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# A pressure-state-response-support framework for assessing regional water environmental carrying status

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The water environment carrying status (WECS) is the embodiment of the ability of an aquatic ecosystem to maintain healthy and stable development; as such, it is an essential factor in the sustainable social and economic development of a region. To evaluate the water environment carrying status of a region, a new Pressure-State-Response-Support (PSRS) framework is proposed firstly. Secondly, a water carrying status index system containing 21 indicators is constructed based on this new model, and a water environment carrying status index (WECSI) is introduced to describe the water environment carrying status. Then, projection pursuit and entropy methods are used to calculate the water environment carrying status index of eight cities along the Yangtze River in Jiangsu province as examples. The results reveal that although the government has made substantial effort, the pressure subsystem is still dominated the changes of water environment carrying status, the eight cities still face significant pressure. The analysis indicated that government departments should commit to alleviating pressure and monitoring and supervising surface water quality while continuing to maintain a supporting force. The proposed framework and methodology is sound and effective for measuring the carrying status of regional water environment, and the methods can provide guidance for the Ecological Environment Department in ensuring the carrying capabilities of water environment and achieving sustainable development mission at regional level.

## KEYWORDS

entropy method, PSRS framework, projection pursuit, water environment carrying status, water environmental status index

## 1 Introduction

### 1.1 Background

Water resource is one of the most important nature resources to support human survival, socioeconomic development and the sustainability of the ecosystem. Water ecological environment system is a social-ecological systems where humans and other organisms interact with each other. With recent increases in population, urbanization,

and the size of the economy, water resources have become over exploited, and the destruction of aquatic environments is causing serious water pollution crises in many regions and countries. A healthy aquatic ecological environment is a key restriction factor in sustainable social and economic development. Measuring water environment status accurately can help environmental management departments make effective decisions for environmental protection and management.

In order to measure water environment status of the water environment capacity, researchers have proposed a number of concepts such as water carrying capacity (WCC) (Magri and Berezowska-Azzag, 2019), water environmental carrying capacity (WECC) (Wang et al., 2018; Wei et al., 2019; Zhang et al., 2019), water resource carrying capacity (WRCC) (Naimi Ait-Aoudia and Berezowska-Azzag, 2016; Ren et al., 2016; Wang et al., 2021), water resource environmental carrying capacity (WRECC) (Zhou et al., 2019), water ecological carrying capacity (WECCC) (Wang et al., 2014; Bu et al., 2020), and water eco-environmental carrying capacity (WEECC) (Zhu et al., 2010). However, these concepts are given based on different research perspective, to ensure the accuracy of study, we need to define the research focus of these concepts firstly. Water environment is a status determined by a number of influencing factors, different with other concepts, water environment carrying capacity is the largest number of people and the largest economic scale that can be accommodated under the premise of meeting the requirement of water quality and quantity without destroying the ecological environment. It emphasizes more on the function of water environment system (Hu and Xie, 2022).

According to the literature, the aforementioned concepts have been used to measure the support capacity for the development of water resources and environments, defined as the maximum population size and economic scale that a water resource and an aquatic environment can sustain in a region without destroying the water ecological balance (Zhu et al., 2010; Wang and Xu, 2015; Zhou et al., 2017; Wei et al., 2019). However, evaluations using WECC, WRCC, WRECC or WECCC in most research have not been consistent with these concepts. For example, Wang (Wang and Xu, 2015) classified WECC in China into different categories based on the values of WEPC, WESCC and WERCC contributions, but assessment results were not associated with maximum population and economic scales. Such situations abound; for example Wei (Wei et al., 2019) calculated Z values to measure WECC of Wuhan in China and Bu (Bu et al., 2020) used the mean of Z value to describe WECCC of Changzhou in China.

To describe the research issues more accurately, we propose the concept water environmental carrying status (WECS) as a key index of whether socioeconomic development is coordinated with the water environment system, and whether the economics and society are sustainable for the watershed. In contrast to previous concepts, the WECS is affected by

socioeconomic factors, water resource attributions, water environment natural conditions, and human activities. In order to maintain the water ecological environment balance, it would be more suitable to use such a framework to present the carrying capacity status. Most research concepts in the literature can be classified within the WECS.

## 1.2 Literature review

Numerous methods have been proposed to assess resource and environmental carrying capacities. These methods can be summarized as the following types: Comprehensive index evaluation (Wang et al., 2018; Bu et al., 2020; Wei et al., 2020; Wu and Hu, 2020; Peng et al., 2021), system dynamics (Feng et al., 2008; Wang et al., 2014; Yang et al., 2015; Zhou et al., 2017), multiple objective programming method (Zhu et al., 2010), principal component analysis method (Zhang et al., 2019), projection pursuit model (Zhang and Dong, 2009; Guo et al., 2018; Wei et al., 2019), variable fuzzy pattern recognition (Wang and Xu, 2015), hybrid model (Wang et al., 2021), grey clustering method (Hu et al., 2019). These evaluation methods can be classified into two types. One type is used to calculate the actual water carrying capacity, maximum population size, and the relevant economic scale; these include system dynamics (Hu et al., 2021) and multiple objective programming methods (Zhu et al., 2010). The other type is used to calculate an index that expresses the carrying status; for example, comprehensive index evaluation (Wu et al., 2021a; Peng et al., 2021), analytic hierarchy process (Wang and Xu, 2015; Wang et al., 2018), fuzzy comprehensive evaluation methods (Wu et al., 2021b), the projection pursuit model (Guo et al., 2018; Wei et al., 2019), and entropy weight methods (Ding et al., 2015). Among them, the second type—focusing on calculating an index of WECS—is more suitable for the research objective of this paper, it can integrate all of indicators into one comprehensive index, which reflect the natural resources, social, economic, technical, environmental, meteorological and other indicators' influences to the water environment carrying status.

The most popular assessment method in water environment carrying status is comprehensive index evaluation (Liu and Borthwick, 2011; Yang et al., 2015) in which an appropriate indicator system is used as a basis for accurate assessment (Wei et al., 2019). In order to construct the indicator system, some frameworks have been used: PSR (Pressure-State-Response) (Huang et al., 2011; Zhou et al., 2013; Lai et al., 2022), DPSIR (Driving force-Pressure-State-Impact-Response) (Pirrone et al., 2005; Pandey and Shrestha S, 2016; Mosaffaie et al., 2021), DPSIRM (Driving force-Pressure-State-Impact-Response-Management) (Guo et al., 2018), eDPSIR (enhanced-Driving force-Pressure-State-Impact-Response) (Niemeijer and de Groot, 2008a), and VPOSRM (Vigor-Pressure-Organization-State-Resilience-Management) (Wei et al., 2019), which are

widely used in research on environmental impacts, sustainable development, and environment management strategies. All these frameworks emphasize causality among relevant factors in environmental systems and reveal causal chains or networks that affect the environmental status (Niemeijer and de Groot, 2008b). Among these frameworks, PSR and DPSIR are the most widely used for integrated environmental reporting and assessment (Carr et al., 2007; Niemeijer and de Groot, 2008a; Gari et al., 2015), which are evolved from Stress-Response (S-R) framework. The PSR framework focus on anthropocentric pressures and responses in its evaluation of environmental problems, it tended to push natural variability aside (Carr et al., 2007). The DPSIR was created based on PSR model, which separated the driving forces from pressure subsystem, the impact subsystem form the state system. In the DPSIR framework, the causal links start with driving forces, pass through pressure to state and impact on society, eventually leading to human's response, with the main purpose to identify the key indicators affecting the state of environment and the impact results. While these two popular frameworks contributed to water environment carrying issues, both of them have different focus. In this study, our focus is the carrying status of water environment, which is different with the frameworks aforementioned, these make the previous framework unsuitable for our study.

Socioeconomic development increases water environment pressure and degrade water aquatic environmental state. In turn, the degradation of the water environment status restricts socioeconomic development. To maintain socioeconomic development, human implementation of response measures is needed. All of these factors form a circular chain of causal relationships. In addition, technological progress and improvement of social services enhances the carrying capacity of water environment systems (Wu et al., 2021a); this can be thought of as a support system for the water environment. There are some reports in the literature that have discussed the above views; for example, Yang (Yang et al., 2015) used pressure-support ratio to measure WECC. Shen (Shen et al., 2020) introduced the ratio of urban loads to urban carrying capacity to evaluate the urban resources environment carrying capacity; they divided the forces affecting the ecosystem into "supporting" and "pressure" types. Wu (Wu and Hu, 2020) established a comprehensive system of evaluation to assess ecological carrying capacity. Different with the research object of PSR and DPSIR, the focus of this study is the evaluation of water environment carrying status, which is determined by pressure, response and support. To make the characterization of the causal chain more complete, systematic, and reasonable, a novel framework, "pressure-state-response-support" (PSRS), is proposed herein.

Among methods using the comprehensive evaluation index to evaluate carrying capacity, the entropy weight (EW) method calculates a comprehensive index based on the amount of information provide by each index, which is widely used. This

method can guarantee the objectivity of the evaluation, and is an ideal scale in multi-objective decision-making and evaluation (Wu et al., 2021a). However, the comprehensive index value calculated by this method is more easy influence by the discreteness of sample data, which brings about the instability of the indicator weight. The projection pursuit (PP) method is widely used in the evaluation of resources, environments and sustainable development problems; this method projects the high-dimensional data into low-dimensional space by searching for the best projection vector to reflect the information contained in the high-dimensional data (Wei et al., 2019). This method is more suitable for multi-index evaluation problems, but it has a difficulty in finding the global optimal value. To make the evaluation result more reliable and stable, we firstly use the two methods separately to evaluate the WECS. If there is no significant difference between the results, we integrated the results of the two methods as the final evaluation results.

### 1.3 Research purpose and innovations

To standardize the research perspective of WECC, the WECS concept was used to deconstruct WECC from the perspective of carrying capacity status; this was done in order to consider the anthropogenic and natural influences on water environment status more appropriately. By coupling human activities with water resource and environment in the analysis of the WECS, a novel conceptual framework containing four subsystems of Pressure, State, Response, and Support was proposed on the basis of the PSR model. This framework, called PSRS, was used to accurately describe causal relationships of subsystems and major influencing factors of environmental status. Based on the PSRS framework, we established the WECS evaluation index system. The proposed evaluation index system based on novel PSRS model was used to evaluate eight cities' WECS along the Yangtze River in Jiangsu Province of China. This paper adds to existing research in the following aspects:

- To deconstruct the WECC from the perspective of carrying status, the concept of "water environment carrying status" was proposed to normalize the research on water environment carrying capacity. This is determined by the pressure, response, support force, and their interactions with the social economy subsystem, natural water resource and environment condition, and habitat needs pressure.
- A novel PSRS concept framework model was proposed to describe the causality chain between different subsystems, and it is more suitable than other frameworks proposed by previous researchers.
- Based on the novel framework, an evaluation index system reflecting the causal relationship between human social

development and water environment was constructed, which is more in line with the evaluation of water environment carrying status.

- Taking eight cities along the Yangtze River in Jiangsu province as example, the proposed PSRS framework, evaluation index system, and evaluation methods are used to assess the WECS to verify the effectiveness of the proposed framework, index system and methods. We can expand the research scope to other regional WECS evaluation.

The remainder of this paper is organized as follows: a novel PSRS framework and WECS evaluation index system are presented in [Section 2](#); the evaluation methods of WECS are presented in [Section 3](#); the application of proposed framework and methods is given in [Section 4](#); and in [Section 5](#) conclusions and future work are discussed.

## 2 The PSRS framework and WECS evaluation index system

The water environment carrying status is determined according to two aspects. The first consists of the nature attribute determined by the self-organization and self-regulation of the water environment; the second consists of social attributes defined as factors that are disturbed by economic and social activities. In this paper, we mainly consider the interference of economic and social activities on the water environment.

### 2.1 A novel pressure-state-response-support (PSRS) model framework for assessing WECS

Along with the development of society and economy, humans inevitably consume water resources and discharge pollutants into water; this exerts pressure on the water environment. At the same time, habitat requirements also bring pressures to the water environment. On the one hand, pressure from human social and economic activities on the water environment alters the state of the water environment; on the other hand, responses are made to control and address water environmental issues by humans to alleviate the pressures and change the status of the water environment. In addition, there is another force, called support, that affects the regional water environment status. The ideal state of WECS is to maintain a dynamic equilibrium of pressure-response-support forces; in other words, to maintain the coordination between human activities and water resources environment. This logic is consistent with the PSR framework. However, another force, namely support, affects the state of the water environment but

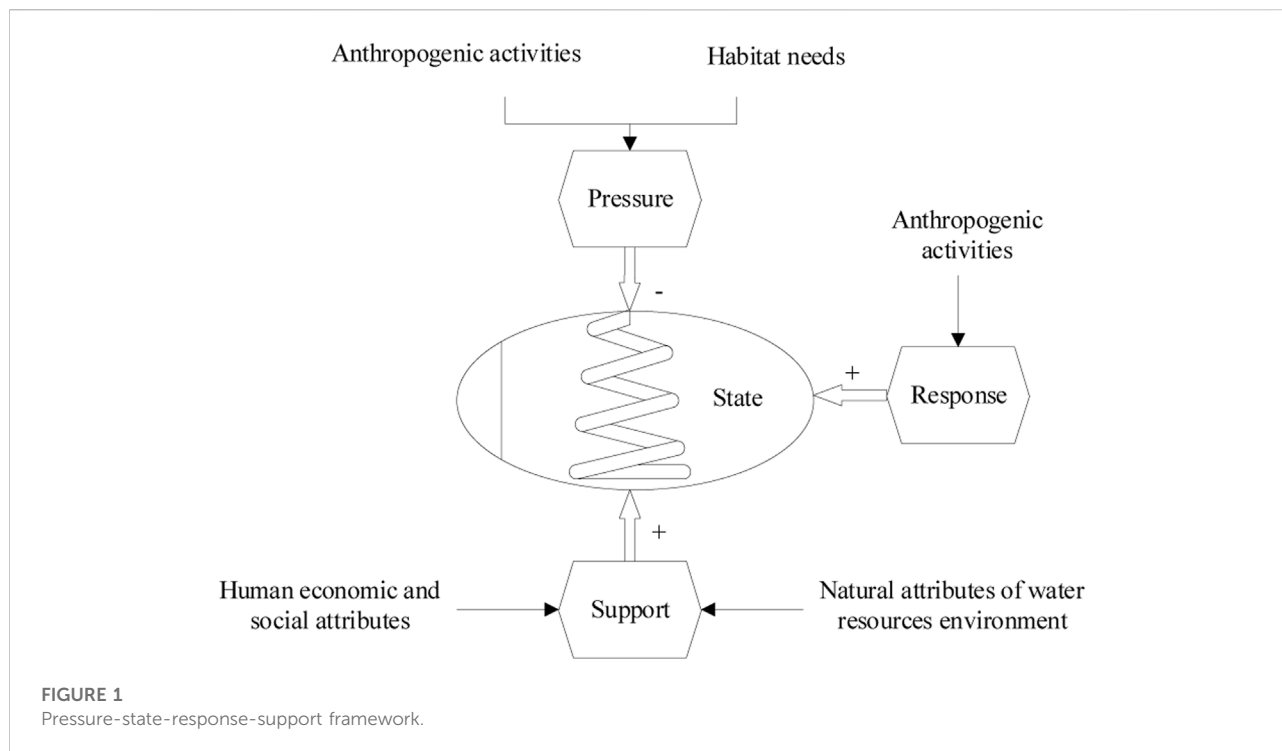
has often been neglected. The WECS is not only a reflection of the natural resources' environment characteristics but is also influenced by human society development, economic and technology development, and the protection status of the aquatic ecological environment. Coordinated development of the four parts is a precondition for the sustainable development of the society, economy, and the water ecological environment system. Based on the causal logic, a novel PSRS framework that consists of Pressure-State-Response-Support and includes causal relationships and the major influencing factors of environmental status is proposed and shown in [Figure 1](#).

In contrast to other assessment frameworks, PSRS has four compartments: a pressure subsystem (P), a state subsystem (S), a response subsystem (R), and a support subsystem (S). Water environment status is determined by human and habitat pressures, supporting elements from natural resources and human social-economic conditions, and human response activities to maintain the balances between human socioeconomic growth and environment protection; the key point is to maintain the ecosystem equilibrium. Detailed descriptions of the subsystems and their causal relationships within the novel conceptual framework are discussed below.

In the PSRS framework, the pressure subsystem includes the pressures of human socioeconomic activities and habitat needs; in the state subsystem, the indicators represent the states of water environment system; the response subsystem includes countermeasures taken by human beings to improve the status of the water environment, and the support subsystem represents the support force from urban construction, environmental protection, and natural attributes of the water resources environment. As for the pressure subsystem, the pressures are imposed by human activities and habitat requirements. On the one hand, humans consume water resources to maintain their essential life activities and socioeconomic development; on the other hand, the human activities result in water pollution and deteriorate the water environment. Under the PSRS framework, indicators in the pressure subsystem are all negative; indicators in the response subsystem are mostly positive, and indicators in the support subsystem are all positive too.

### 2.2 WECS evaluation index system based on PSRS

Developing a proper evaluation index system is a critical step in WECS evaluation. In principle, the evaluation index system should be systematic, science-based, typical, measurable, policy-relevant, and available ([Zhou et al., 2013](#); [Bu et al., 2020](#)). Indicators should neither be too numerous, to avoid cluttering the overview, nor too few to provide sufficient information ([Mosaffaie et al., 2021](#)). The WECS is influenced by the interactions between human activities and natural processes of



aquatic environments. When constructing the evaluation index system of the WESC, we considered factors including human activities, the natural environment, the influences of natural states on human society, and the management policy. Referring to previous research and consulting experts' opinion, based on classical and high-frequency characteristics, we chose evaluation indicators that could be obtained and were relevant to the water environment carrying capacity under each dimension to construct the evaluation index system. Due to the lack of available related data, the evaluation index system of WECS based on the PSRS framework concentrated on the 21 available but key indicators in [Table 1](#).

The pressure from humans can be classified into population, social, and economic pressures caused by human activities that affect the water resources and environment. The pressure that is imposed by the habitat requirements is difficult to measure, as there are no available data. Therefore, we only consider the human pressure in the pressure subsystem. Among the pressures on water environment from humans, pressures caused by industry, agriculture, and residents' life activities is far greater than from other causes. To express direct and indirect impacts of human activities, this study chose 13 pressure indicators to represent the pressure from different perspectives on the water environment; these included population, urbanization, economic scale, water demand, water resource utilization efficiency, industry, agriculture, and residents' life activities.

The state of water environmental system also affects the WECS. The Ecological index reflects the ecological environment

of research region; the higher the value, the better the basic ecological environment of the region and the stronger the supporting force to the water environment. In addition, the quality of surface water function areas and stream monitoring section are two critical state indicators of the WECS.

To maintain the balance between human activity and the natural environment, human beings must take measures to reduce the damage to the water environment; for example, by improving sewage treatment rate and intensifying efforts to curb industrial pollution and control the extent of construction.

WECS is affected by Water resources and water environment endowment, both of which are support forces. In addition to these, urban infrastructure construction is another support force in the water environmental system. In the support subsystem, total water resources, forest coverage, and greenery coverage rate of build-up areas are used to represent the support force.

### 3 Evaluation methods of water environment carrying status

#### 3.1 Assessment of WECS based on projection pursuit

Projection Pursuit is a statistical method. The steps of the Projection Pursuit comprehensive evaluation method are as follows.

Step 1: Standardizing evaluation indexes.

**TABLE 1 Evaluation index system of Water environment carrying status based on pressure-state-response-support framework.**

Category	Indicators	Description	Unit	Attributes
Pressure	Population density	Pressure of population density	Person/Square Kilometer	Negative
	Urbanization rate	Pressure from urbanization	%	Negative
	Gdp	Pressure from economic development	100 Million Yuan	Negative
	Daily domestic water consumption per capita	Water resource pressure from residents	Liter	Negative
	Water consumption per unit gdp	Water resource pressure from economic development	Cubic Meter/10 Thousand Yuan	Negative
	Amount of fertilizer used in agriculture	Water environment pressure from agriculture	Tons	Negative
	Inland waters aquaculture area	Water environment pressure from Freshwater aquaculture	Thousands of Hectares	Negative
	Industrial sewage discharged	Water environment pressure from industry	10 Thousand Tons	Negative
	Cod discharge in industrial sewage	Water environment pressure from industry	Tons	Negative
	Ammonia nitrogen discharge in industrial sewage	Water environment pressure from industry	Tons	Negative
	Domestic sewage discharge	Water environment pressure from residents	10 Thousand Tons	Negative
	Cod discharge in domestic sewage	Water environment pressure from residents	Tons	Negative
	Ammonia nitrogen discharge in domestic sewage	Water environment pressure from residents	Tons	Negative
	State	Ecological index (ei)	Status of ecological environment	
Water quality compliance rate of surface water function areas		Status of surface water function areas	%	Positive
Proportion of water quality above iii in stream monitoring section		Status of stream monitoring section	%	Positive
Response	Urban sewage treatment rate	Technical level of sewage treatment	%	Positive
	Completed investment of industrial pollution prevention and control construction projects	Efforts to prevent and control industrial pollution	10 Thousand Yuan	Positive
Support	Total water resources	Support from water resources	Million Cubic Meters	Positive
	Forest coverage	Support from vegetation	%	Positive
	Greenery coverage rate of built up areas	Support from urban construction	%	Positive

Suppose there are  $n$  evaluation objects, and each object has  $m$  indexes. To make the indexes directly comparable, we use the mini-max normalization method to normalize sample index values.

We use Eq. 1 to normalize positive indicators:

$$x_{ij} = \frac{x_{ij}^* - x_{jmin}^*}{x_{jmax}^* - x_{jmin}^*} \tag{1}$$

To normalize negative indicators, we use Eq. 2:

$$x_{ij} = \frac{x_{jmax}^* - x_{ij}^*}{x_{jmax}^* - x_{jmin}^*} \tag{2}$$

where,  $x_{ij}$  ( $i = 1, 2, \dots, n; j = 1, 2, \dots, m$ ) is the normalized value of the  $j$ th index of  $i$ th object;  $x_{ij}^*$  is the original value; and  $x_{jmin}^*$  and  $x_{jmax}^*$  are the minimum and maximum value of the index  $j$  of all objects, respectively.

Step 2: Calculating projection eigenvalues.

The projection pursuit model synthesizes  $m$ -dimensional data  $\{x(i, j) | j = 1, 2, \dots, m\}$  into one-dimensional projection values  $Z_i$  with  $a(j)$  ( $j = 1, 2, \dots, m$ ) as the projection direction. The projected eigenvalues  $z_i$  are defined as:

$$z_i = \sum_{j=1}^m a(j)x_{ij} \tag{3}$$

where,  $a(j)$  is the projection direction and is a unit length vector,  $0 \leq a(j) \leq 1$  ( $j = 1, 2, \dots, m$ ).

Step 3: Constructing projection objective function.

The projection pursuit method requires that the local projection points of projection value  $z_i$  should be as dense as possible; as a whole, the projection points should be scattered as far as possible. The projection objective function consists of three parts: the maximum of the inter class distance, the minimum of the inner class density, and the maximum entropy value in the projection direction.

The inter class distance. To extract effective information from samples to the maximum extent, projection points should be scattered as much as possible. This is represented by the maximum standard deviation of the projection eigenvalues,  $S(a)$ , which is called inter class distance.

$$S(a) = \left( \sum_{i=1}^n \frac{(z(i) - \bar{z}(i))^2}{n-1} \right)^{0.5} \tag{4}$$

where,  $\bar{z}(i)$  is the mean value of the sequence  $z_i$ ;  $n$  is the number of samples.

The inner class density. Locally, the projection points should be clustered as much as possible. Generally, the inner class density is also called the local density and is denoted by  $D(a)$ .

$$D(a) = \sum_{i=1}^n \sum_{j=1}^n (R - r_{ij})u(R - r_{ij}) \tag{5}$$

where,  $r_{ij}$  is the distance between samples  $i$  and  $j$ ,  $r_{ij} = |z(i) - z(j)|$ ;  $R$  is the window of local density, and the recommended value of its range is  $\max r_{ij}/5 \leq R \leq \max r_{ij}/3$  (Lou et al., 2014). Here we set  $R$  as  $0.1S(a)$ ;  $u(R - r_{ij})$  is the Unit Step Function.

$$u(R - r_{ij}) = \begin{cases} 0 & (R - r_{ij} \leq 0) \\ 1 & (R - r_{ij} > 0) \end{cases} \tag{6}$$

The projection objective function is constructed as follows:

$$Q(a) = S(a) \times D(a) \tag{7}$$

The key of the projection pursuit method is to find the best projection direction that is most likely to represent the characteristic structure of the high-dimensional data. When evaluation objections are given, the projection objective function  $Q(a)$  changes only with the projection direction  $a(j)$  ( $j = 1, 2, \dots, m$ ). The best projection direction can be estimated by the projection objective function maximization problem, as shown in Eq. 8.

$$\begin{cases} \max Q(a) = S(a) \times D(a) \\ \text{s.t. } \sum_{j=1}^m a^2(j) = 1 (0 \leq a(j) \leq 1) \end{cases} \tag{8}$$

This is a complicated non-linear optimization problem taking  $\{a(j) | j = 1, 2, \dots, m\}$  as optimization variables. The particle swarm optimization algorithm is used to solve the high dimensional global optimization problem in this study.

Step 4: Solving the optimal projection objective function via Particle Swarm Optimization Algorithm.

Let the population size of particles be  $N$ ; the position, velocity, and fitness value of the  $l$ th ( $l = 1, 2, \dots, N$ ) particle are expressed as  $s_l$ ,  $v_l$  and  $f_l$ , respectively. In each iteration after random generation of the initial position  $s_1$  and initial velocity  $v_1$ , the particle updates itself by tracking the individual extreme values  $pbest_l(t)$  and the global extreme value  $gbest(t)$  of the best position experienced by the swarm during the flying process. When the two optimal values are found at time  $t+1$ , the particle updates its position and velocity according to the following equation.

$$\begin{cases} v_l(t+1) = wv_l(t) + c_1b_1(t)(pbest_l(t) - s_l(t)) \\ \quad + c_2b_2(t)(gbest(t) - s_l(t)) \\ s_l(t+1) = s_l(t) + v(t+1) \end{cases} \tag{9}$$

where,  $w$  is inertia weight;  $c_1$  and  $c_2$  are learning factors of the particle and population, respectively; and  $b_1(t)$  and  $b_2(t)$  are uniform random numbers located in the interval  $(0, 1)$  that describe the randomness of particles and populations, respectively, in the velocity updating process.

The individual extremum of each particle and the global extremum of all particles are updated as follows.

$$pbest_l(t+1) = \begin{cases} s_l(t+1) & f_l(t+1) \geq f_l(pbest_l(t)) \\ pbest_l(t) & f_l(t+1) < f_l(pbest_l(t)) \end{cases} \quad (10)$$

$$gbest(t+1) = \text{Max}(pbest_l(t+1)) \quad (11)$$

where,  $f_l(t+1)$  is the fitness value of particle  $l$  at time  $t+1$ ;  $f_l(pbest_l(t))$  is the best fitness value that particle  $l$  has experienced; and  $\text{Max}(pbest_l(t+1))$  is the particle position corresponding to the maximum  $f(pbest_l(t))$  of all particles at time  $t+1$ .

When the difference between the optimal particle fitness value at times  $t+1$  and  $t$  is less than a set threshold value or reaches the predetermined iteration number, the algorithm is finished. The projection direction is the optimal projection direction  $a^*$ .

Step 5: Calculating evaluation values.

Substituting the optimal projection direction  $a^*$  obtained in step 4 into Eq. 12, the value of  $E_i$  can be obtained, representing the WECS evaluation value of the sample. We name this value be water environment carrying status index (WECSI). The greater the WECSI, the better the water environment carrying status of the region. As a relative index, WECSI can only represent the relative level and cannot be used to represent the absolute value of the carrying status of water environment.

$$E_i = \sum_{j=1}^m a^2(j)x_{ij} \quad (12)$$

### 3.2 Calculation process of the BP method based on the particle swarm optimization (PSO) algorithm

The calculation process for the BP-PSO method is shown in Figure 2. The calculation was implemented based on the MATLAB programming platform.

### 3.3 Assessment of WECS based on the entropy weight method

The entropy weight method is a mathematical method used to calculate the weight of an indicator that only depends on the discreteness of the sample data. The greater the dispersion of the index, the greater weight of this index in the evaluation of the sample. The steps of the entropy weight method for assessing the WECS are as follows.

Step 1: Standardizing evaluation indexes.

The same as in the projection pursuit method, we use Eqs 1, 2 to normalize positive and negative indicators, respectively.

Step 2: Determining the entropy of an index.

The entropy is calculated as:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n (p_{ij} \times \ln p_{ij}) \quad (13)$$

where,  $e_j(j = 1, 2, \dots, m)$  is the entropy of the  $j$ th index; and  $p_{ij} = x_{ij} / \sum_{i=1}^n x_{ij}$ , when  $p_{ij} = 0$ ,  $p_{ij} \times \ln p_{ij} = 0$ .

Step 3: Calculating the entropy weight of index

$$w_j = (1 - e_j) / \sum_{j=1}^m (1 - e_j) \quad (14)$$

Step 4: Calculating evaluation values.

Substituting the entropy weight  $w_j$  obtained in step 3 into Eq. 15, the value  $E_i$  denoting the WECSI is obtained.

$$E_i = \sum_{j=1}^m w_j x_{ij} \quad (15)$$

## 4 Case study: Eight cities along the Yangtze River in Jiangsu Province

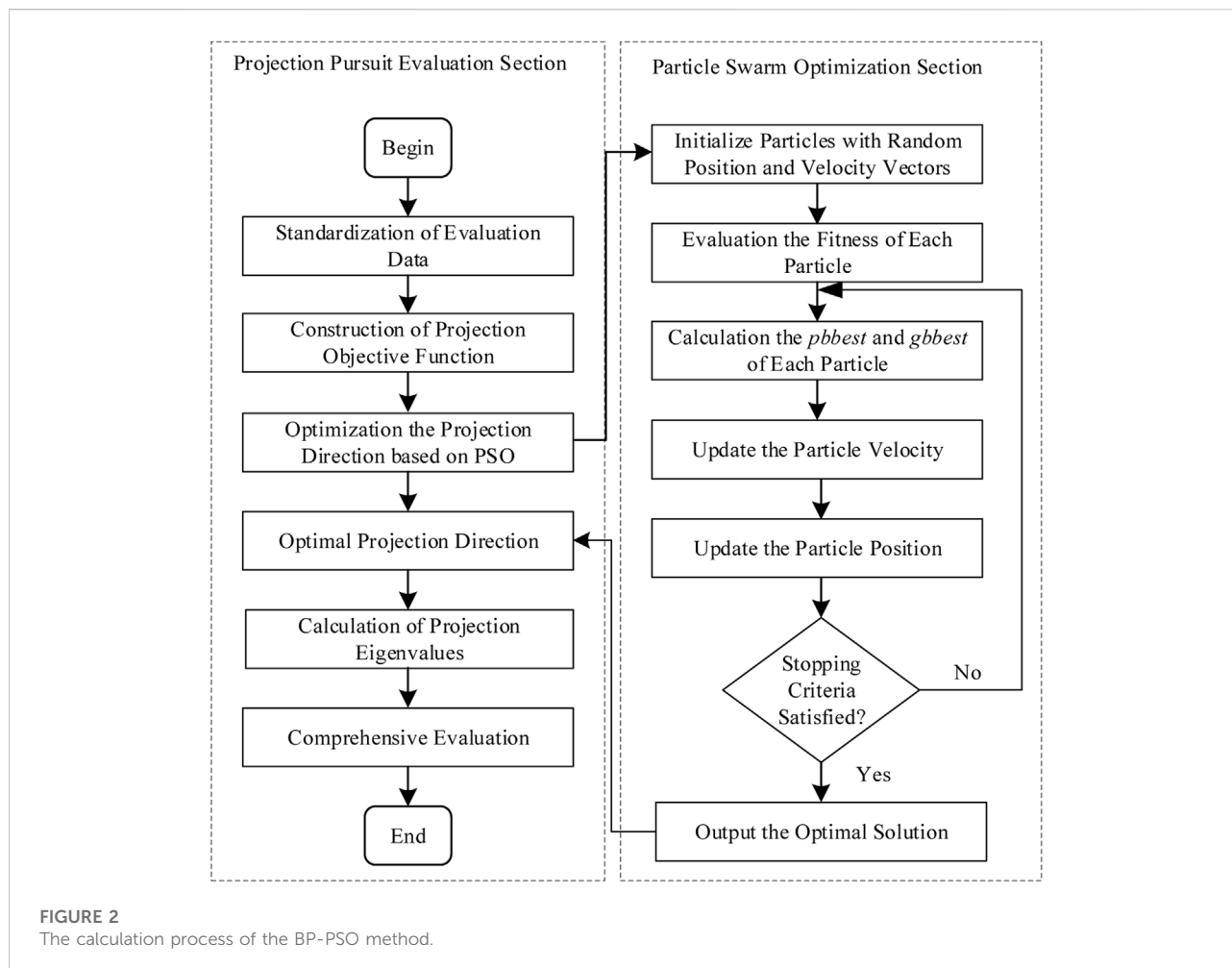
### 4.1 Studied background

The Yangtze Basin stretches across eastern, central and western China, covering nine provinces and two municipalities. With its unique advantages, the regional development of the Yangtze River Basin plays an extremely important role in the construction of a new development pattern in China. Jiangsu province (30°45'–35°08'N, 116°21'–121°56'E), located in the eastern part of the Yangtze River Basin and containing numerous lakes, has 13 prefecture-level administrative regions. By the end of 2019, Jiangsu had 107200 square kilometers of total area and 80.7 million permanent residents, making it the most densely populated province in China. Its *per capita* GDP, regional development, and livelihood index all rank first in China, and it has reached the level of a “middle and upper class” developed country. It is the only province in China where all its prefecture-level administrative regions are among the top of all cities. In the process of promoting Yangtze River Belt development, the status of the water environment and water ecology of the Yangtze River Basin has become increasingly prominent. In this context, we considered eight cities along the Yangtze River as typical research objects of the Yangtze River Basin to evaluate their WECS, and we expect the analysis to provide reference experience for watershed water environmental management and sustainable development. The location of the eight surveyed cities are displayed in Figure 3.

### 4.2 Data sources

In 2012, to promote balanced economic, political, cultural, social and ecological progress, the Chinese government unveiled strategic plans named the “Five-sphere Integrated Plan” for the new era at the





18th National Congress of the Communist Party of China, in which the strategic position of ecological civilization construction has been defined. In this context, this study used data from eight cities in Jiangsu Province along the Yangtze River from 2012 to 2019. We collected the statistics for eight cities concerning the WECS indexes from the Jiangsu Province Statistical Yearbook (2012–2019), the City Statistical Yearbook (2012–2019) of each city, the Jiangsu Province Water Resources Bulletin (2012–2019), the Water Resources bulletin (2012–2019) of each city, the Jiangsu Province Environmental Statistics Yearbook (2012–2019), and the Environmental Statistics Yearbook (2012–2019) of each city.

### 4.3 Evaluation results analysis of WECS by the PP and EW method separately

#### 4.3.1 WECS evaluation of eight cities along the Yangtze River in Jiangsu Province

The WECS of eight cities along the Yangtze River in Jiangsu province was evaluated from two perspectives. One

was an evaluation of the WECS of each city from 2012 to 2019 from a single city view; the other was an evaluation of the WECS of eight cities in each year from a horizontal year view. The WECSI was calculated by applying the methods of projection pursuit and entropy weight as detailed in Section 3.

From the single city perspective, the original data  $x_{ij}^*$  denote the value of  $j$ th index of  $i$ th year. From the horizontal year view, the original data  $x_{ij}^*$  denote the value of the  $j$ th index of the  $i$ th city. The results of WECSI obtained by the PP method from different perspective are shown in Table 2 and Table 3. The results of WECSI obtained by the EW method from different perspective are shown in Table 4 and Table 5.

#### 4.3.2 Trend analysis of WECS from city view

WECSI represents the level of water environment carrying status of a region. In order to compare the evaluation results of WECS more intuitively, the WECSI of eight cities obtained by the PP and EW methods from a single city view are shown in Figure 4.



Figure 4A shows the evaluation results using the PP method, and Figure 4B shows the evaluation results by the EW method. In general, the water environment carrying status obtained from two different methods had the same yearly upward trend from 2012 to 2019. The WECS of Yangzhou was the lowest in the eight cities; Changzhou, Nantong, and Taizhou are in the middle class; Nanjing, Suzhou, and Wuxi had better carrying status, and the WECSs calculated by the two methods for Zhenjiang are quite different.

As shown in Figure 4A, the WECSI values of these eight cities maintained a clear upward trend with the exception of Suzhou, whose WECSI fluctuated. Over the research period, the growth rate of WECSI was fairly similar in different cities. In 2012 and 2013, the WECS of Nanjing city had the lowest value among the eight cities, followed by Wuxi, Nantong, Taizhou, Changzhou, Suzhou and Yangzhou. Zhenjiang's WECS improved the most; this city was the lowest among the eight cities in 2012, but had become the best by 2019.

Figure 4B shows that the WECS of Nanjing and Wuxi steadily improved year by year; in general, the WECS of Nantong, Suzhou, Taizhou and Zhenjiang showed the same trend as Nanjing and Wuxi, but there was a downward trend in some individual years such as 2013 and 2014; the WECS of Changzhou and Yangzhou fluctuated but had an overall upward trend. Among the eight cities, the WECS in Nanjing, Wuxi, Suzhou and Taizhou had the greatest improvement.

The projection direction  $a_i'$  obtained by the PP method and the entropy weight of indicators in the EW method reflected the influence of the corresponding indicators on the WECS. The

projection direction  $a_i'$  obtained by the PP method is shown in Table 6; the weights of each indicator in the  $i$ th city obtained by the EW method are shown in Table 7.

Indicators whose projection direction value exceeded 0.3 in Table 6 include water consumption per unit GDP (WCG), amount of fertilizer used in agriculture (AFA), inland waters aquaculture area (IWA), industrial sewage discharged (ISD), COD discharge in industrial sewage (CIS), ammonia nitrogen discharge in industrial sewage (AIS), domestic sewage discharge (DSD), COD discharge in domestic sewage (CDS), ammonia nitrogen discharge in domestic sewage (ADS), water quality success rate of surface water function areas (QWF), proportion of water quality above III in stream monitoring sections (PSW), greenery coverage rate of built up areas (GCB), and urban sewage treatment rate (STR). These 13 indicators had the greatest impact on the water environment carrying status in the eight cities.

The entropy weights of indicators exceeding 0.06 in Table 7 include water consumption per unit GDP (WCG), amount of fertilizer used in agriculture (AFA), inland waters aquaculture area (IWA), COD discharge in industrial sewage (CIS), ammonia nitrogen discharge in industrial sewage (AIS), domestic sewage discharge (DSD), ammonia nitrogen discharge in domestic sewage (ADS), water quality success rate of surface water function areas (QWF), proportion of water quality above III in stream monitoring sections (PSW), total water resources (TWR), forest coverage (FC), greenery coverage rate of built up area (GCB), urban sewage treatment rate (STR) and completed investment of industrial pollution prevention and control construction projects (CII).

In comparing the major influence indicators obtained by the two methods, 11 indicators are the same, while ISD and CDS indicators in the PP method, and the TWR, FC and CII indicators in the EW method do not appear simultaneously. The comparative analysis shows that the evaluation results of the two methods were generally the same, and suggesting that both of them can be used to evaluate the WECS.

#### 4.3.3 Trend analysis of WECS from the horizontal year view

Figure 5 presents WECSI values calculated by the PP and EW methods from the horizontal year view. The WECSI scale obtained by the EW method was concentrated between 0.4209 and 0.6829, while the WECSI calculated by the PP method fluctuated. Except for Taizhou and Wuxi, the WECS rankings of each city obtained by the two methods were the same.

Figure 5A shows the variation of WECS calculated by the PP method. The WECSI values of the eight cities were ranked every year during the evaluation period. The WECS of Changzhou ranked second twice, third four times, and fifth and sixth once each. Nanjing ranked first twice, fourth, sixth and eighth once each, and seventh three times. Nantong

**TABLE 2** Water environment carrying status index of eight cities along the Yangtze River in Jiangsu province from the city view by the projection pursuit method.

City	2012	2013	2014	2015	2016	2017	2018	2019
Changzhou	0.1929	0.1939	0.2025	0.3658	0.5239	0.6441	0.8520	0.9085
Nanjing	0.0578	0.0425	0.1471	0.2438	0.5647	0.7651	0.8557	0.9432
Nantong	0.1227	0.0770	0.3326	0.4798	0.6354	0.6713	0.7611	0.8681
Suzhou	0.2435	0.3502	0.1333	0.1252	0.6368	0.7665	0.7545	0.8255
Taizhou	0.1534	0.1419	0.1195	0.2080	0.5973	0.6689	0.8030	0.9153
Wuxi	0.0939	0.0899	0.2469	0.2732	0.5172	0.6367	0.8308	0.9449
Yangzhou	0.3451	0.3360	0.3022	0.1558	0.3635	0.5396	0.6760	0.9161
Zhenjiang	0.0477	0.3291	0.4053	0.5103	0.5685	0.7644	0.8199	0.9928

**TABLE 3** Water environment carrying status index of eight cities along the Yangtze River in Jiangsu province from the horizontal year view by the projection pursuit method.

Year	Changzhou	Nanjing	Nantong	Suzhou	Taizhou	Wuxi	Yangzhou	Zhenjiang
2012	0.6020	0.1641	0.6642	0.2295	0.6212	0.6237	0.8273	0.6491
2013	0.7910	0.4148	0.6021	0.2262	0.8337	0.7530	0.8173	0.7619
2014	0.6944	0.3592	0.8311	0.2455	0.8709	0.5539	0.8557	0.8551
2015	0.7900	0.5424	0.6362	0.1740	0.7926	0.7778	0.7575	0.6965
2016	0.8757	0.6925	0.5884	0.0451	0.9050	0.7370	0.7860	0.8978
2017	0.8644	0.7617	0.2191	0.5501	0.5939	0.8792	0.4193	0.8752
2018	0.7499	0.7816	0.4085	0.1776	0.7349	0.7332	0.5647	0.7769
2019	0.7648	0.7866	0.2661	0.3294	0.7464	0.7469	0.7321	0.7438

**TABLE 4** Water environment carrying status index of eight cities along the Yangtze River in Jiangsu province from the city view by the EW method.

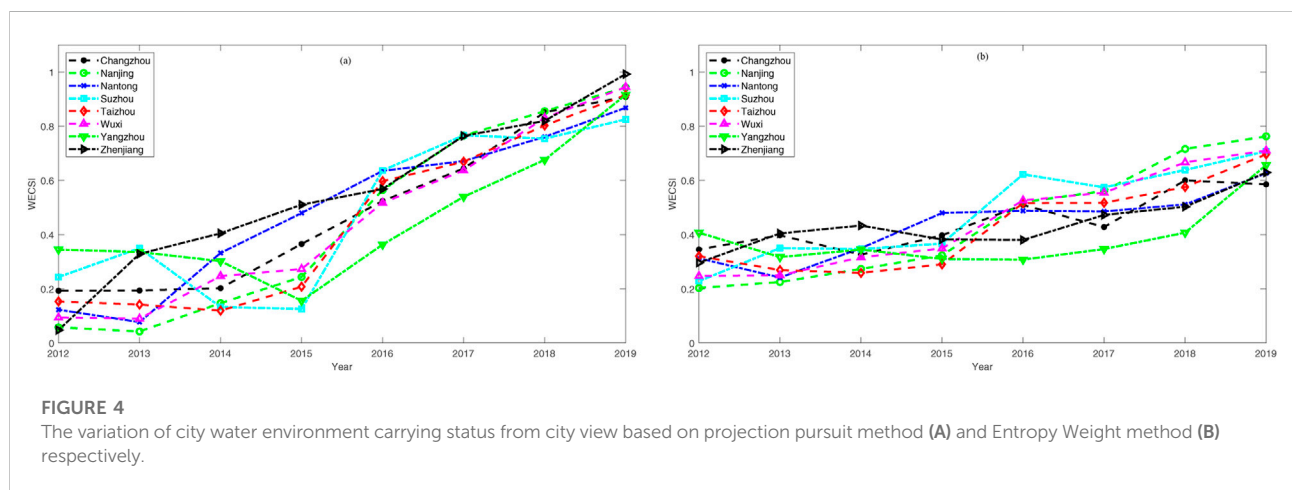
City	2012	2013	2014	2015	2016	2017	2018	2019
Changzhou	0.3453	0.3978	0.3263	0.3977	0.5094	0.4284	0.6001	0.5853
Nanjing	0.2031	0.2253	0.2735	0.3237	0.5199	0.5609	0.7161	0.7629
Nantong	0.3128	0.2417	0.3502	0.4799	0.4877	0.4853	0.5113	0.6266
Suzhou	0.2284	0.3506	0.3467	0.3673	0.6225	0.5742	0.6387	0.7075
Taizhou	0.3206	0.2691	0.2590	0.2904	0.5162	0.5173	0.5757	0.6963
Wuxi	0.2471	0.2500	0.3164	0.3493	0.5261	0.5548	0.6664	0.7104
Yangzhou	0.4075	0.3173	0.3451	0.3105	0.3080	0.3470	0.4075	0.6565
Zhenjiang	0.2963	0.4047	0.4338	0.3824	0.3807	0.4727	0.5027	0.6291

ranked second and fourth once each, and sixth, seventh, and eighth twice each. Suzhou ranked sixth once, seventh twice, and eighth five times. Taizhou ranked first four times and fourth and fifth twice each. Wuxi ranked first, fourth, and

sixth once each, third twice, and fifth three times. Yangzhou first and seventh once each, and second, fourth, and sixth twice each. Zhenjiang ranked second three times, third and fifth twice each, and fourth once. Overall, Suzhou city had the

**TABLE 5** Water environment carrying status index of eight cities along the Yangtze River in Jiangsu province from the horizontal year view by the EW method.

Year	Changzhou	Nanjing	Nantong	Suzhou	Taizhou	Wuxi	Yangzhou	Zhenjiang
2012	0.5806	0.4442	0.5743	0.4314	0.4961	0.6464	0.6563	0.5490
2013	0.5947	0.5332	0.5561	0.4959	0.5424	0.6170	0.6363	0.6748
2014	0.5292	0.5544	0.6440	0.5006	0.5597	0.6697	0.6413	0.6829
2015	0.5281	0.5226	0.6274	0.4749	0.5012	0.6180	0.5560	0.6173
2016	0.5900	0.5790	0.4802	0.5264	0.5208	0.6443	0.4845	0.6484
2017	0.5932	0.5815	0.5266	0.4915	0.5207	0.6412	0.4818	0.6236
2018	0.5854	0.5994	0.5041	0.4695	0.4775	0.6466	0.4637	0.5595
2019	0.4863	0.5220	0.4209	0.4480	0.4565	0.5497	0.5947	0.5305



lowest WECS, followed by Nantong, Nanjing, Wuxi, Yangzhou, Changzhou, Zhenjiang, and Taizhou.

Figure 5B shows the variation of WECS obtained by the EW method. The WECSI values of the eight cities calculated by the EW method were ranked each year. Overall, Suzhou city had the lowest WECS, followed by Taizhou, Nantong, Nanjing, Yangzhou, Changzhou, Zhenjiang, and Wuxi. The WECS of Changzhou ranked third twice, fourth and seventh once each, and fifth twice. Nanjing ranked second once, fourth three times, sixth and seventh once each. Nantong ranked first, third, and fourth once each, fifth three times, and eighth twice. Suzhou ranked fifth once, seventh three times, and eighth four times. Taizhou ranked fifth and seventh once each and sixth six times. Wuxi ranked first two times, second five times and third once. Yangzhou ranked second and seventh once each, first, fourth, and eighth twice each, with clear downward trend and then an upward trend during the research period, similar to the results for the PP method. Zhenjiang ranked first three times, third twice, and second, fourth, and fifth once each.

The projection direction  $a'_i$ , obtained by the PP method from the horizontal year view is shown in Table 8. The weight of each indicator in the  $i$ th year obtained by the EW method is shown in Table 9. The major influence factors of annual WECS obtained by the PP method and EW method were quite different.

Indicators whose projection direction value exceed 0.3 in Table 8 are urbanization rate (UR), GDP, daily domestic water consumption *per capita* (DDW), amount of fertilizer used in agriculture (AFA), industrial sewage discharged (ISD), COD discharge in industrial sewage (CIS), ammonia nitrogen discharge in industrial sewage (AIS), domestic sewage discharge (DSD), ammonia nitrogen discharge in domestic sewage (ADS), ecological index (EI), proportion of water quality above III in stream monitoring sections (PSW), forest coverage (FC), and urban sewage treatment rate (STR).

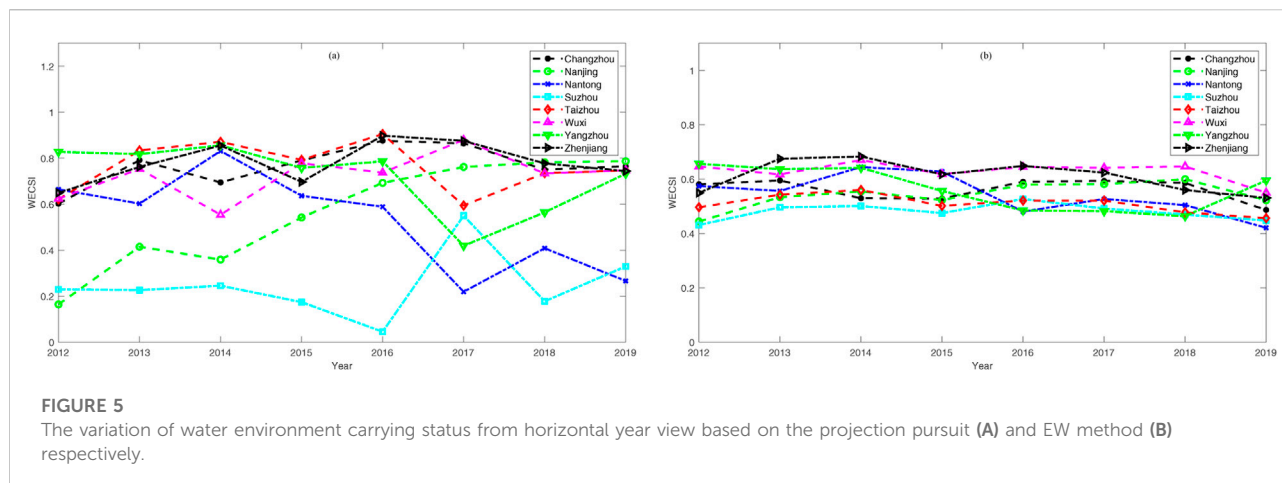
The entropy weights of indicators that exceed 0.06 in Table 9 are daily domestic water consumption *per capita* (DDW), amount of fertilizer used in agriculture (AFA), COD discharge in domestic sewage (CDS), water quality success rate of surface water function areas (QWF), proportion of water quality above

**TABLE 6 Optimal projection direction in different cities.**

City	PD	UR	GDP	DDW	WCG	AFA	IWA	ISD	CIS	AIS	DSD	CDS	ADS	EI	QWF	PSM	TWR	FC	GCB	STR	CII
Changzhou	0.0384	0.0039	0.0158	0.1895	0.3388	0.2923	0.4118	0.0158	0.2262	0.0064	0.2771	0.1483	0.2302	0.1542	0.3343	0.3521	0.0201	0.2094	0.0657	0.2849	0.0008
Nanjing	0.0043	0.0005	0.0459	0.0112	0.1637	0.0714	0.3900	0.2323	0.3784	0.4203	0.0096	0.0864	0.3183	0.1917	0.1291	0.1964	0.1425	0.1139	0.2697	0.3646	0.0123
Nantong	0.2975	0.0040	0.0007	0.0101	0.3271	0.3084	0.3235	0.0797	0.1507	0.1052	0.0172	0.3613	0.2616	0.0151	0.1376	0.1906	0.1183	0.1902	0.4777	0.1662	0.0612
Suzhou	0.0084	0.0882	0.0028	0.1393	0.2197	0.2824	0.1648	0.1085	0.2325	0.2455	0.4613	0.0180	0.3083	0.0143	0.3153	0.4702	0.0007	0.0831	0.0408	0.0515	0.2268
Taizhou	0.1140	0.0119	0.0024	0.1548	0.1928	0.1889	0.3772	0.1617	0.3632	0.3877	0.2427	0.1892	0.3713	0.0091	0.1294	0.2891	0.0481	0.1884	0.1962	0.1660	0.0506
Wuxi	0.0035	0.0049	0.0012	0.0308	0.1603	0.2367	0.3139	0.3561	0.3043	0.2594	0.1992	0.2170	0.3702	0.0089	0.3533	0.2662	0.1683	0.0535	0.0891	0.2688	0.0327
Yangzhou	0.0012	0.0074	0.0219	0.0371	0.1631	0.2061	0.2209	0.1904	0.3453	0.3890	0.4185	0.2873	0.1360	0.1913	0.1770	0.2126	0.0055	0.0981	0.3729	0.1877	0.0131
Zhenjiang	0.0002	0.0004	0.0015	0.0498	0.2637	0.2420	0.2999	0.2576	0.2902	0.2608	0.0195	0.2610	0.2710	0.0784	0.2849	0.2815	0.0158	0.0009	0.3593	0.2355	0.2599

**TABLE 7 Entropy weights of indicators in different cities.**

City	PD	UR	GDP	DDW	WCG	AFA	IWA	ISD	CIS	AIS	DSD	CDS	ADS	EI	QWF	PSM	TWR	FC	GCB	STR	CII
Changzhou	0.0344	0.0463	0.0434	0.0685	0.0318	0.0347	0.0915	0.0303	0.0297	0.0468	0.0570	0.0569	0.0198	0.0344	0.0586	0.0665	0.0571	0.0330	0.0202	0.0381	0.1008
Nanjing	0.0295	0.0333	0.0330	0.0340	0.0307	0.0498	0.1176	0.0476	0.0727	0.0607	0.0436	0.0524	0.0595	0.0623	0.0394	0.0498	0.0330	0.0353	0.0538	0.0352	0.0270
Nantong	0.0419	0.0449	0.0343	0.0204	0.0502	0.1273	0.1136	0.0253	0.0269	0.0242	0.0293	0.0300	0.0341	0.0519	0.0682	0.0598	0.0529	0.0329	0.0619	0.0351	0.0347
Suzhou	0.0428	0.0448	0.0418	0.0275	0.0647	0.0422	0.0724	0.0448	0.0741	0.0459	0.0441	0.0429	0.0521	0.0507	0.0715	0.0579	0.0486	0.0242	0.0315	0.0204	0.0552
Taizhou	0.0241	0.0395	0.0487	0.0497	0.0294	0.0750	0.0530	0.0496	0.0655	0.0538	0.0794	0.0431	0.0530	0.0484	0.0217	0.0714	0.0401	0.0235	0.0536	0.0345	0.0431
Wuxi	0.0381	0.0407	0.0398	0.0298	0.0608	0.0337	0.1037	0.0457	0.0710	0.0365	0.0685	0.0497	0.0604	0.0297	0.0580	0.0228	0.0795	0.0295	0.0334	0.0386	0.0301
Yangzhou	0.0281	0.0403	0.0368	0.0211	0.0327	0.1491	0.0627	0.0431	0.0537	0.0344	0.0211	0.0271	0.0338	0.0319	0.0407	0.0342	0.0373	0.0227	0.1373	0.0581	0.0538
Zhenjiang	0.0389	0.0517	0.0648	0.0344	0.0208	0.0383	0.0854	0.0539	0.0213	0.0204	0.0476	0.0206	0.0223	0.0517	0.0372	0.0405	0.0608	0.1152	0.0367	0.0637	0.0740



III in stream monitoring sections (PSW), total water resources (TWR), forest coverage (FC), greenery coverage rate of built up area (GCB), urban sewage treatment rate (STR), and completed investment of industrial pollution prevention and control construction projects (CII).

## 4.4 Evaluation results analysis of WECS by the integrated method

### 4.4.1 Evaluation results of WECS by the integrated method

PP and EW are sample driven evaluation methods that are intended to reveal the classification and ranking structure of evaluation objects through the exploration of sample data.

From the analysis of part Section 4.3.2 and Section 4.3.3, the evaluation results obtained by PP and EW methods tended to be consistent; both methods can be used to evaluate the WECS of a region. The PP method is used to solve the high-dimensional non-linear problems; the method employs the projection value to reveal the structural characteristics of high-dimensional data, but it does have a certain difficulty in finding the global optimal value. The evaluation results of the EW method are determined by the discreteness of the sample data, so they are stable, but they are also very dependent. In order overcome the weaknesses of the two methods, the evaluation results of these two methods were integrated to obtain the final evaluation results for the WECS of the eight cities in Jiangsu Province. The final evaluation results of the WECSI from the single city view and horizontal year view are shown in Table 11 and Table 12; the indicator weights of different cities by the integrated method are shown in Table 10. These indicator weights are equal to the average of the square of the optimal projection direction  $a^*$  and the entropy weight.

### 4.4.2 Analysis of the evaluation results of city WECS

In order to intuitively analyze the variation trend of WECS of eight cities from 2012 to 2019, the final results of WECSI using the integrated PP and EW method from single city and horizontal year views are shown in Figures 6A, B, respectively.

Table 11 and Figure 6A show the variation of WECS from the city view based on the integrated method. As shown, the WECSI of Nanjing and Zhenjiang city show a trend of continuous increase from 2012 to 2019. During the period from 2012 to 2019, the WECSI of Nantong, Wuxi, Yangzhou, and Taizhou all show a trend of decreasing first and then increasing. The WECSI of Nantong and Wuxi decreased slightly in 2013 and then showed annual increases. The WECSI of Yangzhou decreased annually from 2012 to 2015, then increased annually from 2015 to 2019, while the WECSI of Taizhou decreased from 2012 to 2014 annually, and then increased from 2014 to 2019 year by year. The WECSI of Changzhou and Suzhou displayed the greatest fluctuation; the values of 2013 were higher than in 2012, then decreased in 2014, and increased annually thereafter.

Table 12 and Figure 6B show the variation of WECSI in different years of the eight cities based on the integrated method. During the period 2012 to 2019, Suzhou city had the worst WECS, followed by Nantong, Nanjing, Taizhou, Changzhou, Wuxi, Yangzhou, and Zhenjiang. Combined with the analysis of temporal variation, although the WECS of Nanjing was least among the eight cities as a whole, there was significant improvement from 2012 to 2019; the WECS of Zhenjiang had been improving continuously; compared to the other seven cities, the WECS of Yangzhou changed from a relatively better status at the beginning to a relatively poor status. During the evaluation period, the WECS of Changzhou and Wuxi were always in the upper to middle ranking of the eight cities; Taizhou was in the lower-middle position, and Suzhou and Nantong ranked relatively low, although their WECS improved to some extent.

**TABLE 8 Optimal projection direction in different years.**

Year	PD	UR	GDP	DDW	WCG	AFA	IWA	ISD	CIS	AIS	DSD	CDS	ADS	EI	QWF	PSM	TWR	FC	GCB	STR	CII
2012	0.1755	0.2397	0.1590	0.4122	0.0693	0.4038	0.0004	0.0684	0.1853	0.2373	0.2772	0.1627	0.4167	0.1797	0.0340	0.2499	0.0711	0.0972	0.0416	0.0063	0.2533
2013	0.1233	0.1412	0.3096	0.1262	0.1346	0.1601	0.0287	0.4036	0.3313	0.1682	0.3466	0.0055	0.4319	0.4237	0.0004	0.0127	0.0130	0.0616	0.1283	0.0273	0.0070
2014	0.1043	0.6055	0.3340	0.1999	0.1280	0.0189	0.0413	0.4229	0.1538	0.2607	0.1927	0.1362	0.1148	0.1867	0.0083	0.0072	0.1972	0.1500	0.0004	0.1290	0.0163
2015	0.1300	0.1021	0.3331	0.1658	0.1461	0.0235	0.0026	0.3927	0.2565	0.3187	0.2689	0.0328	0.2947	0.4409	0.0730	0.1089	0.0035	0.2938	0.0627	0.0053	0.1689
2016	0.0731	0.0272	0.4537	0.0787	0.1650	0.0597	0.0302	0.3862	0.4901	0.4582	0.2812	0.0936	0.0813	0.1323	0.0168	0.0098	0.0059	0.1893	0.0479	0.0170	0.0107
2017	0.0024	0.1390	0.1626	0.0366	0.2487	0.5519	0.0218	0.1195	0.3522	0.3423	0.0227	0.1980	0.3859	0.0063	0.1561	0.2156	0.0000	0.2178	0.0165	0.1523	0.0035
2018	0.0010	0.0164	0.0599	0.2487	0.0672	0.2496	0.0803	0.2428	0.4696	0.4277	0.2377	0.0559	0.2726	0.1992	0.1088	0.1079	0.0003	0.3605	0.1175	0.2181	0.1009
2019	0.0744	0.0986	0.2493	0.2059	0.1507	0.2386	0.0036	0.0639	0.3516	0.4149	0.1628	0.0018	0.3172	0.2401	0.1260	0.3407	0.0053	0.2428	0.1428	0.3233	0.0023

**TABLE 9 Entropy weights of indicators in different years.**

Year	PD	UR	GDP	DDW	WCG	AFA	IWA	ISD	CIS	AIS	DSD	CDS	ADS	EI	QWF	PSM	TWR	FC	GCB	STR	CII
2012	0.0515	0.0415	0.0336	0.0669	0.0524	0.0618	0.0348	0.0278	0.0310	0.0299	0.0404	0.0523	0.0390	0.0357	0.0313	0.0842	0.0613	0.0712	0.0380	0.0604	0.0553
2013	0.0546	0.0451	0.0356	0.0877	0.0421	0.0501	0.0367	0.0297	0.0325	0.0312	0.0425	0.0441	0.0428	0.0375	0.0316	0.0756	0.0601	0.0796	0.0385	0.0319	0.0706
2014	0.0594	0.0499	0.0381	0.0767	0.0420	0.0572	0.0407	0.0318	0.0348	0.0337	0.0402	0.0529	0.0372	0.0394	0.0361	0.0724	0.0683	0.0616	0.0373	0.0328	0.0574
2015	0.0549	0.0458	0.0357	0.0612	0.0365	0.0539	0.0369	0.0296	0.0318	0.0306	0.0429	0.0500	0.0393	0.0362	0.0450	0.0643	0.0975	0.0504	0.0381	0.0348	0.0846
2016	0.0535	0.0428	0.0349	0.0610	0.0434	0.0521	0.0356	0.0303	0.0336	0.0304	0.0430	0.0451	0.0440	0.0332	0.0813	0.0643	0.0579	0.0529	0.0468	0.0291	0.0847
2017	0.0545	0.0412	0.0356	0.0525	0.0515	0.0509	0.0352	0.0311	0.0386	0.0315	0.0499	0.0388	0.0356	0.0417	0.0480	0.0403	0.0618	0.0469	0.0751	0.0496	0.0895
2018	0.0504	0.0372	0.0330	0.0621	0.0589	0.0453	0.0325	0.0284	0.0380	0.0279	0.0390	0.0667	0.0322	0.0497	0.0728	0.0355	0.0474	0.0440	0.0716	0.0498	0.0778
2019	0.0461	0.0333	0.0314	0.0661	0.0491	0.0413	0.0301	0.0262	0.0440	0.0263	0.0392	0.0351	0.0245	0.0327	0.0543	0.0234	0.1046	0.0370	0.1519	0.0536	0.0499

TABLE 10 Indicator weights of different cities by the integrated method.

City	PD	UR	GDP	DDW	WCG	AFA	IWA	ISD	CIS	AIS	DSD	CDS	ADS	EI	QWF	PSM	TWR	FC	GCB	STR	CII
Changzhou	0.0180	0.0232	0.0218	0.0522	0.0733	0.0601	0.1305	0.0153	0.0404	0.0234	0.0669	0.0394	0.0364	0.0291	0.0852	0.0952	0.0287	0.0384	0.0123	0.0597	0.0504
Nanjing	0.0148	0.0167	0.0176	0.0171	0.0287	0.0274	0.1349	0.0508	0.1079	0.1187	0.0219	0.0299	0.0804	0.0495	0.0280	0.0442	0.0266	0.0241	0.0633	0.0841	0.0136
Nantong	0.0652	0.0225	0.0171	0.0103	0.0786	0.1112	0.1091	0.0158	0.0248	0.0176	0.0148	0.0803	0.0513	0.0261	0.0436	0.0481	0.0335	0.0346	0.1450	0.0314	0.0192
Suzhou	0.0214	0.0263	0.0209	0.0235	0.0565	0.0610	0.0498	0.0283	0.0641	0.0531	0.1284	0.0216	0.0736	0.0255	0.0854	0.1395	0.0243	0.0156	0.0166	0.0115	0.0533
Taizhou	0.0186	0.0198	0.0244	0.0368	0.0333	0.0553	0.0977	0.0378	0.0987	0.1021	0.0692	0.0395	0.0954	0.0242	0.0192	0.0775	0.0212	0.0295	0.0460	0.0310	0.0228
Wuxi	0.0190	0.0204	0.0199	0.0154	0.0432	0.0449	0.1011	0.0863	0.0818	0.0519	0.0541	0.0484	0.0987	0.0149	0.0914	0.0468	0.0539	0.0162	0.0207	0.0554	0.0156
Yangzhou	0.0140	0.0202	0.0187	0.0112	0.0297	0.0958	0.0557	0.0397	0.0865	0.0929	0.0981	0.0548	0.0262	0.0342	0.0560	0.0397	0.0187	0.0162	0.1382	0.0467	0.0270
Zhenjiang	0.0194	0.0258	0.0324	0.0184	0.0452	0.0484	0.0877	0.0601	0.0528	0.0442	0.0240	0.0444	0.0479	0.0289	0.0592	0.0599	0.0305	0.0576	0.0829	0.0596	0.0708

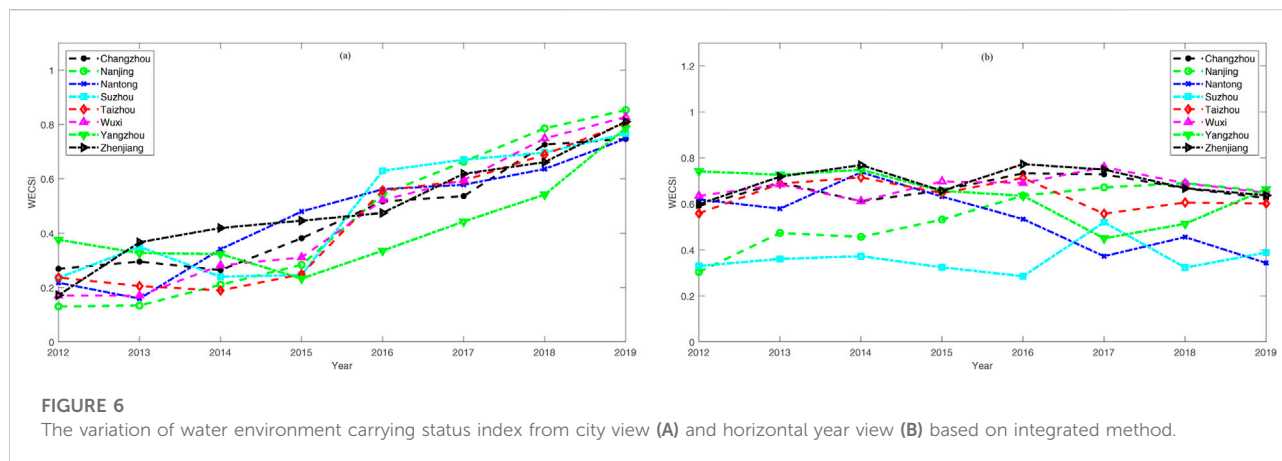
### 4.4.3 Analysis of the major influencing factors of city WECS

The major influence indicators of each city are listed in Table 10. The major influence indicators of WECS in Changzhou are water consumption per unit GDP (WCG), amount of fertilizer used in agriculture (AFA), inland waters aquaculture area (IWA), domestic sewage discharge (DSD), water quality success rate of surface water function areas (QWF) and proportion of water quality above III in stream monitoring section (PSW). In Nanjing the major influence indicators are inland waters aquaculture area (IWA), COD discharge in industrial sewage (CIS), ammonia nitrogen discharge in industrial sewage (AIS), ammonia nitrogen discharge in domestic sewage (ADS), greenery coverage rate of built up area (GCB), and urban sewage treatment rate (STR). In Nantong, they are population density (PD), water consumption per unit GDP (WCG), amount of fertilizer used in agriculture (AFA), inland waters aquaculture area (IWA), COD discharge in domestic sewage (CDS) and greenery coverage rate of built up area (GCB). The amount of fertilizer used in agriculture (AFA), COD discharge in industrial sewage (CIS), domestic sewage discharge (DSD), ammonia nitrogen discharge in domestic sewage (ADS), water quality success rate of surface water function areas (QWF) and proportion of water quality above III in stream monitoring section (PSW) are the major influence indicators of WECS of Suzhou. They are inland waters aquaculture area (IWA), COD discharge in industrial sewage (CIS), ammonia nitrogen discharge in industrial sewage (AIS), domestic sewage discharge (DSD), ammonia nitrogen discharge in domestic sewage (ADS) and proportion of water quality above III in stream monitoring section (PSW) in Taizhou. In Wuxi they are inland water aquaculture area (IWA), industrial sewage discharged (ISD), COD discharge in industrial sewage (CIS), domestic sewage discharge (DSD), ammonia nitrogen discharge in domestic sewage (ADS) and water quality success rate of surface water function areas (QWF). In Yangzhou they are amount of fertilizer used in agriculture (AFA), COD discharge in industrial sewage (CIS), ammonia nitrogen discharge in industrial sewage (AIS), domestic sewage discharge (DSD), and greenery coverage rate of built up area (GCB). In Zhengjiang these are inland waters aquaculture area (IWA), industrial sewage discharged (ISD), water quality success rate of surface water function areas (QWF), proportion of water quality above III in stream monitoring section (PSW), greenery coverage rate of built up area (GCB), urban sewage treatment rate (STR), completed investment of industrial pollution prevention and control construction projects (CII).

### 4.5 Policy suggestions

Among the four subsystems, the pressure and response subsystems had the greatest influence on the WECS. The





pressure subsystem dominates the changes in WECS; the second most important component is the response subsystem, followed by the state subsystem and the support subsystem. This indicates that the WECS of the eight cities still faces significant environmental pressure, even though the government has made substantial effort.

To improve the WECS of the eight cities based on our comprehensive analysis, we propose the following suggestions:

- The top five indicators affecting the WECS of the eight cities in Jiangsu Province are as follows: inland waters aquaculture area (Pressure), COD discharge in industrial sewage (Pressure), proportion of water quality above III in stream monitoring section (State), greenery coverage rate of built up areas (Support) and ammonia nitrogen discharge in domestic sewage (Pressure). Therefore, the department of Ecology and Environment of Jiangsu province should pay more attention to these indicators in the process of environmental control and governance. In order to improve the WECS of Jiangsu Province, the inland waters aquaculture area, COD discharge in industrial sewage and ammonia nitrogen discharge in domestic sewage should be reduced over entire range; the monitoring and supervision of water quality in stream monitoring section should be strengthened.
- For Changzhou, the government should focus on improving the water use efficiency, reducing the amount of fertilizer used in agriculture, and domestic sewage discharge; for Nanjing, COD and ammonia nitrogen discharge in industrial sewage should be reduced, and the urban sewage treatment rate should be improved; for Nantong, the government should focus on improving the water use efficiency, reducing the amount of fertilizer used in agriculture, and reducing COD discharge in domestic sewage; for Suzhou, the amount of fertilizer used in agriculture and domestic sewage discharge should be reduced, and the monitoring and supervision of water quality of surface water function areas should be

strengthened; for Taizhou, the reducing of ammonia nitrogen discharge in industrial sewage and domestic sewage discharge is the governance a key point; for Wuxi, reduction of the industrial sewage discharged and domestic sewage discharge should be reduced, and strengthening the monitoring and supervision of water quality of surface water function areas are key points of government; for Yangzhou, the WECS is under great pressure, and the government should reduce the amount of fertilizer used in agriculture, ammonia nitrogen discharge in industrial sewage and domestic sewage discharge; for Zhenjiang, the government should focus on reducing industrial sewage discharged, strengthening the monitoring and supervision of water quality of surface water function areas, improving the urban sewage treatment rate, and investing in environmental protection.

## 5 Discussion

### 5.1 Main contributions

The main novel contributions of this paper are as follows.

- In this paper we proposed “water environment carrying status” concept to normalize the research on water environment carrying capacity. According to the literature, the WECC was defined as the maximum population size and economic scale that can be accommodated under the premise of meeting the requirement of water quality and quantity without destroying the ecological environment (Guo et al., 2018). However, the evaluation of WECC in most previous studies have not been consistent with WECC concept. To describe the research issues more accurately, we proposed the “water environment carrying status” concept. This status is determined by

**TABLE 11** Water environment carrying status index of eight cities along the Yangtze River in Jiangsu Province from the city view by the integrated method.

City	2012	2013	2014	2015	2016	2017	2018	2019
Changzhou	0.2691	0.2958	0.2644	0.3817	0.5167	0.5363	0.7260	0.7469
Nanjing	0.1305	0.1339	0.2103	0.2837	0.5423	0.6630	0.7859	0.8531
Nantong	0.2178	0.1594	0.3414	0.4798	0.5615	0.5783	0.6362	0.7474
Suzhou	0.2359	0.3504	0.2400	0.2463	0.6296	0.6704	0.6966	0.7665
Taizhou	0.2370	0.2055	0.1892	0.2492	0.5567	0.5931	0.6893	0.8058
Wuxi	0.1705	0.1700	0.2817	0.3112	0.5216	0.5957	0.7486	0.8276
Yangzhou	0.3763	0.3266	0.3237	0.2331	0.3357	0.4433	0.5418	0.7863
Zhenjiang	0.1720	0.3669	0.4195	0.4464	0.4746	0.6186	0.6613	0.8110

**TABLE 12** Water environment carrying status index of eight cities along the Yangtze River in Jiangsu Province from the horizontal year view by integrated method.

Year	Changzhou	Nanjing	Nantong	Suzhou	Taizhou	Wuxi	Yangzhou	Zhenjiang
2012	0.5913	0.3042	0.6192	0.3304	0.5586	0.6350	0.7418	0.5991
Rank	5	8	3	7	6	2	1	4
2013	0.6929	0.4740	0.5791	0.3611	0.6880	0.6850	0.7268	0.7184
Rank	3	7	6	8	4	5	1	2
2014	0.6118	0.4568	0.7376	0.3731	0.7153	0.6118	0.7485	0.7690
Rank	5	7	3	8	4	5	2	1
2015	0.6590	0.5325	0.6318	0.3244	0.6469	0.6979	0.6568	0.6569
Rank	2	7	6	8	5	1	4	3
2016	0.7329	0.6358	0.5343	0.2858	0.7129	0.6907	0.6353	0.7731
Rank	2	5	7	8	3	4	6	1
2017	0.7288	0.6716	0.3728	0.5208	0.5573	0.7602	0.4505	0.7494
Rank	3	4	8	6	5	1	7	2
2018	0.6676	0.6905	0.4563	0.3236	0.6062	0.6899	0.5142	0.6682
Rank	4	1	7	8	5	2	6	3
2019	0.6256	0.6543	0.3435	0.3887	0.6015	0.6483	0.6634	0.6371
Rank	5	2	8	7	6	3	1	4

the pressure, response, support force, and their interactions with the social economy subsystem, natural water resource and environment condition, and habitat needs pressure.

- To consider the anthropogenic and natural influences on water environment status more appropriately, a novel conceptual framework, called PSRS, was proposed on the basis of the PSR model. As shown in [Figure 1](#), the WECS of a region is influenced by the pressure, support force, response and the current state.

So the PSRS framework can describe causal relationships of subsystems and major influencing factors of environmental status accurately, and it is more suitable than other frameworks proposed by previous researchers for the evaluation of WECS.

- Based on the novel framework, an evaluation index system reflecting the causal relationship between human social development and water environment was constructed. Taking eight cities along the Yangtze River in Jiangsu Province of China from

2012 to 2019 as a case study, the results of WECS evaluation were consistent with the characteristics reflected by the original data, suggesting the method is practical and feasible in theory and practice. We can expand the research scope to other regional WECS evaluation.

## 5.2 Limitation and future works

Due to the unavailability of data, some important indicators may have been overlooked in the construction of the evaluation index system; the WECSI introduced to describe the WECS is a relative value, and thus it cannot be compared with each other in different perspective. For these reasons, construction of scientific index system remains difficult, and this will be a focus of future research.

In order to conduct further research, we will try to use other statistical methods for evaluation of WECS and conduct multi-angle comparative analysis to find more effective evaluation method in the future research.

## Data availability statements

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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