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Comprehensive evaluation of water resources security of the Huaihe Eco-economic Belt

Jun Ruan* and Gang He
Anhui University of Science and Technology, Huainan, China
*Corresponding author. Email: ruanjun0415@163.com

JR, 0000-0002-9658-8114

ABSTRACT

The study of water resource security is a basic scientific issue that must be faced in the construction of the ecological environment. To examine the status of regional water resources security in the Huaihe Eco-economic Belt, this study builds a comprehensive evaluation index system based on the 'Driving-Pressure-State-Impact-Response' (DPSIR) framework, combines the entropy weight method and Lotka–Volterra symbiosis model to calculate the water resources security status from 2010 to 2018. Then the fixed effects regression model is used to analyze the factors affecting the water resources system. The results show that: (1) The status of water resources security in the Huaihe Eco-economic belt decreased from 2011 to 2017 and, thereby transitioned from a safe to a dangerous state. The coordination index of the economic system and water resource system was only -0.17 in 2017, and the partial development model benefited the economy but damaged the water resources. (2) The security status of 25 prefecture-level cities improved significantly, and the number of cities with status of alert or above increased from 11 to 15. However, there are apparent differences among the regions. The status has shifted to 'north and south being better than east and west'. The water resources security status of Jining, Linyi, and Lu'an have improved, whereas Yancheng, Taizhou, Pingdingshan, and other cities showed rather poor development during 2017. (3) The correlation coefficient of the economic system was -0.154 and hindered the development of the water resources system. The correlation coefficients of the added value of the tertiary industry and the expenditure on energy conservation and environmental protection was 0.699 and 0.180 respectively and played a positive role in promoting the water resources system. It is necessary to optimize and adjust the industrial structure and protect the environment.

Key words: DPSIR, Huaihe Eco-economic Belt, Lotka–Volterra model, water resources security

HIGHLIGHT

- The Lotka–Volterra symbiosis model is introduced to the paper and has good applicability in water resources security research. The Huaihe Eco-economic Belt is taken as the research area and the empirical results are conducive to promoting the development and implementation of national strategies. ArcGIS software is used to visualize the results and the dynamic change of water resources security status.

INTRODUCTION

Water resources play a vital role in social development. The continuous advancement of industrialization and urbanization has led to an increasing demand for water resources in human society. The over-exploitation and wastage of water resources, water pollution, and other adverse phenomena has intensified, hence pushing China and the rest of the world towards a water resource crisis. According to relevant data, the total precipitation and water resources of China in 2019 have slightly increased compared to 2018, while water efficiency and structure are being continuously optimized. However, the current situation of water resources around China is still not optimistic (Ministry of Water Resources of the People's Republic of China 2019). The scarcity of water resources is a crucial factor that can hamper regional development. Therefore, a reasonable and effective evaluation of water resources security can stimulate the government to formulate tailored plans and achieve sustainable development.

Water security is a complex concept, and the unified international standard has not been formulated yet. The Second World Water Forum, held in The Hague in 2000, defined water security as 'access to sufficiently safe water at an affordable price' (Muhammad *et al.* 2004). David & Claudia (2007) believes that water resource security refers to the acceptable water quantity and quality availability for maintaining health, life, ecology, and production, as well as human, environment, and economic

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endurance, and wading risks. He emphasized the impact of global climate change on water resources security. Cook & Bakker (2012) suggested that water resource security is when one permanently obtains sufficient water with acceptable water quality to ensure the health of mankind and ecosystems. While defining water resources security, Handmer & Lusting (2013) emphasized the role of water pressure, quality of regional water environment, and socio-economic responses. The priority here was given to the self-conditions or external adjustment capabilities of the region's natural, economic, and social systems facing the demand for water resources.

Currently, the research on water resources security mainly focuses on the control technology of water pollution and water resources security evaluation. Given the pollution problem in water resources security, scholars have carried out related studies in the application of new technologies such as wastewater treatment, water purification, and water pollution removal. For example, the new green reducing agent and stabilizer can prepare the $ZnCo_2O_4$–Co_3O_4 nanostructure to eliminate pollutants in the water resources environment (Zinatloo *et al.* 2021a, 2021b). The preparation of Dy2Sn2O7 (it is a nanocompound) nanostructures using *Ficus carica* extract as a natural fuel can be used as a new visible light-sensitive catalyst to effectively remove and destroy organic pollutants in the water (Zinatloo *et al.* 2020). Moreover, the creation of spindle-shaped $PbWO_4$ nanostructures and the introduction of visible light can also be used as an effective way to eliminate water pollution (Zinatloo *et al.* 2021a, 2021b). Luo *et al.* (2019) successfully extracted activated alumina adsorption dam technology to solve the problem of sudden heavy metal pollution in the river basin and it can provide support for the efficient treatment of sudden pollution accidents in the river basin.

Water resources security evaluation is mainly realized quantitatively by constructing an evaluation index system and using the mathematical statistics method. From the evaluation index system perspective, most scholars referred to the 'Pressure-State-Response' (PSR) framework that had been proposed by the Organization for Economic Cooperation and Development in 1990 (Christesen 2002). For instance, Dai *et al.* (2010) used the PSR model to build a comprehensive evaluation index system for the water resources security of Beijing. Mao *et al.* (2014) divided an evaluation index of water resources security into indices of ecological characteristics, ecological function indices, and social environmental indices based on the PSR. Moreover, Hao *et al.* (2018) used PSR to build a water resources security evaluation system that encompassed society, economy, water resources, water environment, and ecology as indicators. The evaluation methods used commonly by scholars include a comprehensive index method, set pair analysis method and fuzzy evaluation method. Yomo *et al.* (2019) used the Improved Fuzzy Comprehensive Evaluation Model (IFCEM) to study the water resources security status of the Oti River. Furthermore, Gohari *et al.* (2017) took the Zayandeh-Rud river basin as a research area and analyzed the feedback relationship between water resources development and social economy using the system dynamics simulation. Li *et al.* (2020) adopted Grey Relational Analysis (GRA) to calculate the water resources security status of the Guizhou Province from 2008 to 2018. Yao *et al.* (2020) combined the coupling coordination degree model and the spatial state model to evaluate the water resources security status of 31 provinces in China. Liu *et al.* (2020) applied the entropy method and the fuzzy set pair analysis to build a comprehensive evaluation model of water resources safety in the Yangtze River Economic Belt. With the rapid technological development, the advanced computational approaches tailored for geosciences such as RS (Remote Sensing), GIS (Geographical Information System), and GPS (Global Positioning System) have been increasingly applied to assess the regional water resources security (Sithirith *et al.* 2016; Wang *et al.* 2017; Yao *et al.* 2017).

There are a lot of achievements in the field of water resources security evaluation. The methods are diversified, but the research on water resources security in the Huaihe River eco-economic belt is still scarce. Considering the important status of the Huaihe River eco-economic belt in China's social and economic development, this paper introduces the Lotka–Volterra symbiosis model to estimate the water resources security status in this region. The Lotka–Volterra symbiosis model assumes that the economic system and the water resource system are two species competing for ecological resources in the ecosystem, and analyzes the relationship between economic development and water resource security. This model can effectively combine the relationship between indicators and weights to reflect the coordinated development degree of the economic system and water resources system (Liu *et al.* 2017).

The paper constructs the comprehensive evaluation index system based on the DPSIR framework of 'Driving- Pressure – State – Impact – Response'. Then, we combined the entropy weight method and Lotka–Volterra model to quantitatively estimate the water resources security state of the Huaihe River eco-economic belt from 2010 to 2018. Furthermore, we made use of the fixed effect regression model to analyze the influencing factors of the water resources system. We hope to provide some theoretical references for regional water resources security evaluation and management.

STUDY AREA AND DATA

Study area

The Huaihe is one of the three major rivers and one of the most important water transportation hubs of China. The Huaihe Eco-economic Belt includes 25 provincial cities and four provinces (Jiangsu, Shandong, Anhui, and Henan) with a substantial population and abundant resources (Yan & Cui 2020). In 2018, the 'Huaihe Eco-economic Belt Development Plan' was officially approved. This plan aims to promote the comprehensive management of the entire river basin, and to combat environmental pollution. Water resources management practices are also important parts of this plan (State Council 2018). Therefore, it is necessary to evaluate the water resources security of the Huaihe Eco-economic Belt.

Datasets

The basic data used in this paper are derived from the annual data provided on the website of the National Bureau of Statistics and the statistics bureaus of cities. In consideration of the scientific nature and accessibility of the data, the statistical data of 25 prefecture-level cities in the Huaihe Economic Belt from 2010 to 2018 are selected as the basic data.

METHODS

Evaluation system

The 'Driving-Pressure-State-Impact-Response' (DPSIR) was adopted to construct the evaluation index system of water resources security (Qin & Cheng 2019), as shown in Table 1. In this model, 'Driving' (D) represents a driving force factor that promotes social development, 'Pressure' (P) is coercion to the water environment in a process of life production, 'State' (S) is the performance of the water environment under the effect of driving force and pressure, 'Impact' (I) stands for a series of impacts on human society when water resources change, 'Response' (R) refers to the measures and the countermeasures taken to improve water resources.

Table 1 | Evaluation index system of water resources security

Target layer	Criterion layer	Index layer	Type of index
Evaluation of water resources security	Driving (D)	GDP per capita	+
		The proportion of tertiary industry	+
		Revenue	+
		Per capita disposable income of urban residents	+
		Per capita disposable income of rural residents	+
		Urbanization rate	+
	Pressure (P)	Water consumption per GDP	−
		Water consumption per capita	−
		Industrial wastewater discharge	−
		Population density	−
		Sown area per capita	−
		Total water consumption	−
	State (S)	Surface water resources	+
		Groundwater resources	+
		Total water resources	+
		Water production modulus	+
		Precipitation	+
	Impact (I)	Effective irrigation area	+
		Water resources per capita	+
		The proportion of construction land	−
		The proportion of primary industry	−
	Response (R)	Park green area per capita	+
		The green coverage rate of built-up area	+
		Centralized sewage treatment rate	+
		Harmless treatment rate of domestic garbage	+
		Total afforestation area	+

The entropy weight method

The entropy weight method is an objective weighting method that determines the weight of an index according to the original index entropy value. The main calculation steps are as follows (Chen *et al.* 2019; Mishra *et al.* 2019; Wu & Hu 2020):

Initially, suppose the original evaluation indicators matrix is as shown below:

$$U = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ u_{m1} & u_{m2} & \cdots & u_{mn} \end{bmatrix} \tag{1}$$

In Equation (1), u_{ij} is the original value of the i_{th} index in the year of j.

The original data are standardized according to the type of index, where a positive indicator is shown in Equation (2) and a negative indicator in Equation (3).

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

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

Next, the normalized matrix is retrieved as shown in Equation (4):

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \ldots & r_{mn} \end{bmatrix} \tag{4}$$

Then, the entropy method is used to calculate the weight matrix.

$$w_i = \frac{1 - e_i}{m - \sum\limits_{i=1}^{m} e_i} \tag{5}$$

The weight is calculated for Equation (5) a as shown below.

$$e_i = -\frac{1}{\ln n}\sum_{j=1}^{n} p_{ij}\ln p_{ij}, \quad p_{ij} = \frac{r_{ij}}{\sum\limits_{j=1}^{n} r_{ij}}, \text{ and } \quad \ln 0 = 0.$$

The weight matrix is$w = (w_1 \quad w_2 \quad \ldots \quad w_m)$.

Lotka–Volterra model

Lotka–Volterra theory

The Lotka–Volterra model was jointly proposed by A.J.Lotka and V.Volterra in the 1940s. It can be used to study the relationship between biological populations, and the basic form of the model is as shown below (Zhang 2014).

$$\frac{dN_1(t)}{dt} = r_1N_1(t)\frac{K_1 - N_1(t) - \alpha N_2(t)}{K_1} \tag{6}$$

$$\frac{dN_2(t)}{dt} = r_2N_2(t)\frac{K_2 - N_2(t) - \beta N_1(t)}{K_2} \tag{7}$$

In Formula (6) and (7), $N_1(t)/N_2(t)$ are the number of populations (S_1/S_2); K_1/K_2 are the environmental capacity of the populations (S_1/S_2); r_1/r_2 are the growth rate of populations; $\alpha$is the competition coefficient of population S_2 versus population S_1, and $\beta$is the competition coefficient of population S_1 versus population S_2.

Then, the Lotka–Volterra symbiosis model is introduced to evaluate water resources security, and the specific form is as follows (Wu *et al.* 2019):

$$\frac{dF(t)}{dt} = r_F F(t)\frac{C - F(t) - \alpha E(t)}{C} \tag{8}$$

$$\frac{dE(t)}{dt} = r_E E(t)\frac{C - E(t) - \beta F(t)}{C} \tag{9}$$

In Equations (8) and (9): $F(t)$ is the comprehensive level of the economic system, $E(t)$ is the comprehensive level of the water resources system, C is the environmental capacity, r_F is the growth rate of the economic system, r_E is the growth rate of the water resources system, $\alpha$is the effective coefficient of the water resources system on the economic system, and β is the effective coefficient of the economic system on the water resources system.

Calculation of the competition coefficient

Here, α and β in the solution model are the keys for studying the interaction between the economic system and the water system. The specific solution steps are as follows (Zhang 2017):

$$F(k+1) - F(k) = \frac{F(k) - F(k-1)}{F(k-1)} \cdot F(k)\frac{C(k) - F(k) - \alpha(k)E(k)}{C(k)} \tag{10}$$

$$E(k+1) - E(k) = \frac{E(k) - E(k-1)}{E(k-1)} \cdot E(k)\frac{C(k) - E(k) - \beta(k)F(k)}{C(k)} \tag{11}$$

The solution of the formula (based on Equations (10) and (11)) yields the expression shown in Equations (12) and (13):

$$\alpha(k) = \frac{\varphi F(k)C(k) - F(k)}{E(k)} \tag{12}$$

$$\beta(k) = \frac{\varphi E(k)C(k) - E(k)}{F(k)} \tag{13}$$

where

$$\varphi_F(k) = 1 - \frac{F(k+1) - F(k)}{F(k)} \cdot \frac{F(k-1)}{F(k) - F(k-1)} = 1 - \frac{r_F(k+1)}{r_F(k)} \tag{14}$$

$$\varphi_E(k) = 1 - \frac{E(k+1) - E(k)}{E(k)} \cdot \frac{E(k-1)}{E(k) - E(k-1)} = 1 - \frac{r_E(k+1)}{r_E(k)} \tag{15}$$

According to the competition coefficients α and β, the interaction of the economic system and the water system can be expressed and understood, as shown in Figure 1.

Construction and calculation of coordination index

According to the estimates of α and β, the force indices of the economic system and the water system can be defined, and the specific process is as follows (Equations (16) and (17)):

$$S_F(k) = -\alpha(k) = -\frac{(\varphi F(k)C(k) - F(k))}{E(k)} \tag{16}$$

$$S_E(k) = -\beta(k) = -\frac{(\varphi E(k)C(k) - E(k))}{F(k)} \tag{17}$$

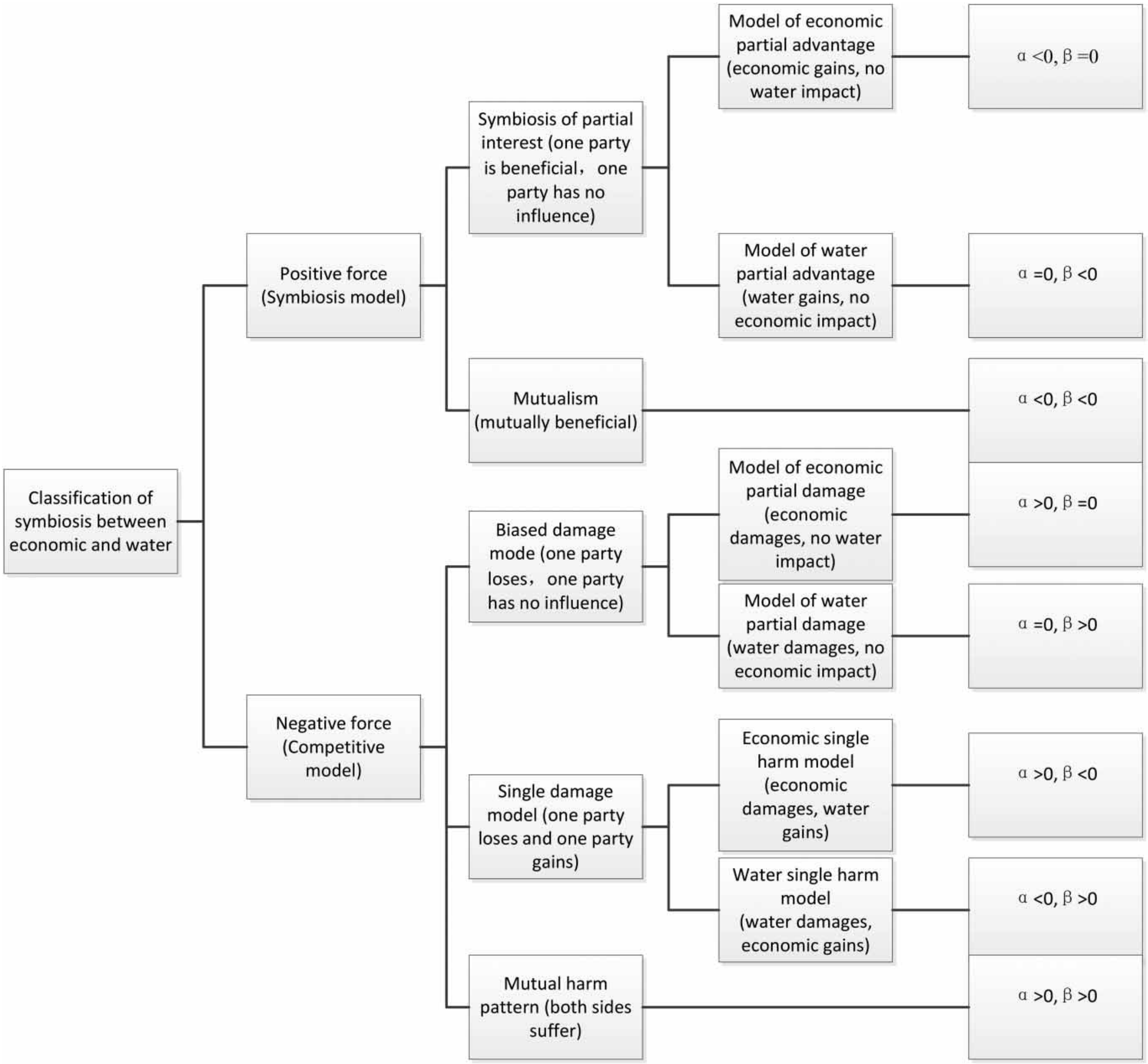

Figure 1 | Classification of symbiosis.

Then, the coordination index $S(k)$ between the economic system and the water resource system can be calculated using Equation (18):

$$S(k) = \frac{S_F(k) + S_E(k)}{\sqrt{S_F^2(k) + S_E^2(k)}} \tag{18}$$

It can be inferred from Equation (18) that $S(k) \in [-\sqrt{2}, \sqrt{2}]$. The larger the value of $S(k)$, the better the coordination state of the economic system and the water resources system.

The driving subsystem can be considered as the economic development system (F), impact and response subsystem as environmental capacity (C), pressure and state subsystem as a water resource security system (E) to construct the evaluation index system for water resources security based on the DPSIR and the Lotka–Volterra model (Figure 2).

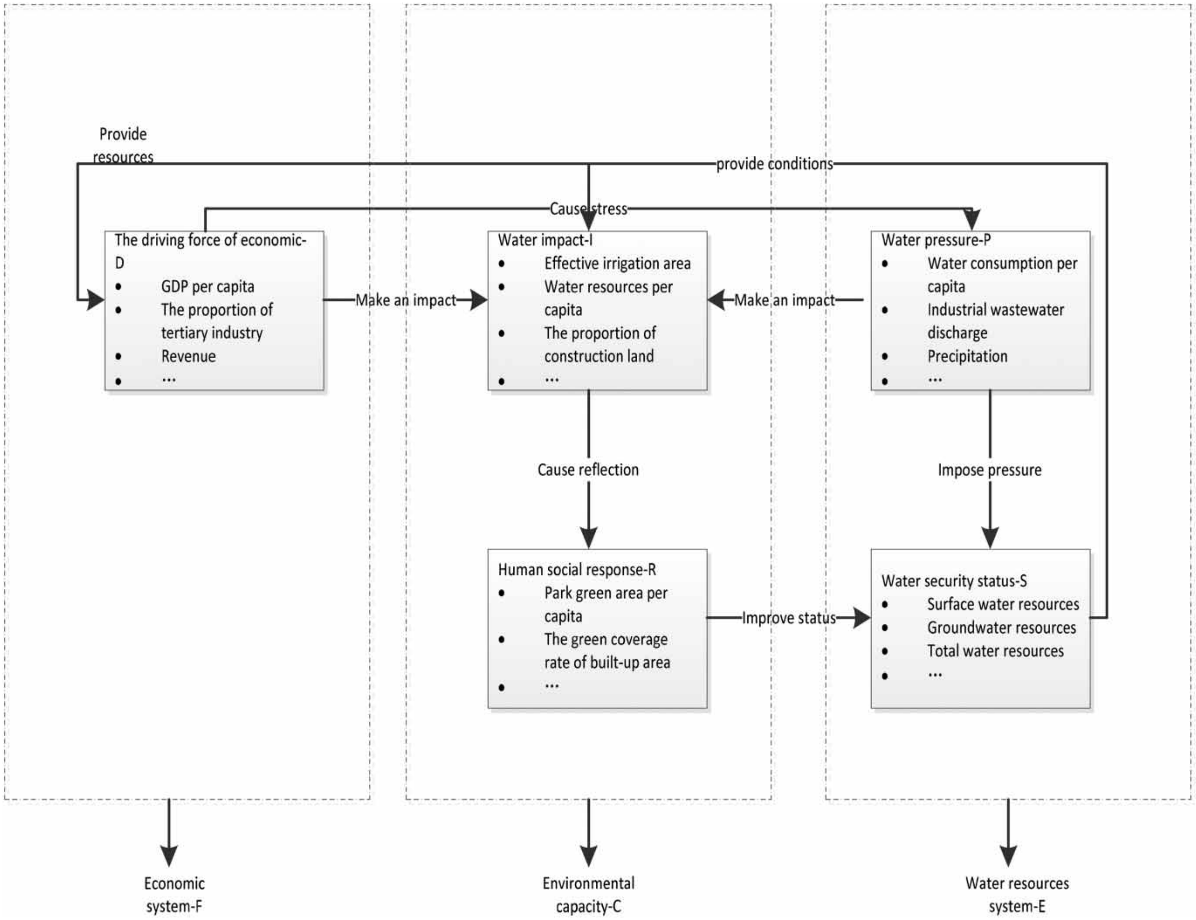

Figure 2 | Frame diagram of the DPSIR model.

Classification of standards

Given the previous research findings (Liu & Wang 2020; Wu *et al.* 2020), the water security status of the study area is divided according to the conditions and standards in Table 2. Note that different security states can be transformed into each other.

Table 2 | Classification of standards

Serial number	Force index of the water security	Coordination level	Corresponding relations	State of water	Grade of status
1	$S_E(k) > 0$	$1 < S(k) < \sqrt{2}$	Mutualism	Safe	I
2	$S_E(k) > 0$	$0 < S(k) < 1$	Economic damages and water resources gain	Relatively safe	II
3	$S_E(k) < 0$	$0 < S(k) < 1$	Economic gains and water resources damage	Vigilant	III
4	$S_E(k) > 0$	$-1 < S(k) < 0$	Economic damages and water resources gain	Bad	IV
5	$S_E(k) < 0$	$-1 < S(k) < 0$	Economic gains and water resources damage	Dangerous	V
6	$S_E(k) < 0$	$-\sqrt{2} < S(k) < -1$	Mutual harm	Highly dangerous	VI

Construction of influencing factor model

The comprehensive level of the water resources system is used here as a dependent variable to explore the factors influencing the water resources system. An independent variable is constructed from five aspects including economic development, industrial structure optimization, environmental protection, social security, and technological progress (see the selection in Table 3).

To avoid the impact of different data units, the logarithm of the variables is processed to achieve standardization. The model is shown in Equation (19):

$$\ln\ water_{it} = \alpha + \beta_1 \ln GDP_{it} + \beta_2 \ln industry_{it} + \beta_3 \ln worker_{it} + \beta_4 \ln expenditure_{it} + \beta_5\ job_{it} + \beta_6 \ln patent_{it} + \varepsilon \tag{19}$$

In the formula above $water_{it}$ is the development level of a region i in a period t, α is a constant, ε is a random error, and $\beta_1, \beta_2 \cdots \beta_6$ are the undetermined coefficients of each dependent variable.

RESULTS OF WATER RESOURCES SECURITY EVALUATION

Analysis on water resources security of the Huaihe Eco-economic Belt

The results in Figure 3 show that the economic system of the Huaihe Eco-economic Belt had developed well from 2010 to 2018. The comprehensive level linearly increased from 0.00 to 0.22, which is a considerable change. There are two types

Table 3 | Index system of influencing factors

Type of variable	Name of variable layer	Name of the indicator layer	Symbol
Dependent variable		Water resources system	Water
Independent variable	Economic development	Gross Regional Product	GDP
	Industrial structure optimization	Added value of the tertiary industry	Industry
	environmental protection	Number of environmental protection personnel	Worker
		Energy-saving and environmental protection expenditure	Expenditure
	Social security	employed population	Job
	Technological progress	Number of patent applications granted	Patent

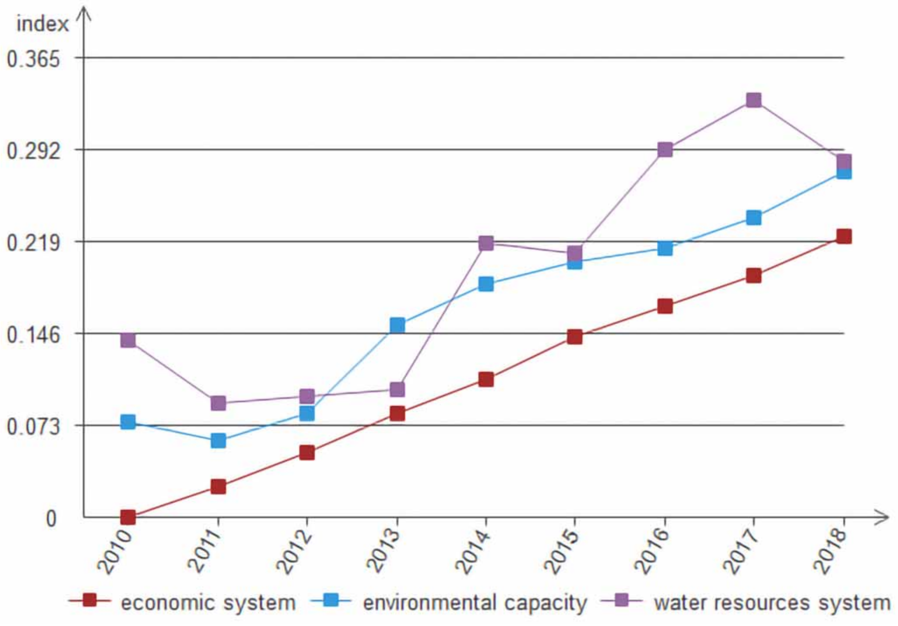

Figure 3 | The comprehensive development level.

of drivers for this change. On the one hand, indicators such as the speed of economic development, population living standards, and urbanization progress are all in rapid growth after the reform and opening up of China. On the other hand, the change is driven by the strong support of national policies, such as the 'Huaihe Eco-economic Belt Development Plan' of 2018 and the 'Outline of the Yangtze River Delta Regional Integration Development Plan' of 2019 (State Council 2018; State Council 2019). Jiangsu and Shandong are established economic provinces in China and can promote the economic development of the inland Anhui and Henan. Therefore, it is safe to assume that sharing of economic resources can be fostered by pushing the regional limitations, integrating advantages, and promoting the overall economic development of the Huaihe Eco-economic Belt.

From 2010 to 2018, the environmental capacity value was relatively stable, rising only from 0.08 to 0.28. The change can be divided into two stages. The first stage is the 2010–2012 period, when the environmental capacity level initially dropped (from 0.08 to 0.06) but then rebounded to 0.08. The main drivers of such a change are occupation and utilization of ecological resources, both increasing with the growth of urbanization, and declined in the carrying capacity of the environment. The second stage is the 2013–2018 period, when the environmental capacity level rapidly increased due to the environmental measures, such as a green area of parks per capita and a significant increase in centralized sewage treatment indicators. These factors have certainly contributed to the situation of the environmental capacity of the Huaihe Eco-economic Belt.

An estimate of the water resources system exhibited an inverted 'N' shaped change in 2010–2018. Although the status of water resources security is annually improving, the pressure on the water resources system is also increasing. For example, the indexes such as industrial wastewater discharge and total water consumption remain high. Thus, a comprehensive level of the water resources system is relatively turbulent, and more attention and vigilance will be needed in the future.

Furthermore, the coordination index calculated by Equations (16) and (18), is shown in Figure 4. The force index of the economic system was always positive except in 2011. It shows that the water resource system has continuously played a positive role in promoting economic development. The force index and coordination index of the water resource system has always been positive from 2011 to 2014, and the water resources security was good; however, in recent years, it has been hindered by economic factors. In 2017, the coordination index decreased to −0.17, indicating the dangerous state of the system. Overall, the water resources security status of the Huaihe Eco-economic Belt displayed a downward trend.

Analysis on water resources security of the prefecture-level cities

The results of the water resources security in the 25 prefecture-level cities are shown in Table 4 and Figure 5. The status of water resources changes from the pattern of east and west being better than north and south in 2011 to southeast leading and

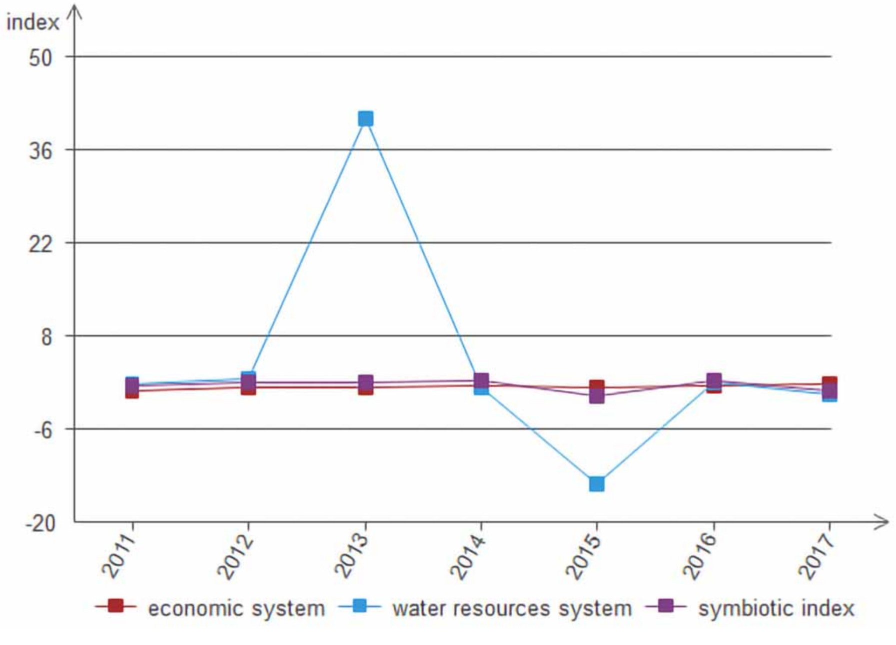

Figure 4 | The coordination index between the economic system and the water resources system.

Table 4 | Water resources security of prefecture-level cities

City	2011	2012	2013	2014	2015	2016	2017
Bengbu	I	V	I	I	V	I	I
Huainan	II	V	I	IV	II	I	V
Fuyang	VI	I	I	III	V	I	III
Luan	VI	VI	V	I	I	I	I
Bozhou	VI	II	V	V	V	I	I
Suzhou	II	I	V	V	V	I	I
Huaibei	VI	IV	I	III	V	I	I
Chuzhou	V	I	I	V	II	VI	V
Xinyang	VI	II	I	I	I	I	V
Zhumadian	I	I	I	V	I	I	V
Zhoukou	II	VI	I	V	V	I	I
Luohe	VI	II	VI	V	V	I	V
Shangqiu	II	I	I	I	VI	I	V
Pingdingshan	II	II	V	I	I	I	V
Zaozhuang	II	VI	V	VI	V	I	I
Jining	VI	VI	III	V	I	I	I
Linyi	VI	I	V	I	III	I	I
Heze	II	V	II	V	I	I	III
Huaian	II	V	I	I	I	I	I
Yancheng	II	I	V	I	I	V	V
Suqian	VI	II	VI	V	V	III	I
Xuzhou	VI	VI	V	I	I	I	III
Lianyungang	VI	II	II	III	I	I	III
Yangzhou	VI	I	V	I	I	I	V
Taizhou	VI	VI	V	I	I	III	V

northwest laggings in 2014. Ultimately, the pattern has shifted to north and south being better than east and west, and the latter was worse in 2017.

The water security status of the 25 prefecture-level cities has significantly improved from 2010 to 2018, although they remain at a low level. There are differences in the internal development, and the water security status of eastern cities is slightly better than that of inland cities. The water security status of some eastern cities significantly fluctuates. The main reason for the fluctuation is that Jiangsu is in the Yangtze River Delta region of China with bright prospects for economic development and improvement of the society. The water security issues have been examined for a long time in Jiangsu, which led to the marked results seen presently. In the cities of this province, the industrial wastewater discharge of Huai'an, Xuzhou, and Taizhou dropped down to a low level in 2018. The total amount of water resources in Yancheng significantly exceeds those in other cities. Jiangsu is being actively transformed and upgraded from an industrial perspective whereas the proportion of tertiary industries is gradually increasing. On the one hand, the consumption and utilization of water resources have been reduced. On the other hand, the governance of environment has been accelerated, and tree planting and urban greening outcomes are palpable nowadays. However, the rapid economic development still puts huge pressure on the water resources security. For example, the water consumption per 10,000-yuan GDP in Yangzhou and Taizhou is still at a high level. Shandong features convenient transportation, stable economic development, and abundant water resources. In recent years, the tourism industry has been actively developed and environmental protection has been strengthened. For example, the per capita water consumption and effective irrigation area is relatively high, while centralized sewage treatment

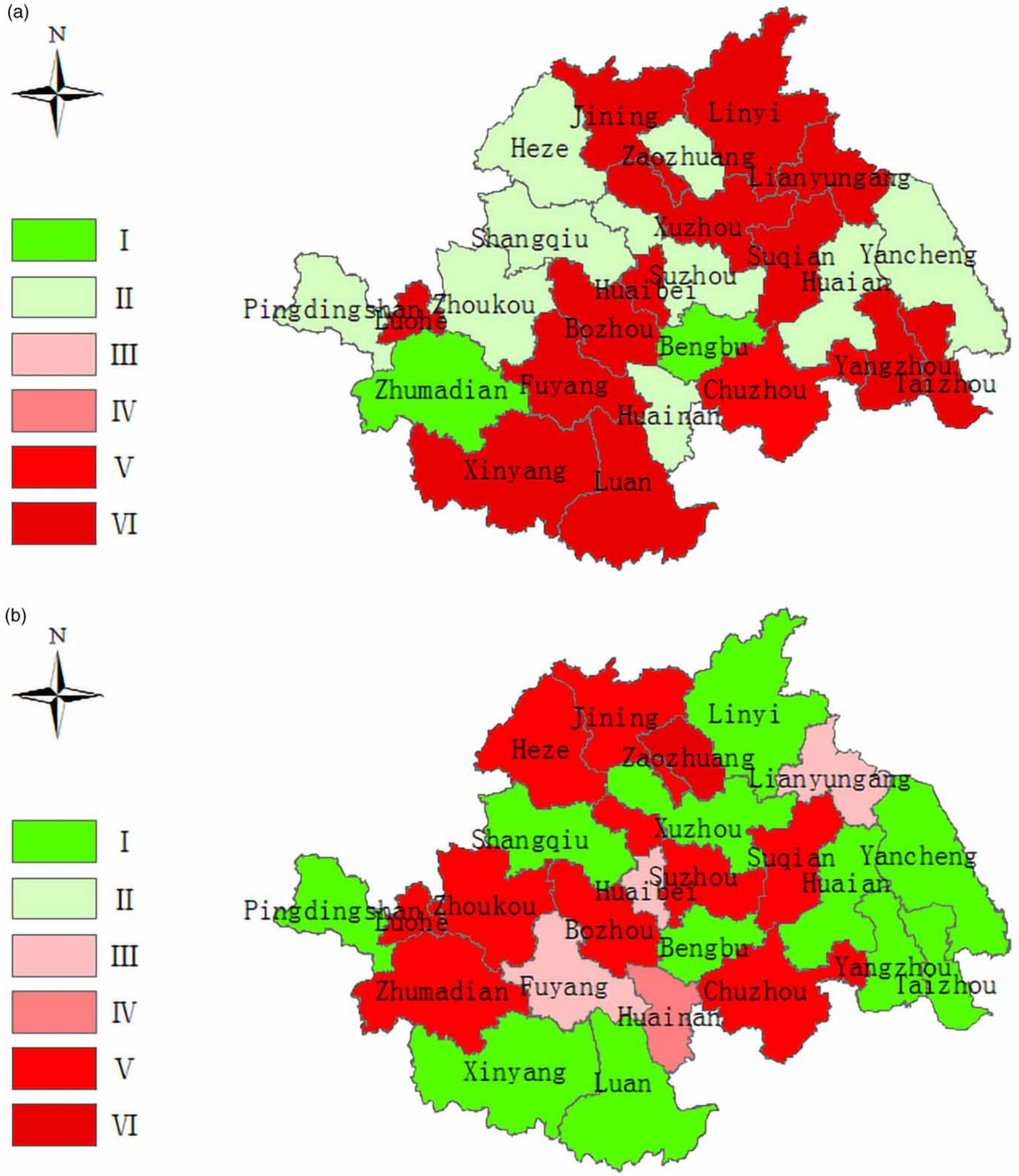

Figure 5 | Distribution of water resources security of prefecture-level cities. (a) in 2011, (b) in 2014, (c) in 2017. (*continued*).

and the proportion of harmless treatment of domestic garbage have gradually increased. The security of water resources is being improved continuously.

The water security status of Henan and Anhui is poor. Firstly, Henan has fewer water resources, a larger regional population, and fewer economic development prospects. Secondly, the primary industry of these provinces has been actively developed, thus consuming water resources for many years. In recent years, Henan has actively carried environmental governance, while the water resources security has been significantly improved. The total afforestation area of Xinyang, Zhumadian and, Pingdingshan has been increasing. The tertiary industry of Pingdingshan accounted for 44.9% in 2018

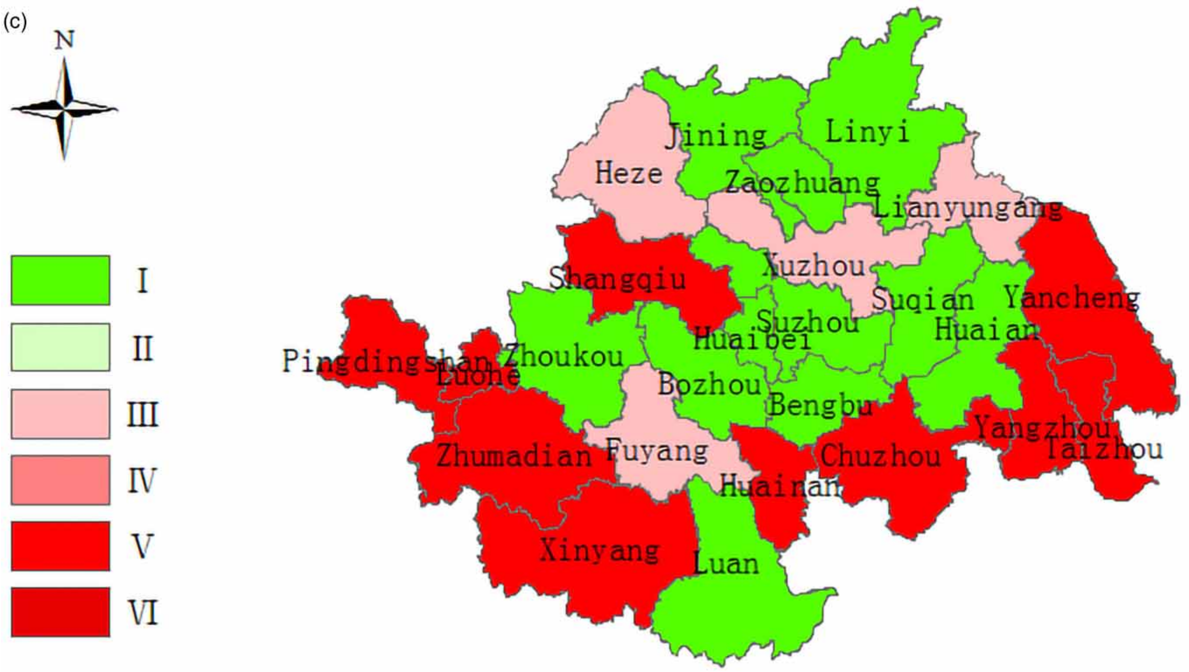

Figure 5 | (continued).

and the adjustment of industrial structure can relieve the pressure from the water resources. The security of the water resources of Anhui has also significantly improved. Most of the urban areas in Anhui are resource-based cities. For a long time, these cities had solely specialized in a single production of energy. The economic development was slow, the environmental resources were consumed, and the water resources security was at a poor level at the beginning of the research. Today, Anhui takes advantage of the synergy of high technology with coal resources to adjust the industrial structure and has also committed to the development of a green economy. In addition, environmental protection measures are formulated to promote the improvement of regional water resources security status.

Analysis of influencing factors of water resources security

The specific process of analyzing the influencing factors of the water resources system includes three steps. Firstly, EViews is used to perform a unit root test on nine variables, and the test results show that all variables are stable. Secondly, the Hausman test is used to confirm that the panel data are suitable for the fixed effects regression model. Finally, a regression test is performed on the panel data (see the results in Table 5). In these influencing factors, the correlation coefficient of GDP is -0.154. Although this did not pass the significance level test, it shows that economic development has a restrictive effect on water resources. The correlation coefficient of the added value of the tertiary industry is significant (10% level) and is equal to 0.699. It shows that the adjustment of the industrial structure plays a positive role by improving water resources. The correlation coefficient of energy conservation and environmental protection expenditure is also significant (10% level) and is equal to 0.180. This finding indicates that active environmental protection can also promote the development of water resource security. Therefore, the Huaihe Eco-economic Belt should promptly adjust the industrial structure, implement environmental protection actively, and promote sustainable development of the water resources security.

DISCUSSION

Water resources are basic natural resources and strategic economic resources, its security has become a serious restriction factor for economic and social development and ecological civilization construction. Research on water resources security can better identify potential risks of regional water resources security and help improve the status quo of regional water resources security. With the rapid development of society and economy, the influence of human activities on water resources security has intensified, and the relevant research methods are constantly enriched.

Table 5 | Test results

Independent variable	Coef.	Std. Err.	t	P
GDP	−0.154	0.605	−0.25	0.799
Industry	0.699	0.409	1.71	0.090
Worker	−0.195	0.162	−1.21	0.229
Expenditure	0.180	0.107	1.68	0.095
Job	−0.185	0.138	−1.33	0.184
Patent	0.078	0.127	0.61	0.541
_cons	−7.167	2.033	−3.53	0.001
Prob > F	0.000			
F	14.41			

At present, many researchers have studied the evaluation of regional water resources security. For example, Xiao *et al.* (2008) adopted the multi-level and multi-objective analytic hierarchy process to study the current situation of water resources security in inland river basins. You *et al.* (2018) used the fuzzy comprehensive evaluation method to evaluate the water resources security in the Rao River Basin from 2005 to 2016 in a long time series. Su *et al.* (2019) used the set pair analysis method to evaluate the current situation of water resources security in Japan from the spatial dimension. Based on a review of relevant literature, the current researchers mainly adopted two kinds of methods to evaluate water resources security: the characteristic index method and the index system method. Although the feature index method (such as the ecological footprint method) has overall ecological and economic significance and can directly understand the measurement results, the transformation of a single index into a characteristic index will lead to significant errors and loss of its own ecological and economic significance. Moreover, it is not conducive to the analysis of the causes of water resources security. In contrast, each index of the index system has ecological and economic significance, but they do not have intuitive ecological and economic significance after dimensionless and weighted treatment. Due to these shortcomings, we introduced the Lotka–Volterra biological model in this paper to integrate the advantages of the characteristic index method and index system method. The model can construct a coupling measure method for feature index method and index system method and combine the relationship between the index and weight effectively. We studied the competition or symbiotic relationship between different populations in the use of ecological resources in the same time and space.

Compared with previous methods, the Lotka–Volterra model can not only calculate the comprehensive results of regional water resources security status, but also calculate the stress level in water resources security and analyze the causes of the changes of water resources security status. However, there are a few limitations to our study. Firstly, we selected 2010–2018 as the research period. The calculation of the growth rate in the Lotka–Volterra model measures the state of water resources security only from 2011 to 2017. The period is relatively short, and it is difficult to obtain a long-term understanding of the water resources security status in the study area. To alleviate these shortcomings, more extensive data should be collected. Secondly, water resources security is affected by numerous factors, and its evaluation index system has not been established as a unified standard. Therefore, there are many discrepancies in the results of the water resources security evaluation. Based on this, the effective construction of water resources security evaluation index system, the selection of long time series as the research period, or the effective combination of the Lotka–Volterra symbiosis model and other common mathematical models should be the focus of future research.

CONCLUSIONS

Water resource security is an important foundation for social development. This study uses the Huaihe Eco-economic Belt as a research region by constructing the evaluation index system based on the DPSIR. The entropy weight method and the Lotka–Volterra model are combined to measure the water resources security from 2010 to 2018, and the fixed effects regression model is used to identify the influencing factors of the water resources system. The conclusions are as follows:

(1) From a developmental perspective, a comprehensive level of the economic system and water resources system of the Huaihe Eco-economic Belt reached a high level from 2010 to 2018. However, the water security status has exhibited a

downward trend. The force index and the coordination index of the water resources system has been positive from 2011 to 2014, and the water resources security was good. We note that it has been hindered by the economic system in recent years. In 2017, the coordination index decreased to −0.17, marking a dangerous state. Overall, the water resources security status of the Huaihe Eco-economic Belt presented a downward trend.

(2) From an internal regional development standpoint, the water security status of the 25 prefecture-level cities in the Huaihe Eco-economic Belt has significantly improved from 2010 to 2018 but is still at a low level. There are differences in the internal development among the regions, where the pattern has changed to north and south being better than east and west in 2017. Finally, the water resources security status of Jining, Linyi, and Lu'an has been developed well, but Yancheng, Taizhou, Pingdingshan and other cities still have a poor water security status.

(3) The analysis of the influencing factors revealed that economic development hinders the water resources system, and the added value of the tertiary industry, energy conservation, and environmental protection expenditures have played a positive role in promoting the water resources system. Therefore, it is now necessary to optimize and upgrade the regional industrial structure by increasing environmental protection, and promoting the development of a green economy.

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CONFLICT OF INTEREST

None declared.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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