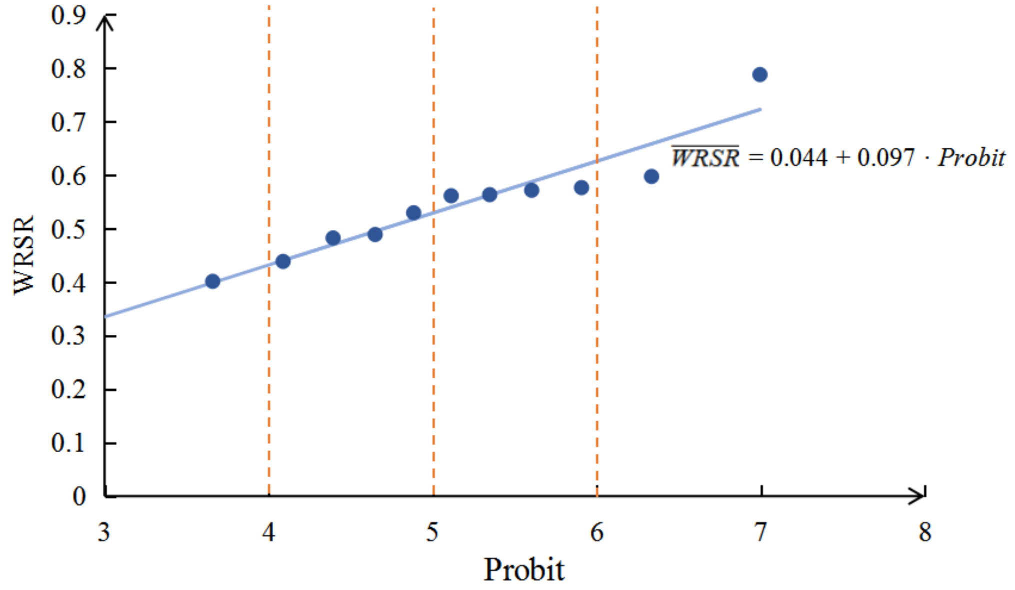

Fig.1 Linear regression image and classification

During the study period, the regional differences of water ecological environment in 11 provinces of the Yangtze River Economic Belt are obvious, which can be divided into four grades. There are two provinces with excellent water ecological environment grade, namely Zhejiang and Jiangsu, with $\overline{WRSR}$ greater than 0.626.There are four provinces in good grade, which are Yunnan, Guizhou, Anhui and Jiangxi respectively, with (0.529, 0.626] $\overline{WRSR}$. There are 4 provinces in the middle grade, namely Sichuan, Chongqing, Hubei and Hunan, with (0.432, 0.529] $\overline{WRSR}$. There is one province in the poor grade, namely Shanghai, with $\overline{WRSR}$ less than 0.432. It can be concluded that there are 6 provinces with good grade or above, accounting for 54.5% of the total sample. In general, most provinces of the Yangtze River Economic Belt are in the lower middle level, and the reasons for the classification differences are illustrated as follows:

As the core area of the Yangtze River Economic Belt, Zhejiang and Jiangsu province, with excellent water ecological environment, has its advantages in the control of carrying sources and the adjustment of carrying state. For example, Zhejiang province has paid more attention to the discharge of industrial solid waste and recycling of waste water, and clarified the water ecological pollution caused by traditional industries. The measure of comprehensive treatment has relieved the pressure of water environment brought by industrialization to a certain extent. While Jiangsu tends to strengthen the supervision of water quality, it has continuously issued environmental protection policies and enhanced the protection of water ecological environment by means of management, which has effectively curbed the development trend of water pollution.

Yunnan, Guizhou, Anhui and Jiangxi have gained higher water ecological environment assessment as a result of natural conditions, but there is still a certain gap compared with excellent provinces. In terms of Anhui and Jiangxi, they invest a lot in urban environmental infrastructure and pay attention to the control of pollution and water quality. However, they also face with the challenges of industrial water efficiency and improvement of consumption structure. As an ecological barrier in the upper reaches of the Yangtze River, Yunnan has been continuously promoting the development of science and technology agriculture in recent years, and achieved remarkable results. However, the low level of industrialization has brought about large waste water discharge and less investment in pollution control, which has a direct negative impact on the water ecological environment. Industrial innovation and transformation are still complicated task.

From above forms, we can conclude that the area with medium water ecological environment is Hunan, Sichuan, Chongqing as well as Hubei and the area with poor water ecological environment is Shanghai. Combined with the overall index, it can be seen that most provinces are faced with problems such as imbalance of ecological structure and water environment, indicating that regional production factors have not been reasonably allocated and traditional industries have not been substantially updated, resulting in poor regional water ecological environment quality. Besides, the state of water ecology in Shanghai and Hubei is also not optimistic. As for Hubei, it also has went through challenges including the low efficiency of water resources allocation and utilization, the insufficient ecological optimization ability and the low water resources. Shanghai is located in the eastern lower reaches of the Yangtze River and has a large population density. Shanghai is mainly burdened with upstream water pollution pressure, thus it is difficult to reduce the water environment effectively in a short time. Therefore, it is necessary to pay attention to the population agglomeration and resource consumption caused by urbanization, which affect the water ecological environment.

The analysis of regional rankings

The weighted rank sum ratio model divides the water ecological environment of the 11 provinces in the Yangtze River Economic Belt into four grades, but it cannot carry out a more detailed ranking of the advantages and disadvantages of each region. Therefore, adversarial interpretative structure model (AISM) is introduced to determine the water ecological environment ranking in the Yangtze River Economic Belt provinces. In this study, the corresponding Probit value of each province is taken as the decision matrix, and the reachable matrix can be obtained according to partial order rules and formula (7) and formula (8), which is shown in Table 4. Then, level extraction is carried out to obtain the confrontational level topology shown in Figure 2.

Table 4 Reachable matrix

$R_{11\times11}$	Shanghai	Jiangsu	Zhejiang	Anhui	Jiangxi	Hubei	Hunan	Chongqing	Sichuan	Guizhou	Yunnan
Shanghai	1	1	1	1	1	1	1	1	1	1	1
Jiangsu	0	1	1	0	0	0	0	0	0	0	0
Zhejiang	0	0	1	0	0	0	0	0	0	0	0
Anhui	0	1	1	1	0	0	0	0	0	1	1
Jiangxi	0	1	1	1	1	0	0	0	0	1	1
Hubei	0	1	1	1	1	1	0	1	1	1	1
Hunan	0	1	1	1	1	1	1	1	1	1	1
Chongqing	0	1	1	1	1	0	0	1	1	1	1
Sichuan	0	1	1	1	1	0	0	0	1	1	1
Guizhou	0	1	1	0	0	0	0	0	0	1	1
Yunnan	0	1	1	0	0	0	0	0	0	0	1

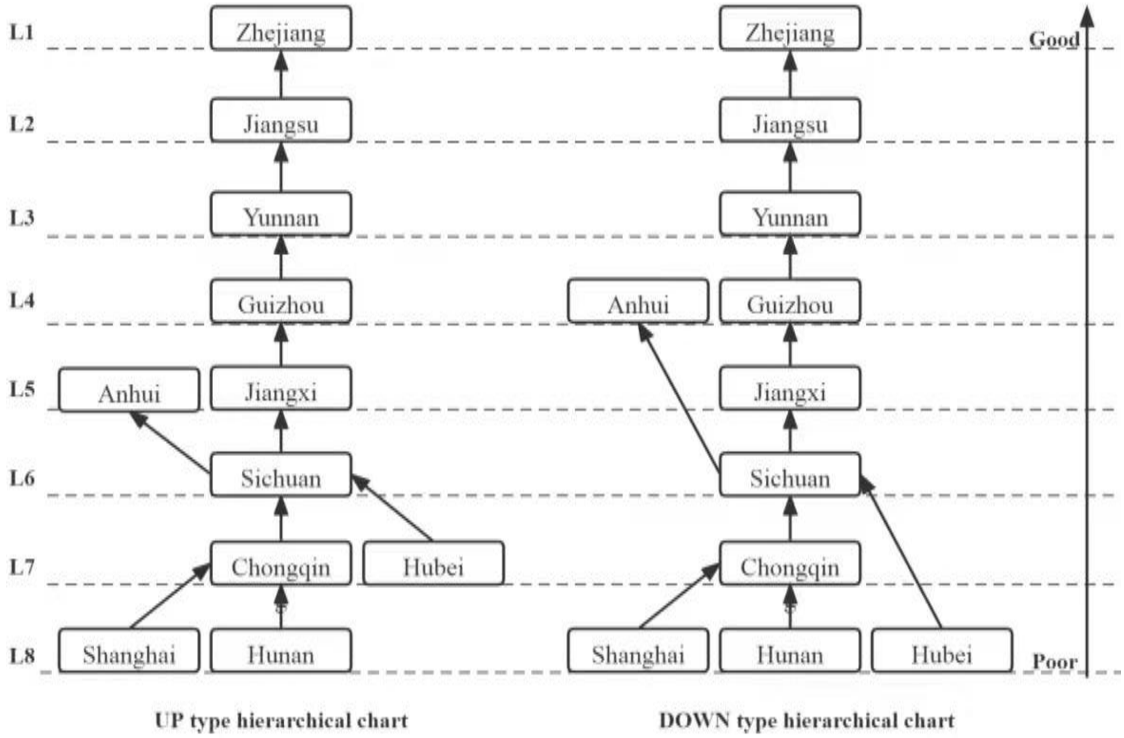

Fig. 2 Adversarial hierarchical topology graph

In the hierarchical topology of UP and DOWN (Figure 2, respectively), the samples of all provinces were arranged hierarchically and orderly. The sample province of the root layer contains only a single firing arrow, which is generally the lowest level of the topological system. Its function is to calculate the intersection of the lowest level of the two hierarchical graphs, namely {Shanghai, Hunan} ∩ {Shanghai, Hunan, Hubei} = {Shanghai, Hunan}. Similarly, the result layer is the uppermost sample, which calculates the intersection of the uppermost layer, namely {Zhejiang} ∩ {Zhejiang} = {Zhejiang}. In this paper, the analysis of the uppermost sample, the middle sample and the bottom sample is as follows.

In the topological diagram, the topmost L1 province sample is Zhejiang, and the other samples are in the middle and bottom layer. There are many topological systems, which indicates that the water ecological environment level of the Yangtze River basin is different and the regional heterogeneity is prominent. As the top sample of the main line of the two maps, Zhejiang has an absolute advantage in its water ecological environment from 2010 to 2019. It shows that the implementation of sustainable development strategy can effectively cope with various ecological pressure factors and make the water eco-environment stay in good state.

The middle layer contains samples from Jiangsu, Yunnan, Guizhou, Anhui, Jiangxi, Sichuan, Chongqing and Hubei, which are distributed in L2 to L7 levels. According to the division principle that the better the high level, the worse the lower level, it can be seen that the water ecological environment status of the 8 provinces becomes worse successively. The comparison of the 2 topological maps shows that the ordering of the main line samples is consistent, indicating that the spatial disequilibrium caused by ecological resource endowment is an important reason for the regional differences of water ecological environment during the study period. The hierarchy changes in Anhui and Hubei indicate that the system is extensional. Besides, compared with other provinces, the water ecological environment of these 2 samples is more unstable, which needs to be improved greatly. The transformation from extensive development of traditional energy to high quality energy saving industry can reduce the poor state of water ecosystem. In addition, the ecological management of the government also plays a role to some extent, which ensures the regional economic development. However, it is also necessary to strengthen water recycling utilization to make a real difference.

Shanghai and Hunan are at the bottom of L8 indicating the water ecological environment in these two areas is affected by agricultural non-point source pollution and insufficient water resource supply, which lead to the worse state of the water ecological environment. It also proves that the traditional treatment methods can no longer adapt to the current needs of ecological development. Thus, it is urgent to change the way of thinking, strengthen the guiding role of policy, and improve the integrated capacity of pollution treatment.

Discussion

As a country with fragile water ecological environment, China's water ecological problem has gradually become an important constraint factor for sustainable economic and social development. The study of water ecological environment assessment can provide scientific basis for promoting ecological civilization construction and optimizing resource allocation.

At present, many scholars have carried out regional water ecological environment assessment research. For example, using survey data from 2010 to 2018, Zhao quantitatively analyzed the water ecosystem service capacity of Taihu Lake in China using functional classification (Zhao et al. 2021). Han used the coupling coordination degree model to analyze the coordination relationship between urbanization and water ecosystems in the Yangtze River Economic Belt and combined it with a barrier degree model to diagnose the key barrier factors of water ecosystems (Han et al. 2019). Abdi-Dehkordi adopted system dynamics method to model integrated water resources system of Big Karun Watershed in Iran. The distributed zoning model was also used to evaluate the sustainability and integrated management capability of water system (Abdi-Dehkordi et al. 2021). Currently, there are many methods of water ecological comprehensive evaluation, while the studies on the spatial difference of water ecological environment in the basin are rare. Though the current method can grade the evaluation object, it is still in low possibility to give a accurate hierarchical division based on performance indicators.

Based on the fact, this paper introduces the weighted rank sum ratio model to grade the water ecological environment status of the Yangtze River Economic Belt. Besides, the paper also combines with the ranking of evaluation objects in adversarial interpretative structure model to avoid the subjectivity and randomness of the evaluation process. In the way, the assessment results tend to be more accurate and objective. The weighted rank sum ratio model can reflect the slight changes of all the indicators and is suitable for all kinds of grading evaluation. The adversarial interpretative structure model fully considers the internal differences and relationships of evaluation objects and visualizes the grading results, which leads to the formation of topological hierarchical structure map with directed properties. At present, a great deal of researches on this field have been conducted. However, most scholars are limited to the analysis of ecological indicators and regional status in the comprehensive evaluation of water ecological environment. Compared with previous studies, this paper combines the actual situation of regional water ecological environment with previous studies to quantify the evaluation indexes reasonably, so that the evaluation results are more consistent with the actual situation of the research area. Furthermore, this paper also optimizes the indicator system by adopting water ecological management indicators, and clarifies the differences and the restricting factors of water ecological environment in each region of the basin. Based on this, the feasible development countermeasures and suggestions are put forward.

However, there are some weaknesses in this study. In terms of research methods, the weighted rank sum ratio model relies on the rank of the original data, which may be biased in classification and archiving. The adversarial interpretative structure model only divides the hierarchy of the research object making it difficult to explore the coupling relationship between the indicators. In terms of research content, different regions have varied water ecological conditions, causing the evaluation indicator system may not be perfect. It is hoped that the future research should study how to construct a scientific evaluation indicator system of water ecological environment and optimize the research content.

Conclusion and suggestion

Conclusion

As an important part of the earth's natural environment, water ecological environment is the basis for human survival. On the premise of ensuring the sustainable development of water ecological environment, promoting the overall green transformation of economy and society is the focus of water ecological civilization construction at the present stage. As the most developed inland river basin in China, the Yangtze River Economic Belt has faced with a series of water ecological environment problems in the process of economic development. Therefore, it is of strategic significance to study the state of its water ecological environment. Based on the DCSM framework, the comprehensive evaluation indicator system of water ecological environment was established in this paper. Besides, the paper also adopts the entropy weight method to determine the weight. Significantly, the weighted rank-sum ratio model and adversarial interpretative structure model was introduced to evaluate the water ecological environment state of the Yangtze River Economic Belt from 2010 to 2019. Finally, the conclusions are made as follows:

(1) From the perspective of geographical distribution, the Yangtze River Economic Belt has presented great regional differences in areas with the upper showing a good water ecology, and the middle and lower reaches polarized. The areas with good water ecological grade and above are mostly located in ecological demonstration area and green industry development area, while the middle areas nearly lie in traditional industry transformation provinces. The poor area is characterized by extensive industrial agglomeration and high degree of ecological development.

(2) From the perspective of water ecological index system, the results of water ecological classification are affected by multiple subsystems. The reuse rate of industrial wastewater, water consumption and industrial value-added wastewater discharge has a significant impact on the state of water ecological environment, which further confirms that the pollution of production activities has a strong inhibition effect on the sustainable development of water ecological. Therefore, in the future, it is necessary to pay attention to the coordinated development of all subsystems.

(3) It finds that the overall water ecological environment of the Yangtze River Economic Belt is in middle state and the problems such as insufficient investment in environmental protection and low utilization rate of water resources are prominent. Though the government management and regulation is beneficial to the sustainable development of water ecology, it still lacks of

comprehensive and powerful reform. In the future, it is hoped to optimize the investment and financing structure of water environment governance, promote the participation of the whole society, and then realize the improvement of the overall state of regional water ecological environment.

Suggestion

(1) In the future development, the Yangtze River Economic Belt should focus on economic transformation, strengthen industrial pollution control and pay attention to water pollution recycling. Besides, the chemical production enterprises should be classifies and regulated to conform to the low-carbon strategy and achieve high-quality economic development.

(2) The assessment of water ecological security should be accelerated. It is also of great significance to establish a sound legal system, and give full play to the supervision role of ecological and environmental protection departments. Rectifying the prominent water environment problems in the Yangtze River basin is an important task. Moreover, the government and enterprises should fulfill their legal responsibilities to provide organizational guarantee for the ecological environment supervision of the Yangtze River, and create a social atmosphere of co-governance and co-management.

(3) It is necessary to actively respond to the national carbon neutral development strategy and raise the awareness of water ecological protection throughout the society. To make a difference, all regions should be guided in formulating differentiated environmental standards to carry out water ecological environment restoration work in light of local conditions. Rational planning of water resources is also in great need to achieve positive interaction between upstream, middle and downstream industries, which will provides ecological guarantee for deepening supply-side reform.

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Data availability Data used in this manuscript is available from http://www.yangtze.org.cn/, http://www.craes.cn/ and http://www.mwr.gov.cn/.

Declarations

Ethics approval We declare that this manuscript has complied with all the ethical requirements of the journal.

Consent to participate All authors of this manuscript have agreed to participate in the writing of the manuscript.

Consent for publication All the authors of this manuscript consented to its publication.

Competing interests The authors declare no competing interests.

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