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RESEARCH ARTICLE

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, an inland economic zone with global influence, has shown a trend of prosperous economic development in recent years. Economic development, water pollution, resource depletion, and other environmental problems continue to emerge. The steady state of the water ecological environment is an important aspect of ecological security. To investigate the regional water ecological security state, this study constructs a comprehensive evaluation indicator system within the framework of "driving force-carrying source-state-management" (DCSM). The entropy weight method was used to determine the weight of each indicator, and the weighted rank sum ratio model was introduced to classify the water ecological environment of the Yangtze River Economic Belt from 2010 to 2019. Finally, an adversarial interpretative structure model is used to refine the ranking of each region. The results show that the bearing state and driving force subsystems are closely related to the water ecological environment. The top three indicators are wastewater discharge of industrial added value of 10,000 yuan, water consumption per 10,000 yuan of industrial gross product, and water consumption per 10,000 yuan of tertiary gross domestic product. In addition, there are clear differences in the water ecological environment of the Yangtze River Economic Belt. The classification results show that Zhejiang and Jiangsu are rated as "excellent''; Yunnan, Guizhou, Anhui, and Jiangxi are in the "good" level; and Sichuan, Hunan, Chongqing, and Hubei are in the "medium" level. Shanghai is "poor." As a whole, the downstream is superior, the upstream is second, and the midstream is poor in an asymmetric "U"-shaped distribution. During the study period, the overall state of water ecology in the Yangtze River Economic Belt was at a medium level and has not yet reached a safe and steady state. The performance of areas with traditional industrialization as the main development path was poor. Therefore, it is necessary to pay attention to the overall water ecological security in the basin in the future, strengthen the regulatory role of the government's water ecological management, promote reform of traditional industries and resource-based regions, and achieve the sustainable development of the water ecological environment.

Keywords Water ecological environment · Entropy weight method · Weighted rank sum ratio model · Adversarial interpretative structure model · Evaluation · Yangtze River Economic Belt

Introduction

As an environmental carrier that bears the pressure of human daily activities, water ecology is closely related to human production and life, and its stability and safety are vulnerable to external disturbances and threats (Kay and Schneider 1992). The specific manifestations include an increase in population density, an increase in resource consumption, and environmental problems, such as excessive pollutant discharge. Sustainable development of the economy and society and maintenance of a good ecological environment must consider the carrying capacity of water resources. Therefore, a reasonable and reliable regional water ecological evaluation is important for improving the quality of the water ecological environment.

At present, there are many researches on water ecological environment in academia, which are mainly divided into the following aspects.

The first aspect is the researches of water ecological environment, which mainly focus on water ecological protection, carrying capacity calculation, water ecological risk

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identification, and so on. Based on Constanza's theory of ecosystem health (1992), Eisela et al. introduced hydrological parameters into water eco-environment assessments and explored the importance of hydrological criteria in river water environment assessments (Eisele et al. 2003). Ghazavi and Ebrahimi used seven environmental parameters to characterize the hydrogeological environment in Iran and identified the risk of water pollution in different areas (Ghazavi and Ebrahimi 2015). Leeuwen considered the sustainability of development of urban water cycle services and carried out water resource management to create space for the optimization of urban water environments (Leeuwen 2013). Milner et al. 2015) monitored the combined effects of glacier changes on rivers and coastal oceans and proved that the shrinking of glaciers has aggravated the ecological pollution of the global water environment to a certain extent (Milner et al. 2017). Tian et al. established a water resource carrying system to quantitatively evaluate the spatial and temporal changes in the water resource carrying capacity of urban agglomerations in the middle reaches of the Yangtze River from 2012 to 2018 and calculated the degree of coupling coordination among various subsystems (Tian et al. 2021). Our research emphasizes the coordination between the water ecological environment and economic development and the maximum pollutant-holding capacity to withstand the discharge of human activities.

The second aspect is the construction and application of an evaluation index for the water ecological environment. The purpose of this study was to establish a reasonable model framework and provide an effective indicator reference for the comprehensive evaluation of the water ecological environment in the region. At present, the comprehensive evaluation of the water ecological environment has not yet formed a unified index system, and the widely used frameworks are the "pressure-state-response" (PSR) framework (Cheng and Li 2013), "drive-pressure-state-response" (DPSR) framework (Shi et al. 2018), and "drive-pressure-state-influence-response" (DPSIR) framework (Newton et al. 2013). For example, Wang et al. constructed an evaluation index system of water ecological sustainability in Beijing based on the PSR model from four aspects: water resources, economy, society, and environment (Wang et al. 2018a, b). Huang et al. combined sustainability theory and the DPSR framework to construct a water ecology evaluation index system for the Yangtze River basin (Huang et al. 2020). Christos et al. 2014 used GIS methods and the DPSIR framework to explore the main causes and sources of water ecological stress in the Gallikos Watershed in northern Greece. (Christos et al. 2014). Although the existing index framework has enriched the evaluation scale of the water ecological environment, the impact of subjective human behavior has been ignored in the evaluation process. Therefore, based on the existing indicator framework, the driving force-carrying source-state-management (DCSM) framework, which includes the management subsystem, is proposed, which emphasizes the regulatory effect of subjective human initiative on the water ecological environment.

The third aspect studied the choice of water ecological environment evolution methods. At present, the evaluation methods of water ecological security are mainly divided into the following three types: water ecological pressure, geospatial, and hierarchical evaluation models. Among them, the representative methods are the fuzzy comprehensive evaluation method, ecological footprint method, gray correlation model, and analytic hierarchy process. For example, Lin et al. used the TOPSIS model and Monte Carlo simulation method to assess the eutrophication of Erhai Lake Basin in China (Lin et al. 2020). Mu et al. established a spatial econometric model to quantitatively study the level of water resources utilization in northwest China (Mu et al. 2021). Based on the system dynamics theory and analytic hierarchy process (AHP), Wang et al. established an index system for the water environment assessment of the Bosten Lake Basin, which includes industry, agriculture, population, and other factors (Wang et al. 2018a, b). Based on AHP and geographic remote sensing images, Qiao et al. established a surface water environmental risk index assessment model (Qiao et al. 2021). Wang et al. introduced a fuzzy comprehensive evaluation method, grey correlation analysis, and multiple linear regression model to predict and evaluate urban water environments (Wang et al. 2020). Based on the water environment characteristics of the Three Gorges Reservoir, Li et al. established a gray prediction model (GM) with an improved initial index to predict the trend of water environment pollution risk (Li et al. 2017). Although these evaluation methods have achieved certain results, there are still some deficiencies in their practical application. If the fuzzy comprehensive evaluation process is complicated, mutual influence between the indicators cannot be eliminated (Gao et al. 2019). The weights obtained by the AHP are highly subjective (Zhao et al. 2021). The gray correlation model cannot determine the optimal value of the index, and the existing quantitative model has a narrow scope of application (Chen et al. 2021). The ecological environment of water has both social and natural attributes, and the influence of multiple subsystems must be considered. These methods cannot fully reflect the scientificity and reliability of water ecological environment assessments. Therefore, an objective weighted rank and ratio model was introduced to grade each region according to the actual situation of the study area, the nature of water ecological indicators, and the change in rank. Subsequently, combined with the adversarial interpretative structure model (AISM) to refine the superiority and inferiority ranking of the evaluation objects, the influence of the intrinsic relevance of the indicators on the evaluation results can be explored.

In summary, most of the existing water ecological environment assessments focus on the study of a single region, lack of overall evaluation of larger watersheds, and few studies on the classification of the water ecological environment and regional differences. This study selects Yangtze River Economic Belt, China, as the water ecological environment evaluation object; comprehensively measures the impact of industrial, agricultural, and domestic sources of pollution on the water ecological environment; and constructs a model based on "driving force-carrying source-state-management" (DCSM) framework of the comprehensive evaluation index system of water ecological environment. Then, using the entropy weight method, weighted rank sum ratio model (WRSR), and adversarial interpretative structure model (AISM), the water ecological status classification results of the Yangtze River Economic Belt from 2010 to 2019 were calculated, and the differences between regions were identified. We hope to provide a scientific basis for promoting the coordination of sustainable utilization of water resources, economic and social development, and ecological environment protection in the Yangtze River Economic Belt.

Research methods and models

Entropy weight method

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

Assume that the original evaluation indicators matrix is as follows:

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

The dimensions of each evaluation indicator were different, and the original matrix was standardized:

1. The following are the positive indicators:

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

2. The following are the negative indicators:

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

3. The normalized matrix was as follows:

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

4. The weight matrix was calculated as shown in Eq. (5):

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

where $e_j = -\frac{1}{\ln(n)}\sum_{j=1}^{m} p_{ij}\ln p_{ij}$, $p_{ij} = \frac{u_{ij}}{\sum_{j=1}^{m} u_{ij}}$, and $\ln 0 = 0$.

The entropy weight method was used to calculate the weight matrix $W = (\omega_1\ \omega_2 \ldots \omega_m)$.

Weighted rank sum ratio model

The rank sum ratio (RSR) model, proposed by the Chinese statistician Tian Fengdiao in 1988, is mainly applied to the comprehensive rating of statistical analysis. 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. A larger RSR value indicates a more comprehensive evaluation (Li et al. 2010; Chen et al. 2015). The weighted rank sum ratio model (WRSR) fully considers the indicator weights based on RSR and is more sensitive to small changes within the indicators. Compared with TOPSIS, DEA, and AHP, WRSR can avoid the influence of subjective opinions and make the evaluation results more objective (Tan et al. 2017). WRSR contains three elements: the rank, indicator weights, and probit. Rank refers to the ranking of the sample under the indicator. Under positive indicators, the smaller the rank, the better the performance, which is the opposite of the negative indicators. The indicator weight indicates the importance of the indicator, and probit is the probability unit corresponding to WRSR result, which reflects the fitting degree of the model. The calculation process for the WRSR model is as follows:

(1) In the matrix of indicators, the evaluation indicators are composed of positive and negative indicators, which are positively correlated with the evaluation results and ranked from smallest to largest, while the opposite is true for the negative indicators.

(2) WRSR is obtained by combining the rank and weight, which is expressed in Eq. (6):

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

where n and m represent the number of evaluation objects and indicators, respectively, and 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 the indicators.

(3) Calculate the WRSR of objects, and rank them from smallest to largest. The downward cumulative frequency was calculated, and the corresponding probit was solved. Finally, it is necessary to carry out a regression analysis and calculate the corresponding regression equation according to the least-squares method.

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

Adversarial interpretative structure model

AISM is proposed based on the interpretative structure model (ISM) which can be used to analyze the relationship of factors in complex systems (Tan et al. 2019). It integrates the game adversarial idea in the traditional ISM and establishes the simplest hierarchical directed topological hierarchical graph with an adversarial idea based on the reachable matrix obtained from the relational matrix and principle of opposite level extraction. Owing 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. 2021a, b, c). The specific calculation process is as follows:

1. In 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 and y satisfy
2. Positive indicators: $d_{(x,p1)} \geq d_{(y,p1)}$ and $d_{(x,p2)} \geq d_{(y,p2)}$ and $\cdots$ and $d_{(x,pm)} \geq d_{(y,pm)}$.
3. Negative indicators: $d_{(x,q1)} \leq d_{(y,q1)}$ and $d_{(x,q2)} \leq d_{(y,q2)}$ and $\cdots$ and $d_{(x,qm)} \leq d_{(y,qm)}$.
4. 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 $A = (a)_{n\times n}$ was obtained.
5. Calculating the reachable matrix of the relation matrix A, which is shown in Eqs. (7) and (8):

$$B = A + I \quad (7)$$

$$B^k = B^{k+1} = R \quad (8)$$

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

4. The result of the hierarchical graph is determined by antecedent set Q, common set T, and reachable set R. In the relational matrix A, its elements satisfy the following requirements: the antecedent set $Q(e_i)$ comprises all elements corresponding to column 1, and the reachable set $R(e_i)$ comprises all the elements corresponding to line 1. The common set $T(e_i)$ is the intersection of both sets.
5. Divide the hierarchy according to the priority of the results, let $R(e_i) = T(e_i)$, and place the extracted samples in 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 order from bottom to top to obtain the DOWN-type hierarchy graph. The UP- and DOWN-types 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 the study subjects was determined according to the results.

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

1. A regional water ecological environment evaluation indicator matrix $O = [o_{ij}]_{n\times m}$, where 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 a normalization operation.
2. The weight matrix is $W = \{\omega_1, \omega_2, \ldots \omega_m\}$, based on the entropy weight method, to determine the weight of each indicator.
3. The WRSR and cumulative frequency corresponding to n samples were obtained according to Eq. (6). With the probit value as the independent variable and WRSR as the dependent variable, n groups of (probit, WRSR) data were linearly fitted, and the partial differential of error was calculated. The general equation of the linear fitting is $y = a + bx$, which can be expressed as

$$\overline{WRSR} = \alpha + b \cdot Probit \quad (9)$$

4. In the consistency testing of the fitted results, based on previous experience, the Kendall test was generally used in a discrete data context, as shown in Eq. (10) (Betensky et al. 1999), where W_k denotes the Kendall concordance coefficient.

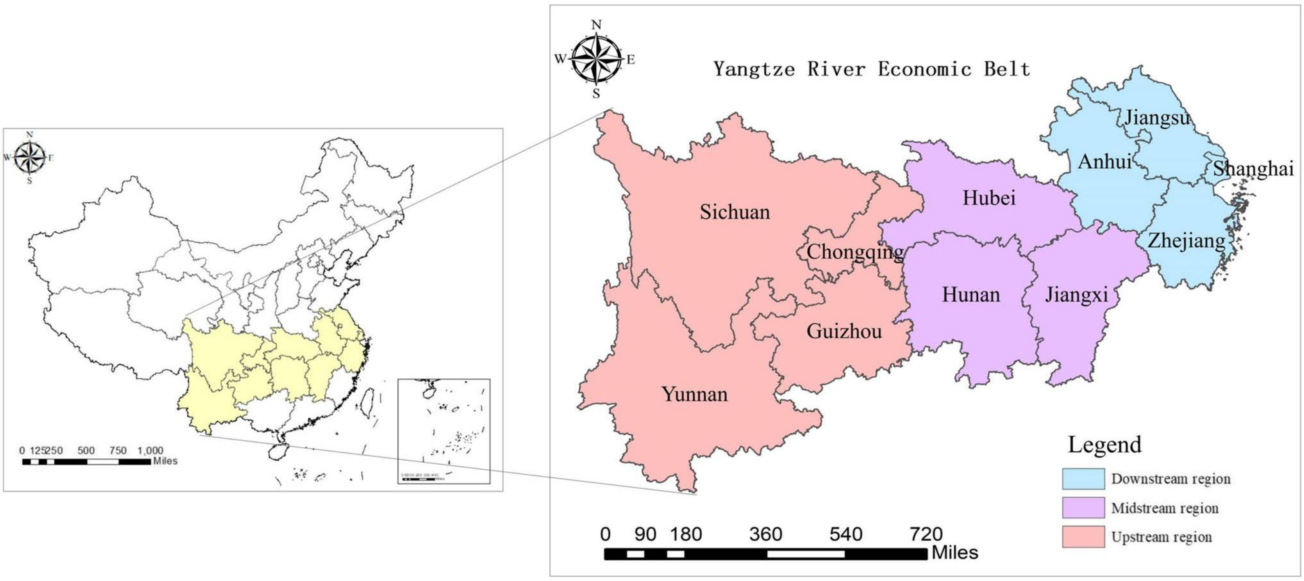


Fig. 1 The location of the Yangtze River Economic Belt

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

5. The linear images were classified according to the probit, and the evaluation results were tested by hypotheses.
6. WRSR and probit were combined to form a decision matrix, and the corresponding reachable matrix was calculated according to the partial-order rule: Eqs. (7) and (8) and the antecedent and reachable sets were extracted.
7. The samples were placed according to the result priority rule and cause priority rule, and a set of UP- and DOWN-type directed topological hierarchical graphs with adversarial properties was obtained. Considering the adversarial structure and Pareto optimality principle, the highest level element intersection set was taken as the optimal sample, and the lowest level element intersection set was taken as the worst sample. Each level determined the ranking of the evaluation samples from which the final comprehensive evaluation results can be obtained.

Research materials

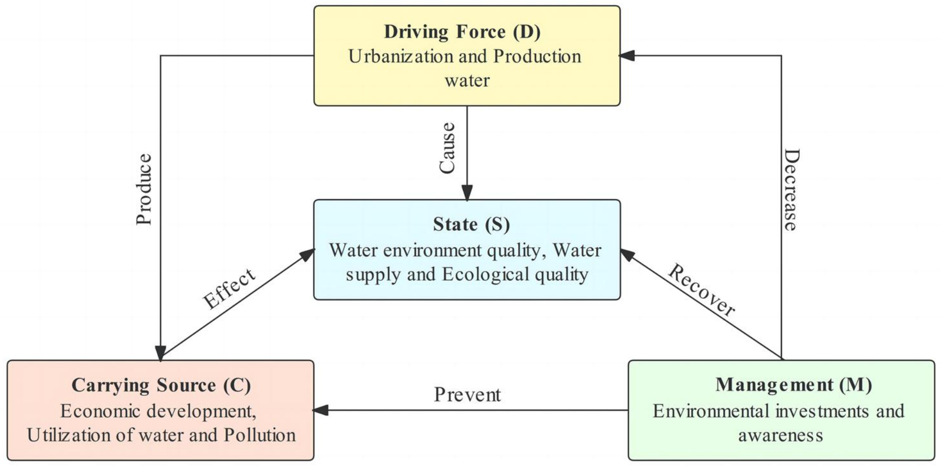
Research area

The Yangtze River Economic Belt is a super-large economic development area, with the Yangtze River Delta urban agglomeration, the middle reaches of the Yangtze River urban agglomeration, and the Chengdu-Chongqing urban agglomeration as the main body. Its geographical location is illustrated in Fig. 1. As shown in Fig. 1, the Yangtze River Economic Belt covers 11 provinces and cities: 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. In addition, 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 a global influence because of its developed water system and abundant resources. However, in recent years, it has faced problems such as excessive concentration in the heavy chemical industry and inefficient utilization of water resources, which leads to a poor water ecological environment. Thus, protection of water ecology is of great urgency (Chen et al. 2017).

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. In this framework, *D* is the support effect of the water environment on human production activities and regional development driving factors, *C* is the pollution source of the water ecological environment brought about by social production activities, *S* is the state of the water ecological environment under pressure, and *M* reflects the water ecological management measures and ability of society to regulate water pollution. A causal feedback loop is formed according to the connection between the various subsystems, and the

Fig. 2 The schematic diagram of DCSM structure



specific structure is shown in Fig. 2. The evaluation indicator system is divided into four standard layers, including 21 evaluation indicators, as listed in Table 1.

Result

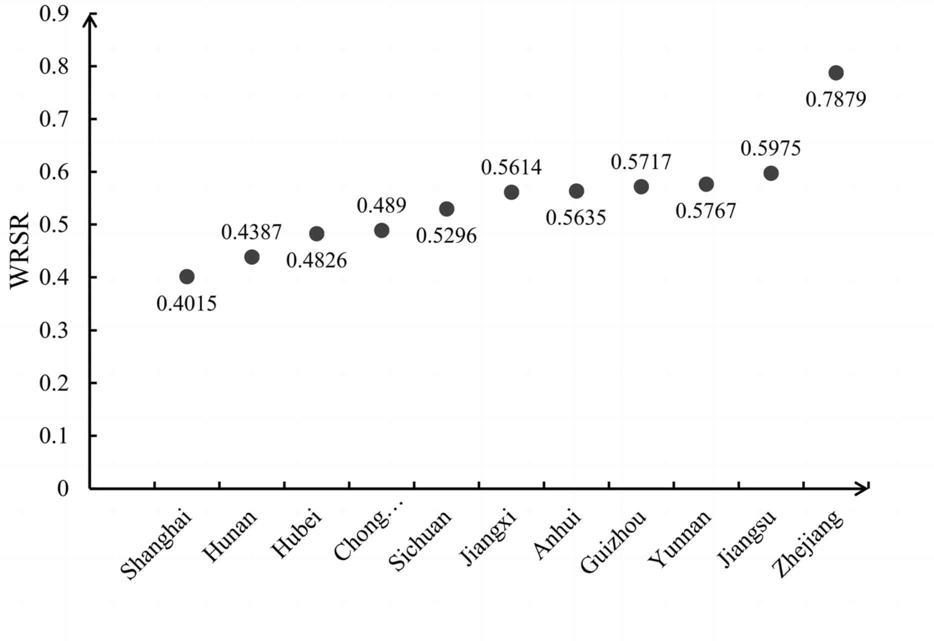
Analysis of indicator weights

The evaluation indicator matrix was formed by the weighted average of the original data over the years. The weights of each indicator were calculated using

Table 1 Comprehensive evaluation indicator system of water ecological environment in the 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
		Water quality monitor section 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 investment in water ecological protection to regional GDP (M1)	+	0.0504
		Water infrastructure investment in proportion of fixed assets (M2)	+	0.0249
		Investment in treatment of “three wastes” (M3)	+	0.0764

Fig. 3 The distribution of WRSR



the entropy weight method; the calculation results are listed 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 resource development and utilization rate > proportion of investment in water ecological protection to regional GDP > output of industrial solid waste > regional green coverage rate > regional forest coverage > water resources per capita > water quality monitor section compliance rate > average water consumption per acre of regional farmland > domestic waste pollution per capita > park area per capita > urbanization rate > water infrastructure investment in proportion of fixed assets > 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 criterion layer, the indicator weights were ordered as follows: driving force > state > carrying source > management.

Analysis of regional classifications

According to WRSR and the least squares method, the downward cumulative frequency and the corresponding standard normal deviation μ were calculated using MATLAB, and the unit probability value (probit) was obtained. The WRSR distribution is shown in Fig. 3. Due to statistical errors, the interval estimation of WRSR values of all evaluation objects is performed next. Calculate the intermediate variable with $Y = \arcsin(\sqrt{\mathrm{WRSR}} \cdot \frac{180}{\pi})$ to get a 95% confidence interval for Y. The confidence interval for Y is calculated as follows:

$$Y \pm u \cdot s_y \tag{11}$$

In Eq. (11), $u = 1 +$ evaluation probability and $s_y = \sqrt{820.7/n/m}$. The confidence interval of each evaluation object can be inferred from the confidence interval of WRSR, and the specific distribution is shown in Fig. 4. The confidence intervals for Y are shown in Table 2.

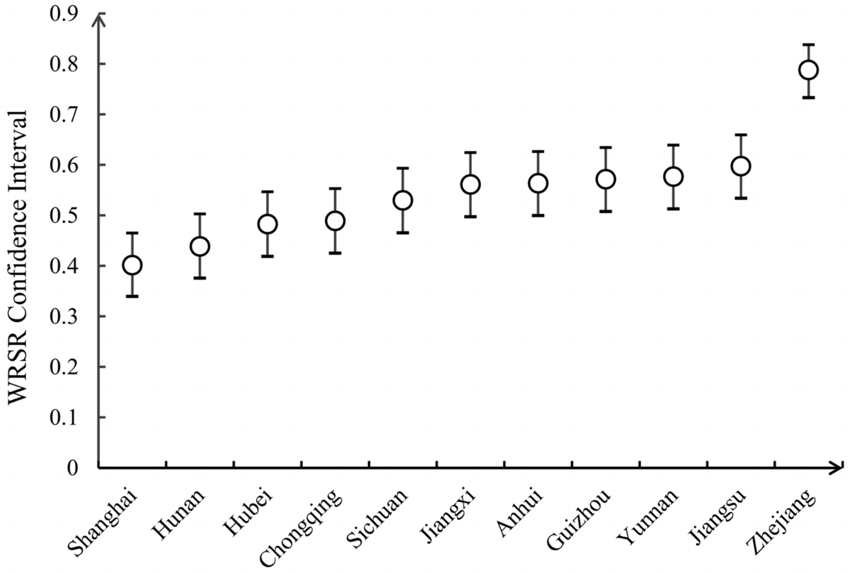
Regression analysis was performed with the WRSR as the dependent variable and probit as the independent variable. The regression equation was as follows:

$$\overline{WRSR} = 0.044 + 0.097 \cdot Probit \tag{12}$$

The regression equation was tested using parameters and the correlation coefficient $r^2 = 0.58968$, with a positive linear correlation between $\overline{WRSR}$ and probit. $F = 78.19$ and $p < 0.01$, proving 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). The following shows the hypothesis test on the results of classification:

Fig. 4 Confidence interval for WRSR (95%)



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

Table 2 *Y* and the confidence interval for *Y*

Province	*Y*	$S_y = 1.8849$	
		Lower limit of confidence interval (95%)	Upper limit of confidence interval (95%)
Shanghai	39.3192	35.6437	42.9947
Hunan	41.4786	37.8031	45.1541
Hubei	44.0025	40.327	47.678
Chongqing	44.37	40.6945	48.0455
Sichuan	46.6973	43.0218	50.3728
Jiangxi	48.5272	44.8517	52.2027
Anhui	48.6485	44.973	52.324
Guizhou	49.1224	45.4469	52.7979
Yunnan	49.4122	45.7367	53.0877
Jiangsu	50.6223	46.9468	54.2978
Zhejiang	62.5782	58.9027	66.2537

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

Equation (10) was used to calculate $W_k = 0.1137$, which satisfies $D(n-1) \cdot W_k \sim \chi^2(n-1)$ and $p > 0.1137$. Thus, the original hypothesis was accepted. The classification results were independent of one another. The linear model was statistically significant. The results for each parameter are presented in Table 3. The classification results for the water ecological environment in the Yangtze River Economic Belt are shown in Table 4.

Table 3 Results of WRSR, probit, and other parameters

Province	*WRSR*	Downward cumulative frequency	*Probit*	$\overline{\text{WRSR}}$
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

During the study period, the regional differences in the water ecological environment in 11 provinces of the Yangtze River Economic Belt were obvious and could be divided into four grades. There were two provinces with excellent water ecological environment grades, Zhejiang and Jiangsu, with WRSR greater than 0.626. There were four provinces in good grade, Yunnan, Guizhou, Anhui, and Jiangxi, with (0.529, 0.626] WRSR. There were four provinces in the middle grade, Sichuan, Chongqing, Hubei, and Hunan, with (0.432, 0.529] WRSR. There was one province in the poor grade, namely, Shanghai, with WRSR of less than 0.432. It

Table 4 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

can be concluded that there were six provinces with good grades or above, accounting for 54.5% of the total sample. In general, most provinces of the Yangtze River Economic Belt were in the lower-middle level, and the reasons for the classification differences are as follows.

As the core area of the Yangtze River Economic Belt, Zhejiang and Jiangsu provinces, with an excellent water ecological environment, have advantages in the control of carrying sources and the adjustment of the carrying state. For example, Zhejiang province has paid more attention to the discharge of industrial solid waste and recycling of wastewater and clarified the water ecological pollution caused by traditional industries. Comprehensive treatment has relieved the pressure on the 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 the water ecological environment through management, which has effectively curbed the developing 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 gap compared with excellent provinces. Anhui and Jiangxi invested a lot in urban environmental infrastructure and paid attention to pollution control and water quality. However, they also face the challenges of industrial water efficiency and the improvement of the consumption structure. As an ecological barrier in the upper reaches of the Yangtze River, Yunnan has been continuously promoting the development of agricultural science and technology in recent years and has achieved remarkable results. However, the low level of industrialization has brought about large wastewater discharge and less investment in pollution control, which has a direct negative impact on the ecological environment. Industrial innovation and transformation remain complicated.

From the above forms, we can conclude that the areas with a medium water ecological environment are Hunan, Sichuan, Chongqing, and Hubei, and the area with a poor water ecological environment is Shanghai. Combined with the overall index, it can be seen that most provinces are faced with problems such as an 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. Although Sichuan and Chongqing are located in the upstream area, they have certain advantages in terms of forest coverage and water quality compliance rate. However, the contradiction between development and protection in the region is prominent, and there are problems with the water environment that emphasizes the main streams over the tributaries and the urban areas over the rural areas. Moreover, the state of water ecology in Shanghai and Hubei is not optimistic. Hubei has also faced challenges, including low efficiency of water resource allocation and utilization, insufficient ecological optimization ability, and low water resources. Shanghai is located in the lower reaches of the eastern Yangtze River. The water flow in the Yangtze River will inevitably cause Shanghai to undertake water pollution from the upper reaches, and the resulting spatial differences in the water ecological environment will be difficult to eliminate in a short period of time. In addition, the urban population is concentrated, and the sewage treatment capacity does not meet the standard. This is also the cause of the deterioration of Shanghai's water ecological environment. Therefore, at this stage, the overall water ecological environment of the Yangtze River Economic Belt has not yet reached a safe, coordinated, and steady state, showing an asymmetric "U"-shaped pattern in which the downstream is superior, the upstream is second, and the midstream is poor. It is necessary to pay attention to the problems of population concentration and resource consumption brought about by urbanization, which affect the water ecological environment.

Analysis of regional rankings

The WRSR model divides the water ecological environment of the 11 provinces in the Yangtze River Economic Belt into four grades, but it cannot provide a more detailed ranking of the advantages and disadvantages of each region. Therefore, AISM was 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 the partial order rules and Eqs. (7) and (8), which are listed in Table 5. Level extraction is then performed to obtain the confrontational level topology shown in Fig. 5.

Table 5 Reachable matrix

$R_{11\times 11}$	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

In the hierarchical topology of UP and DOWN (Fig. 5), 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 study, the analysis of the uppermost, middle, and bottom samples is as follows.

In the topological diagram, the top L1 province sample was Zhejiang and the other samples were in the middle and bottom layers. There are many topological systems, which indicate 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 had an absolute advantage in its water ecological environment from 2010 to 2019. This shows that the implementation of a sustainable development strategy can effectively cope with various ecological pressure factors and maintain the water ecological environment in a good state.

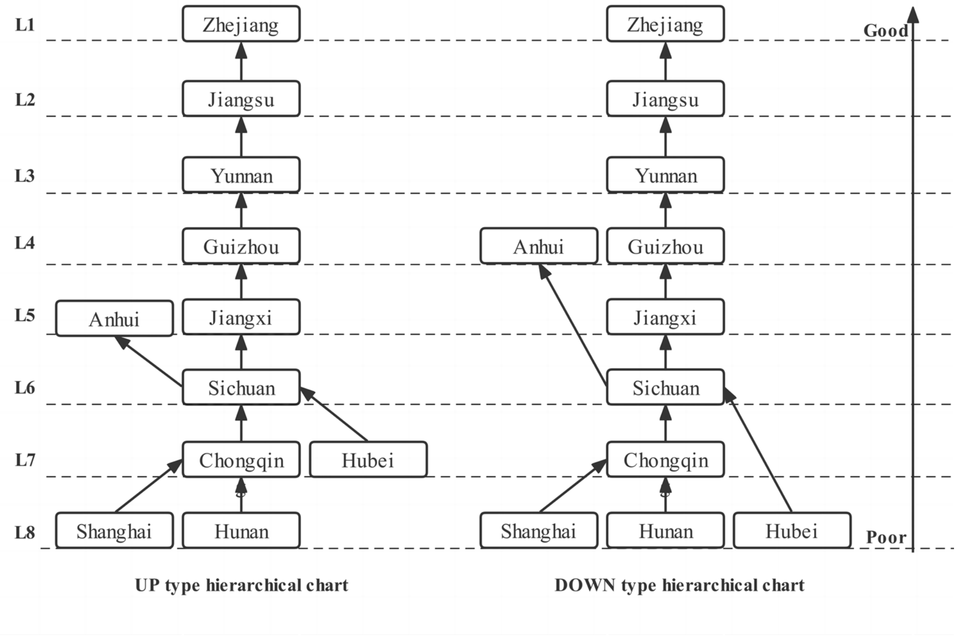
The middle layer contained samples from Jiangsu, Yunnan, Guizhou, Anhui, Jiangxi, Sichuan, Chongqing, and Hubei, which were distributed in the L2–L7 levels. According to the division principle, the better the high level, the worse the lower level, and it can be seen that the water eco-environment status of the eight provinces becomes worse successively. The comparison of the two topological maps shows that the ordering of the mainline samples is consistent, indicating that there are obvious differences in the water ecological environment among these provinces; the hierarchy is clear, and there is obvious spatial disequilibrium. The advantages and disadvantages of the water ecological environment are jointly determined by multiple indicators, and high-weight indicators have a greater impact on the ranking results. The hierarchical changes in Anhui and Hubei indicate that the system was extensional. In addition, compared with other provinces, the water ecological environment of these two samples is more unstable and needs to be improved greatly. The transformation from the extensive development of traditional energy to a high-quality energy-saving industry can improve the poor state of the aquatic ecosystem. In addition, the government's ecological management also plays a role to some extent, which ensures 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 that the water ecological environment in these two areas is affected by agricultural nonpoint source pollution and insufficient water resource supply, which leads to a worse state of the water ecological environment. This also proves that traditional treatment methods can no longer adapt to the current needs of ecological development. Thus, there is an urgent need 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 a fragile water ecological environment, China's water ecological problem has gradually become an important constraint for sustainable economic and social development. The study of water ecological environment assessment can provide a scientific basis for promoting ecological civilization construction and optimizing resource allocation. (Zhao and Wang 2021). The Yangtze River Economic Belt covers a vast area and is rich in water resources. This rough economic growth pattern has deteriorated water quality and caused frequent functional water shortages.

Fig. 5 Adversarial hierarchical topology graph



Therefore, it is necessary to evaluate the water ecological environment of the Yangtze River Economic Belt.

The DCSM framework introduced in this study for evaluating the water ecological environment of the Yangtze River Economic Belt is based on the actual characteristics of the watershed and availability of data. In contrast to previous evaluation index frameworks, DCSM emphasizes the support of the watershed water environment for human production activities and the ability of people and society to regulate and respond to the water ecological environment. It can not only provide a framework for water ecological evaluation but can also be applied to the evaluation of land, atmosphere, etc. It has a strong universality. The application of the entropy weight method and WRSR model can objectively identify high-weight indicators and determine their degree of influence. The combination of the two can reflect slight changes in all indicator information and is suitable for water environment classification evaluation. AISM fully considers the internal differences and connections of the evaluation objects, visualizes the classification results, and forms a directional topological hierarchical structure diagram, which is suitable for analyzing the differences in the status of the water ecological environment between various local areas from the perspective of geographic space.

Using multiple models and methods to comprehensively evaluate the water ecological environment status of the Yangtze River Economic Belt from 2010 to 2019 breaks through the subjective limitations of a single evaluation method. The evaluation results show that the water ecological environment is different in different regions, and the problem of water ecological pressure overload in Shanghai and Hunan remains prominent. In the long run, the sustainable development of the water ecological environment in these two regions is low, and it will be difficult to withstand the pressure of future social production activities (Han et al. 2019). Regional governments and ecological management departments should reasonably restrain the pollution discharge of various industries and innovate the economic development model to reduce the burden on the water ecological environment of the Yangtze River Economic Belt. In addition, the indicator weight results show that the driving force factor is the focus of attention in the future and economically developed regions often have strong reform execution capabilities. Simultaneously, it is worth noting that by the end of the “14th Five-Year Plan” period, the proportion of the total economic volume in the central region of the Yangtze River Economic Belt will further increase, and the urbanization rate will exceed 67% (Zhang et al. 2021a, b, c). The courses of action to alleviate population aggregation and the water ecology brought about by environmental stress in industrial clusters deserve further study.

Overall, this study still has some limitations, but it is close to the results of previous studies (Chai and Zhou 2022). In terms of research methods, the WRSR model relies on the rank of the original data, which may be biased when classified and filed. AISM only divides the research objects into levels, and it is difficult to explore the coupling relationship between various indicators. In terms of research content, the water ecological environment conditions in different regions are different and the evaluation index system may not be perfect. The methods to build a scientific water ecological environment evaluation index system and optimize the research content are also a focus of future research.

Conclusion and suggestion

Conclusion

As an important part of the Earth's natural environment, the water ecological environment is the basis for human survival. On the premise of ensuring the sustainable development of the 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 a series of water ecological environmental 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, a comprehensive evaluation indicator system for the water ecological environment was established in this study. Moreover, this study adopted the entropy weight method to determine the weight. The WRSR model and AISM were introduced to evaluate the state of the water ecological environment of the Yangtze River Economic Belt from 2010 to 2019. The conclusions are as follows:

(1) From the perspective of geographical distribution, the water ecology in the upper reaches of the Yangtze River Economic Belt is relatively good, while the middle and lower reaches show a state of polarization, with large regional differences, showing an asymmetric "U"-shaped distribution pattern overall. The areas with good water ecological grade and above are mostly located in the ecological demonstration area and green industry development area, while the middle areas lie nearly in traditional industry transformation provinces. The poor area is characterized by extensive industrial agglomeration and a high degree of ecological development.

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

(3) The results show that the overall water ecological environment of the Yangtze River Economic Belt is in the middle state, and problems such as insufficient investment in environmental protection and a low utilization rate of water resources are prominent. Although government management and regulation are beneficial for the sustainable development of water ecology, comprehensive and powerful reforms are still lacking. In the future, we hope to optimize the investment and financing structure of water environment governance, promote the participation of society as a whole, and improve the overall state of the regional water ecological environment.

Suggestions

(1) Focus on economic transformation, strengthening industrial pollution control, and preventing water ecological environmental risks. The water ecological environment is still the main focus of sustainable ecological development in the Yangtze River Economic Belt, and problems such as heavy industrial surface source pollution and water ecological damage are still prominent, improving the level of green and sustainable development, strengthening research on pollution traceability and reduction, and paying attention to the recycling of water pollution. Real-time monitoring of water ecological risks brought about by industrial agglomeration on both sides of the river, priority and strict classification, and rectification of chemical production enterprises, combined with the overall development of urban and rural areas and industrial transformation and upgrading, in line with the "low-carbon" strategic layout, weakening of industrial pollution from surface sources, to achieve standardized management.

(2) Strengthen ecological management, establish and improve the rule of law system, and implement the supervisory role of ecological and environmental protection departments. Fully implement the "party and government share responsibility" for water ecological environmental protection, improve the system and mechanism for joint protection, rectify outstanding problems in the Yangtze River Basin, consolidate the main responsibility of each tributary river chief, promote the government and enterprises to implement corresponding legal responsibilities, and unite all levels social entities work together to form a networked governance structure with equal rights and responsibilities, providing organizational guarantee for the Yangtze River ecological environment supervision.

(3) Promote regional linkage, follow high-quality development routes, and coordinate to promote comprehensive water environment management. The development gap between the upper, middle, and lower reaches of the Yangtze River Economic Belt reflects the strong endogenous driving force for industrial transfer. Relying on the transportation advantages and linkage effect of the golden waterway, establishing, and improving the coordinated protection mechanism of the Yangtze River Basin across administrative regions can optimize the distribution of regional productivity, promote the rational flow and optimal allocation of production factors across regions, lead to the development of green industries, and realize the benign interaction of upstream, midstream, and downstream industries.

Author contribution Xu Yue and Yang Li were responsible for the selection of the topic and the data processing calculation of the manuscript, while Zhang Chi and Zhu Junqi jointly completed the paper writing.

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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 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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