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Systematic Evaluation and Influencing Factors Analysis of Water Environmental Carrying Capacity in Taihu Basin, China

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Abstract: Systematic evaluation of water environment carrying capacity (WECC) is a prerequisite for achieving sustainable development, which reflects the water environment comprehensive condition of lake basin under the current economic development scenario. Therefore, taking the Taihu Basin as a case study, a scientific comprehensive evaluation index system of WECC was established based on the Pressure-State-Response (PSR) assessment framework, which included water resources (WR), pollution emission (PE), water quality (WQ), water ecology (WE), and land use (LU) sub-systems. An expert group was invited to determine the weights of each indicator using the group analytic hierarchy process (G-AHP) method, and the indicators in the WR, PE, WQ, WE, and LU sub-systems were 6.5%, 21.8%, 27.9%, 11.1%, and 32.9%, respectively. According to the evaluation results, the WECC index of Taihu Basin increased by 51.4% from 2007 to 2019, but it still slightly exceeded the carrying capacity of the water environment; the water quality and pollution discharge indices had the most significant improvement. Algal blooms are a major factor challenging WECC in the Taihu Basin. Therefore, the overall restoration of the water eco-system must receive more attention in the future.

Keywords: water environment management; Taihu Lake; water environmental carrying capacity; water quality; algal bloom

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1. Introduction

Owing to their superior natural conditions, lake basins attract intense human activities and developed economies, such as the Great Lakes urban agglomeration in North America, Taihu Basin, and Hongze Lake area in China, etc. [1,2]. However, population density and urbanization often bring about an imbalance in the ecological environment of lake basins. Scientific evaluations of the carrying capacity of lake basins are crucial for maintaining a balance between human activities and the lake basin environment, as well as realizing regional sustainable development goals [3].

The Taihu basin is one of the most economically developed regions in China, and it includes the megacity Shanghai, large and medium-sized cities such as Hangzhou, Suzhou, Wuxi, Changzhou, Zhenjiang, Jiaxing, and Huzhou, among many other rapidly developing small cities and towns, forming an urban system with complete levels, an increasingly rational population structure, and an urbanization rate reaching 72.6%. The total population of the Taihu Basin reached 145 million in 2019, accounting for 10.4% of China's total population, but the land area only accounts for 0.4% of the total area and 18.3% of the GDP. The rapid development of economy has brought a high load of pollution emissions in Taihu Basin, which began in the 1990s. The government imposed the ecological environment management of the Taihu Lake; however, in the beginning, the anti-pollution efforts were far behind the ecological environment destruction and river water quality deterioration. There was a defining event in 2007, when large cyanobacterial outbreaks in

Taihu Lake caused a major water crisis. Since then, the water environmental management of Taihu Basin has gradually changed from a terminal treatment to comprehensive treatment. Based on the implementation plan of comprehensive water environment management of the Taihu Basin, the restoration and improvement of the ecological environment of Taihu Basin has been continuously promoted from various aspects, such as laws and regulations, management systems, capital input, and market regulation. Therefore, at this stage of comprehensive management, it is necessary to change the narrow water quality and environmental capacity management to the comprehensive ecological environment assessment of lake basins.

Water environmental carrying capacity (WECC) expresses the comprehensive state of the water ecological environment in a watershed and reflects the ability of an ecological environment to support human activities. The WECC can be divided into narrow and generalized [4]. The narrow WECC refers to the capacity of a water body to contain pollutants, which is mainly explained by the water quality compliance rate or water environmental capacity (WEC) [5]. Research methods exploring narrow WECC include creating water quality simulation models to study the variation of WECC under seasonal and manual dispatching conditions [6–8]. These methods also allow us to conduct statistical induction, including using the WQI evaluation method and the PCA method to reduce the dimension of monitoring values of long sequence and multiple types of N,P, as well as heavy metals, based on the monitored water quality [9–11]. The narrow WECC only reflects a single water environmental quality and focuses on the interior of the water body, without involving the terrigenous factors that lead to water quality exceeding the standard; thus, the comprehensive evaluation of large lake basins is not systematic enough [12,13]. For example, in the Taihu Lake region, N and P monitoring indicators and pollutant flux into the lake decreased significantly from 2007 to 2017, but the eutrophication and cyanobacterial blooms were still prominent [14]. Therefore, based on the water environment quality assessment, there is an urgent need to introduce indicators in a broader scope, including resources, ecology, and land use, to improve the comprehensive evaluation of WECC in lake basins.

The generalized WECC has a more abundant connotation than that of the narrow WECC, with the core content to establish a scientific, comprehensive, and objective evaluation system [15]. The generalized WECC usually includes the contents of the narrow WECC, such as water quality over standard rate, water environmental capacity, etc. At the same time, the generalized WECC includes more factors, such as ecosystem, water resources, population, and economic scale, which are assessments of the comprehensive ecological environment of the lake basin. Until now, a unified theoretical system has not been established for a generalized WECC study. The mainstream research approaches are the system dynamics (SD) model and comprehensive evaluation method. The SD model is able to reflect the interactions within each system, and it essentially places more emphasis on studying the socio-economic and pollution situation of the region, as well as the internal relationship between water quality and ecological factors to find the relevant changes. For example, Zhou et al. [13] analyzed the spatio-temporal changes in the WECC in the urban evolution process of Changzhou city using the SD model. Dai et al. [16] combined grid geographic information technology to construct a spatial SD model for the spatio-temporal pattern of water resource utilization change in the Yongding River Basin and analyzed the spatio-temporal heterogeneity of the WECC. However, its application in large watershed basins where information is lacking is limited due to the large number of parameters and information required [17,18].

The index evaluation method has a wider scope of application, relatively, and the most important issue to this method is to select an appropriate model that incorporates the most suitable evaluation index and determines the index weight. The commonly used methods include the AHP method, which is based on artificial grading evaluation; the entropy weight method, based on the characteristics of the data set; and the fuzzy evaluation method, based on the fuzzy mathematics principles. Chen et al. [19] developed a comprehensive WECC assessment framework that included an indicator system and a novel variable fuzzy pattern recognition (VFPR) approach and applied it to the Dongjiang River Basin in Guangdong Province. Wang et al. [20] constructed a novel integrated model framework to evaluate and predict the WECCs of nine cities in the Guangdong-Hong Kong-Macao Greater Bay area by coupling the entropy weight method, multi-objective linear weighting function, cloud model, and Markov chain. The AHP method has significant advantages in watershed management, and other advantages include its simplicity and systematic approach. However, its application is limited due to the supervisor factor of the rater. To avoid the uncertainty factor brought by a single rater, the expanded expert group formed the G-AHP method, which not only retained the AHP system, but also minimize the subjective factors influencing individual weight, underscoring the importance of the WECC evaluation weight [21,22].

Based on the pressure-state-response (PSR) framework, this study extended the existing narrow WECC assessment scope of Taihu Basin and constructed a generalized WECC assessment system consisting of five sub-systems: water resources, water environment, pollution discharge, water ecology, and land use. Sixty experts were invited to score and determine the weight of each indicator using the G-AHP method. The results of the WECC index were obtained after the normalized treatment of each index, change trend, and hindering factors from 2007 to 2019, which were calculated, which will accurately judge the comprehensive eco-environment status of Taihu Basin, identify the weak links in the current eco-environment management of the basin, and provide support for the comprehensive environmental management of the basin.

2. Materials and Methods

2.1. Study Area

Taihu Basin is located in the Yangtze River Delta (30°55′40″~31°32′58″ N, 119°52′32″ ~120°36′10″ E). It has a humid northern subtropical climate zone with observable monsoon characteristics and four distinct seasons. The total area of the basin is 36,900 km^2. It is a famous plain river network area with a water surface area of 5551 km^2 and a water surface rate of 15%, including 3159 km^2 of lakes and 120,000 km of river length with a river density of 3.3 km per km^2 (Figure 1).

2.2. Indicator Screening and Determination

The indicators of WECC assessment were selected from 65 highly cited studies of the keywords "Water Environmental carrying capacity" from the Web of science database and published water environment assessment technical specifications in China, forming a preliminary WECC indicator database. According to their characteristics, the selected indicators are divided into five sub-systems: water resources, pollution emission, water quality, water ecology, and land use.

In this study, the PSR assessment framework was used to reflect the logical relationship of the WECC assessment indicators [23–25]. After the frequency analysis to choose high frequency of each type of indicators index, and based on PSR assessment framework from the pressure of human activities on the environment, water environment condition and control index of the screening enable the selected indicators to cover the bearing capacity of water environment pressure, state, and response level in order to better reflect the relationship between human activities and water environment. Considering the representativeness, comprehensiveness, scientificity, and accessibility of the indicators, 26 indicators were selected for WECC assessment in Taihu Lake Basin after three rounds of consultation by the Delphi method.

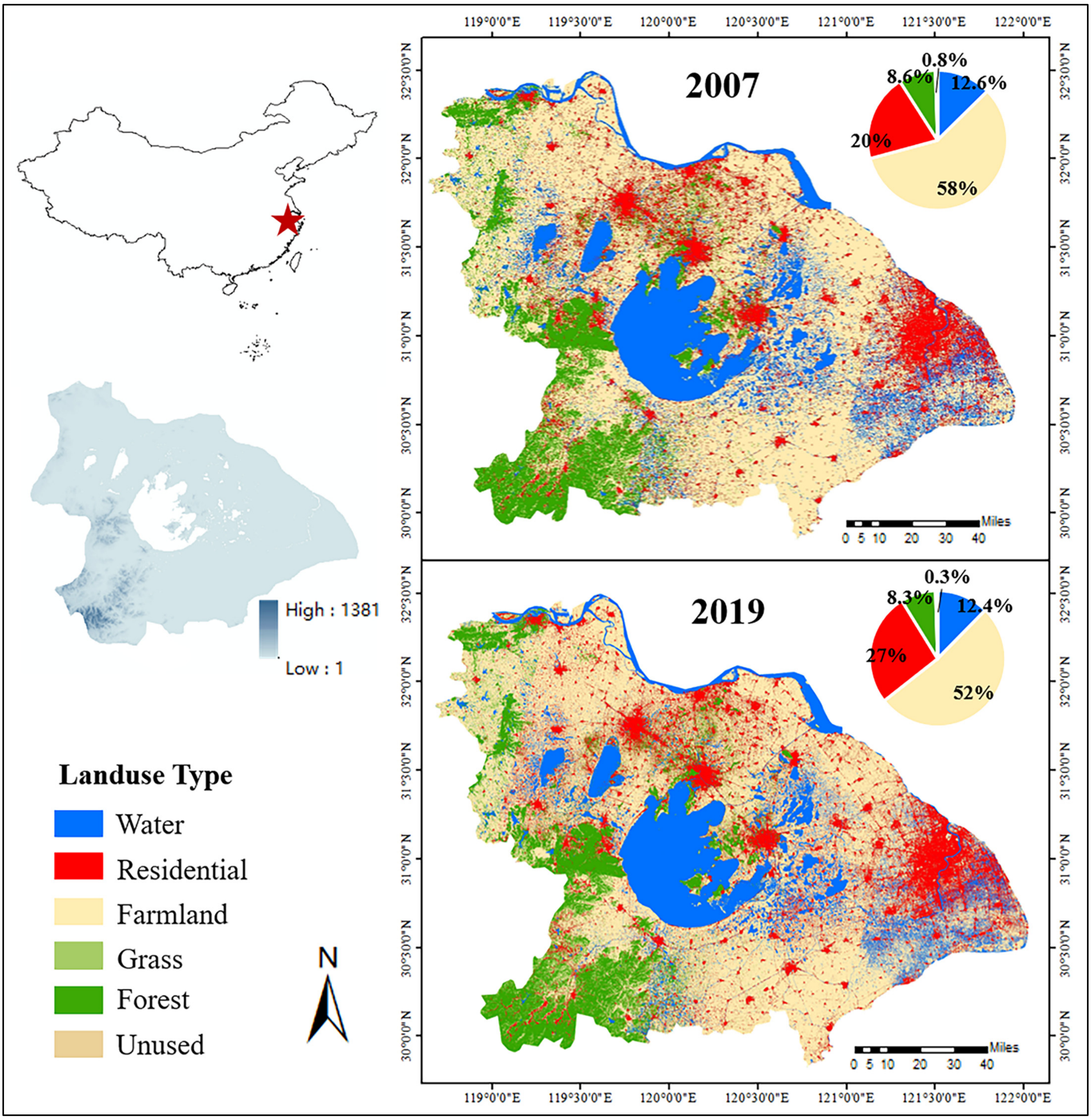


Figure 1. Location and land use type distribution of the study area.

2.3. Group Analytic Hierarchy Process (G-AHP) Method

AHP is a highly subjective evaluation method used to reduce the impact of the AHP method on subjective scoring weight, and this study expanded the scope and number of expert scoring, forming the group analytic hierarchy process (G-AHP) [26,27]. It adheres to the following steps:

Step 1: Hierarchy. In order to avoid confusion in indicator comparison and improve the pass rate of consistency test of judgment matrix, the hierarchy was designed with no more than five elements in each layer. The target layer is WECC, and the criterion layer consists of water resources, pollution discharge, water quality, water ecology, land use, and, finally, the specific indicators.

Step 2: Construction of a single expert judgment matrix and consistency test. Each expert used the 1–9 numerical scale (Table 1) to make a comparison of the different indicators to obtain the judgment matrix at each level, and each expert calculated the consistency index (*CI*) of the judgment matrix with the following equation:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

where λ_{max} refers to the maximum eigenvalue of the matrix; and, to measure the size of *CI*, the random consistency index (*RI*) is introduced by:

$$RI = \frac{CI_1 + CI_2 + \ldots + CI_n}{n} \tag{2}$$

Table 1. Scale of preference between two elements.

Number Scale	Definition (Compare the Factor i and j)
1	*i* is as important as *j*
3	*i* is slightly more important than *j*
5	*i* is stronger than *j*
7	*i* is more important than *j*
9	*i* is significantly more important than *j*
2, 4, 6, 8	the intermediate value of two adjacent judgments
$1/b_{ij}$	when the comparison factor *j* is more important than *i*

Considering the test coefficient of *CI* and *RI*, the following equation was used:

$$CR = \frac{CI}{RI} \tag{3}$$

If $CR < 0.1$, the judgment matrix passed the consistency test; otherwise, the judgment matrix should be adjusted and modified to meet the required test coefficient of $CR > 0.1$.

Step 3: Group weight determination. In order to eliminate the influence of individual expert factors on the results, the experts are classified by the systematic clustering method based on the eigenvectors' similarity, S_{ij}, to the expert judgment matrix, where the similarity is calculated using the following formula [28,29]:

$$S_{ij} = \cos\theta_{ij} = \frac{\vec{i} \cdot \vec{j}}{\left|\vec{i}\right| \cdot \left|\vec{j}\right|} \tag{4}$$

where the $\vec{i}, \vec{j}$ are the eigenvectors of the judgment matrix given by the *i*th and *j*th experts. Classify the *n* scoring experts into *m* classes by the similarity of the eigenvectors, and, in the class containing more experts, the evaluation information expressed by the experts represents the opinions of most experts and has more information density, so the corresponding experts are given a larger weighting factor.

Suppose an expert *E* is in a group of class X containing a vector of features ($X \in [1, m]$), and we consider that the group weight is proportional to the group size, then the weight λ_E of individuals in the group of class X is:

$$\lambda_E = \frac{\varphi_X}{\sum_{x=1}^{m} \varphi_X} \tag{5}$$

$$\sum_{x=1}^{n} \lambda_E = 1 \tag{6}$$

Step 4: Indicators weight determination. The weight coefficients of the experts are weighted and summed with the results of the experts' weight calculations for each index ω_E to obtain the final weight results of WECC:

$$\omega_{\text{in}} = \sum_{x=1}^{n} \lambda_E \cdot \omega_E \tag{7}$$

2.4. Calculation Unit and Grade Classification

When calculating the WECC of the entire watershed, the weighted sum of all index scores in the index system was calculated. When the carrying capacity of a certain administrative division of the basin (or only the lakes) was calculated, the lake body (or the river network) indicator was removed, and then the remaining indicators were calculated separately and scaled up to 100%. The calculation method of each indicator is given in the attachment file.

According to the WECC index results, the WECC index was divided into five grades: severe overload, medium overload, mild overload, no overload, and healthy. Each state was divided into two types, intensified and moderated, which were used to represent the dynamic changes between years (Table 2).

Table 2. WECC trend status and index classification.

WECC Warning Ode		WECC Type				
		Severe Overload	Medium Overload	Mild Overload	No Overload	Healthy
Trend	Worse	Dark Red	Dark Orange	Dark Yellow	Dark Blue	Dark Green
		0–60	60–70	70–75	75–85	85–100
	Better	Red	Orange	Yellow	Blue	Green
		0–60	60–70	70–75	75–85	85–100

2.5. Evaluation of the Obstacle Degree

To clarify the hindrance factors of the regional WECC, the hindrance effects of each index of the WECC were quantitatively analyzed by the obstacle model [30,31]:

$$Z_{ij} = \left|1 - S_{ij}\right| \tag{8}$$

$$O_{ij} = \frac{\omega_{ij} \times Z_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{n} \omega_{ij} \times Z_{ij}} \tag{9}$$

where ω_{ij} is the contribution degree of the factor, representing the weight of item j of the index in the i-th sub-system in the bearing capacity evaluation; z_{ij} is the deviation degree of factor, representing the difference between the index and the standardized target S_{ij}; and O_{ij} represents the obstacle degree of item j in the i-th sub-system of the WECC index.

2.6. Data Source

Data in this study were obtained from the China Urban Statistical Yearbook (2007–2019), water resources data were obtained from the Water Resources Bulletin (2007–2019), and pollution discharge data were obtained from the environmental statistics data of Jiangsu and Zhejiang Province (2007–2019). The data of bloom and aquatic plants in Taihu Lake were obtained from The Health Report of Taihu Lake, published on the website of the Taihu Basin administration bureau (http://www.tba.gov.cn/ (accessed on 6 August 2021)), and the data of water ecology in river network area were obtained from the monitoring data of the Institute of Hydrobiology, Chinese Academy of Sciences.

3. Results

3.1. Establishing and Evaluating the WECC Index System

In this study, 60 experts (above the professor level) were involved in the Taihu Basin research to participate, including those from institutions of higher learning, management departments, and scientific research institutions. Finally, 52 valid questionnaires that passed the consistency test were collected as samples for systematic clustering of each layer of eigenvectors, and the experts were grouped after systematic clustering of each layer of eigenvectors.

Taking the criterion layer as an example, the criterion layers WR, PE, LU, WQ, and WE for the target layer WECC judgment matrix were divided into four groups using the systematic clustering algorithm, with each group containing 14, 34, 3, and 1 experts, respectively (Figure 2). The scoring results of experts in each group were basically similar, and the first group of experts generally thought that the importance of WE indicator was more than 50%; the second group occupied 68% of the total purpose of experts, and those in this group thought that WQ and WE should occupy 25–35% and 30–40% of the total weight, respectively; the third group of experts of the general PE subsystem had the highest weight, while the fourth group of experts thought that the LU subsystem had the highest weight.

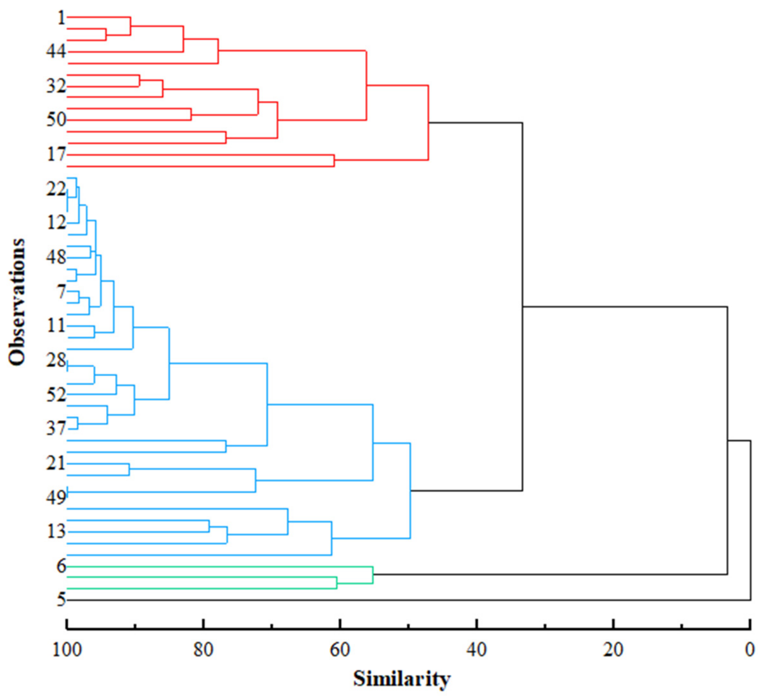


Figure 2. Systematic clustering results of expert group eigenvectors.

The weight coefficients of the experts were calculated according to the number of experts in the groups to obtain the weight calculation results of the final WECC indicators (Table 3). According to the assessment results of the expert group and from the sub-systems perspective, the corresponding weights of WR, PE, LU, WQ, and WE were 6.5%, 21.8%, 27.9%, 11.1%, and 32.9%, respectively. Based on these results, experts generally agreed that pollution control and water ecological governance were innately more important for the comprehensive ecological environment assessment of Taihu Basin (Figure 3), meanwhile, the relative weights of water resources and land use sub-systems are relatively low. In the WECC index system, the indices with the highest weights were the total pollution emission into the lake (9.2%), the water quality that exceeded multiple values of the lake (9.1%), and bloom outbreak (9.0%), which represent the pollution pressure, water environmental quality, and water ecology in the lake basin, respectively.

Table 3. Water Environmental Carrying Capacity (WECC) indicator system.

Target Layer	Rule Layer	Factors Layer	Unit	PSR Type	River/Lake Type	Weight
WECC	Water resource (WR)	Water resources utilization rate (WRUR)	%	P	R	1.4%
		Water area ratio (WAA)	%	P	R	0.8%
		Water consumption per 10,000 GDP (WCGDP)	ton/10^4 CNY	R	R	1.6%
		Water resources allocation (WRA)	%	R	L	2.7%
	Pollution emission (PE)	River network pollution emission intensity (PEIRN)	kg/10^4 CNY	R	R	1.9%
		Total pollution emission into the lake (PEIIL)	Ton	R	L	9.2%
		Total allowable pollutants in river network (TAPRN)	%	P	R	3.8%
		Wastewater treatment rate (WTR)	%	P	R	6.9%
	Land use (LU)	Land use pattern (LUP)	%	P	R	1.4%
		Shoreline development rate (SDR)	%	P	L	1.7%
		Water conservation function (WCF)	/	S	R	0.9%
		Runoff regulation function (RRF)	/	S	R	1.0%
		Water purification function (WPF)	/	S	R	1.6%
		Ecological sensitive area protection (ESAP)	/	R	C	4.5%
	Water quality (WQ)	River network water quality (RNWQ)	%	S	R	5.9%
		Entry-exit water quality (EXWQ)	/	S	R	4.2%
		Water quality exceed multiple of the lake (WQMESL)	/	S	L	9.1%
		Water quality exceed ratio of the lake (WQOSRL)	%	S	L	8.7%
	Water ecological (WE)	Forest and grass coverage rate (FGCR)	%	S	R	2.9%
		Wetland vegetation coverage rate (WVCR)	%	S	R	3.8%
		Submerged plant coverage (SPC)	%	S	L	4.6%
		Lakeside natural shoreline rate (LNSR)	%	R	L	3.1%
		Bloom outbreak (BO)	/	R	L	9.0%
		Ecological restoration (ER)	%	R	C	4.1%
		River connectivity (RC)	%	R	R	2.4%
		Guarantee rate of ecological water demand (GRWDEM)	/	R	R	2.8%

Note(s): The calculation method for each indicator has been uploaded to the Supplementary Materials.

3.2. Spatio-Temporal Variation and Trend Analysis of the WECC in the Taihu Basin

The WECC index system was constructed to assess changes in the ecological environment in Taihu Basin from 2007 to 2019. The WECC in the Taihu Basin showed a trend of continuous improvement. The trend status value increased from 44.2 (severe overload) in 2007 to 66.9 (medium overload) in 2019 (Figure 4a), indicating a 51.4% increase in the WECC in the Taihu Basin over the past decade. The WECC of the entire basin includes the WECC of the river network and lake areas. Lake area refers to large lakes, such as Taihu Lake in the basin, and river network area refers to rivers and land areas in the basin.

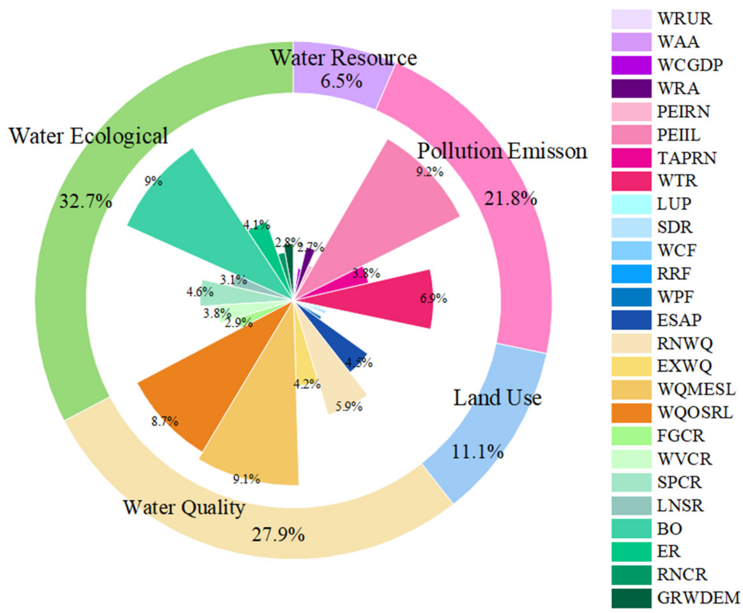


Figure 3. Contribution of each WECC sub-system and their index factors.

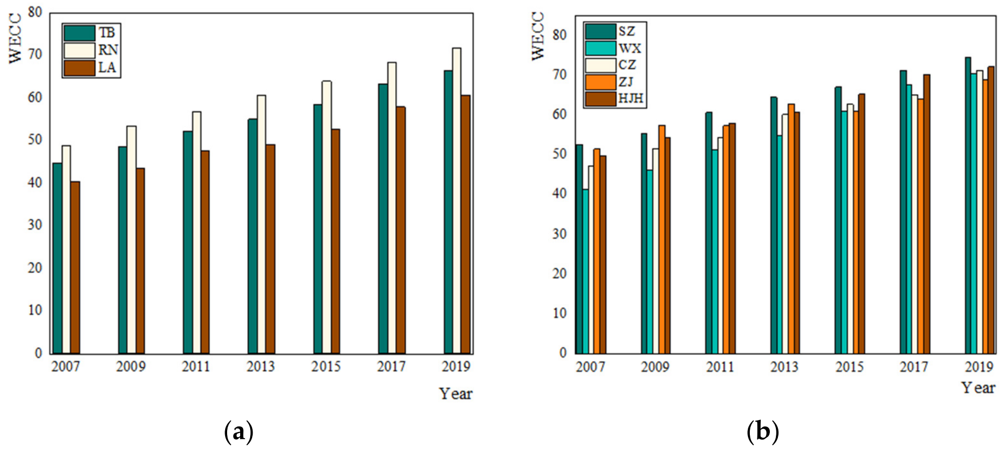


Figure 4. WECC dynamic development trend from 2007 to 2019. (**a**) Taihu Basin, river network area and Taihu lake area. (**b**) Administrative regions in the Taihu Basin.

From a spatial change perspective, the WECC index of Taihu Lake was lower than that of the river network areas. In 2007, the WECC index of Taihu Lake had the lowest values in the pollution discharge and water quality indices. From 2019, the WECC index values of lake water resources, land use, and pollution discharge were higher. However, the values of the water quality and water ecology indices, with a larger proportion of index weight, were lower. The WECC index value of the water quality sub-system had the greatest overall change, increasing by 137% from 2007 to 2019. The WECC changes in the river network area were reflected by the changes in the six cities (Figure 4b). In 2007, the WECC index value of Wuxi was only 41.3, followed by Jiaxing and Changzhou. The WECC index value of the inflow area of Taihu Basin was lower than that of the downstream outlet area, especially regarding the water quality and pollution discharge. By 2019, Zhenjiang, which was the only city with a medium overload in 2019, had the lowest WECC index value of 68.8. The other five cities had a mild overload. The WECC index value of Zhenjiang was in the range of 70–75.

From the perspective of WECC change, each sub-system in the Taihu Basin also showed an improving trend, but the rates of change in each sub-system haddifferent signs (Figure 5). The index values of WQ subsystem changed the fastest, from 30.6 (severe overload) in 2007 to 76.1 (no overload) in 2019, indicating that the water environmental quality of the basin improved markedly. The range of improvement of the PE sub-system is second only to that of the WQ sub-system, which means that the pollution emission control of Taihu Basin has achieved some results, with the PE score currently possessing a no-overload grade. The WR index score also improved from the medium overload to mild overload grade. However, the variation range of the LU and WE sub-systems is relatively small, and the coefficients of the WE and LU sub-systems were in the severe or medium overload grade from 2007 to 2019.

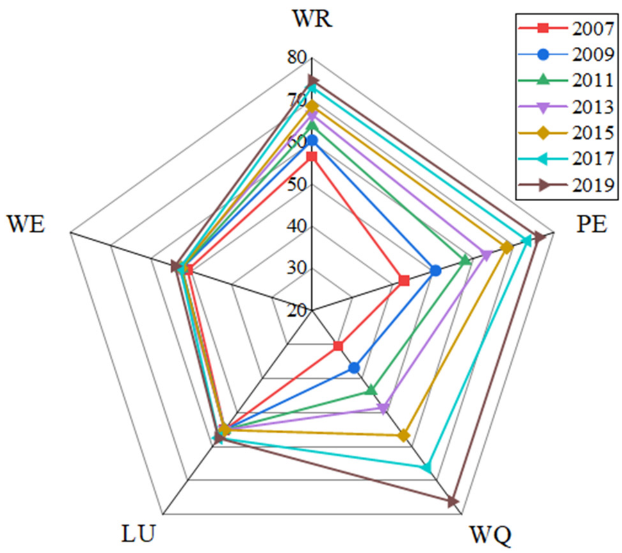


Figure 5. The variation trend of the WECC sub-system scores in Taihu Basin.

3.3. Analysis of Obstacle Factors of WECC in Taihu Basin

The WECC barriers for each sub-index were calculated over a 10-year period (Figure 6), and the results showed that the obstacle factors affecting the WECC in the Taihu Basin had changed over a 12-year period. In 2007, the major barriers to the WECC in the Taihu Basin were the water quality and pollution discharge sub-systems. The three most important obstacles were revealed for the water quality, which exceeded multiples of the lake (11.2%), water quality exceeding the ratio of the lake (11%), and total pollution emission into the lake (9.5%). However, by 2019, the bloom outbreak (12%) had replaced the water quality, which exceeded multiples of the lake (10%) in the Taihu Basin. Simultaneously, the water quality exceeded a ratio of Taihu Lake, which remained high (8.1%), and, as shown, the overall degree of the water ecological indices increased significantly; thus, the water quality index obstacle degree cannot be ignored.

According to the obstacle degree analysis of a single WECC evaluation in each space, the obstacle degree of the EP and WQ sub-systems required to reach the WECC standard decreased every year. The WE gradually replaced the EP and WQ sub-systems and became the main factor restricting lake bodies and administrative regions in the Taihu Basin (Figure 7). The overall obstacle factors of each administrative region in the region were similar, and the WE sub-system accounted for a large proportion, from approximately 30% in 2007 to over 50% in 2019, while the proportion of the EP and WQ sub-systems decreased markedly. For the Taihu Lake body, the WQ and WE sub-systems have always occupied a large proportion of the obstruction degree, from 29% and 46% in 2007 to 45% and 35% in 2019, respectively.

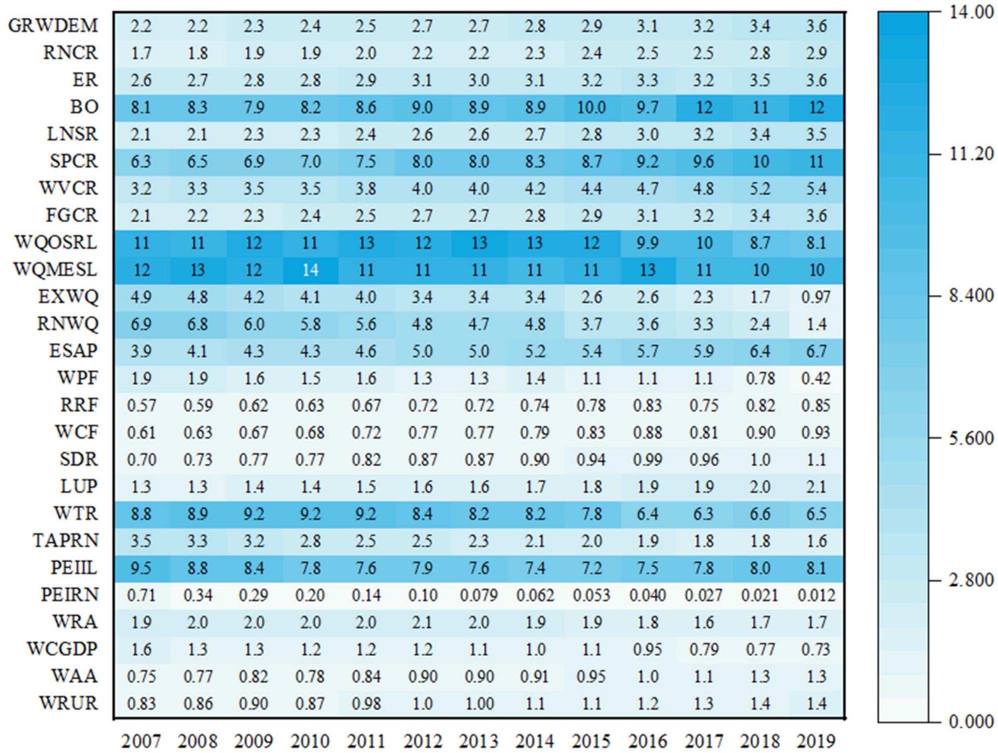
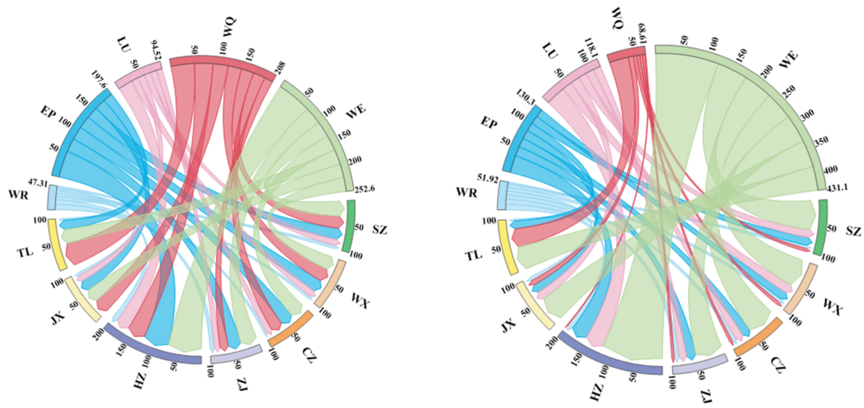


Figure 6. Obstacle factors of the WECC in the Taihu Basin from 2007 to 2019. The shade of color of each hotspot indicates the size of the obstacle factor.



(**a**) 2007 (**b**) 2019

Figure 7. Obstacle factor barriers of subsystems of the regional WECC in (**a**) 2007 and (**b**) 2019.

4. Discussion

4.1. Applicability of the WECC Assessment Indicators in the Taihu Basin

In this study, we constructed a WECC assessment system that included water resources, water ecology, water quality, pollution discharge, and land use, which are consistent with the concept of integrated planning of various factors in the current watershed management research [32]. Compared with the current narrow WECC management in the Taihu Basin, this study not only included the original water quality standards and total control amount, but also compared the assessment of individual water resources, water quality, and biomass. The comprehensive assessment can provide researchers and managers with a more accurate understanding of the ecological environment state of watershed as a whole [8,9,33].

From the perspective of the selection of indicators, this study added the pollution control of lake inflow, rate of water function area, influence of bloom, and other indicators to consider in Taihu Basin [20,25,34,35]. The purpose was to integrate the current water environment management policies of the Taihu Basin, such as water functional zone management, total control amount of pollutants entering the lake, and water ecological function zoning, so as to clearly express the WECC status from the administrators perspective [14,36–39]. In addition, the index system also considered other factors affecting the WECC of lake basins, such as water resource allocation and river network connectivity, owing to the high urbanization and frequent water diversion [19,40–42]. Simultaneously, the fluvial and lacustrine indices of lake basins were calculated separately, as they consider the different factor characteristics of water and land areas. These indicators fully reflect the characteristics of the Taihu Basin, which could more accurately assess the comprehensive ecological environment and provide a scientific basis for other, similar plain and lake basin management decisions. The index weight results of this study showed that the water ecology, pollutant discharge, and water environmental quality are often of more concern in the Taihu basin, consistent with previous research trends in the ecological environment field in the Taihu Basin [36,43]. Owing to the abundant water supply in the Taihu Basin, most of the studies in this area have focused on algal blooms and pollutant control, as water resources are not a major constraint factor for the WECC [44]. From the perspective of the single indicator with high weight, the total pollution emission into the lake is a quantitative form of the impact of human activities on the ecological environment of the lake basin, and it is the main source of nitrogen and phosphorus pollutants in the lake, so it has attracted much attention [45,46]. The water quality exceeding the lake standard in the assessment section of the Taihu Basin is the commonly used index to evaluate the water environmental quality and characteristics of nutrient concentration in the lake water and reflects the administrative requirements of the management department [47]. As an unsolved problem in the Taihu Lake, bloom outbreak is an important factor affecting the regional ecological environment quality, which also highlights the characteristics of the Taihu Lake [48,49].

4.2. The Spatio-Temporal Variation of the WECC Shows the Effectiveness and Problems of Basin Management

According to the WECC assessment results of Taihu Lake in the past decade, the WECC of both the Taihu Lake body and districts improved every year, with significant improvement in the PE and WQ indicators, which is consistent with the overall trend of research on water quality in the Taihu Basin [33,50]. Since the water supply crisis of Wuxi city was caused by the severe cyanobacteria outbreak in Taihu Lake in 2007, the water quality in the Taihu Basin has attracted much attention from of all sectors of society and government [51]. The central government formulated a plan for the comprehensive treatment of the water environment in the Taihu Basin. The water environment of Taihu Lake has been systematically regulated by many aspects, including legal standards, management systems, treatment projects, and financial support, which are the main reasons for the continuous improvement of the overall water quality in Taihu Basin. In addition, the continuous implementation of the river chief system in the Taihu Basin, which links the water quality standards with the performance of officials, incentivizes the ruling officials to attach importance to the water environment of rivers and lakes [52–54]. More than a decade of continuous remediation of the Taihu Basin is the reason for the improvement of WECC, which is mainly reflected in the reduction of pollution into the lake and the decrease in water concentration. Regarding the WR, LU, and WE sub-systems, the WR is subject to the needs of regional flood control and production, as well as life, and it is difficult to make substantial changes, especially because a strict water resource management system has been implemented in the basin [55]. The LU and WE sub-systems basically remained unchanged in the past ten years, owing to the delay in improving the water ecology in the basin. Therefore, observing apparent ecological restoration effects takes time. Owing to the complexity of the ecosystem, the biological characteristics of aquatic animals and plants are still being studied to understand the mechanism of cyanobacteria outbreaks [56,57].

Regarding the spatial heterogeneity of the WECC, the WECC index value of the Taihu Lake is lower than that of the river network index. This is because the management departments have inconsistent assessment standards for rivers and lakes [58]. For Taihu Basin, the total phosphorous (TP) water quality target of rivers under the same water body function is 0.2 mg/L, while the TP water quality target of lake and reservoir areas is 0.05 mg/L. Lake water quality is significantly affected by land rivers, but they have different standards, therefore, compared with lake areas, it is easier to obtain better indicators of water quality compliance rate and water quality that exceeds the standard by multiple times in the river network area. In addition, the weight proportion of these indicators are generally high, resulting in the WECC of the cities with a river network area being higher than that of the Taihu Lake. Regarding the district in the Taihu Basin, more than ten years have passed for each administrative region under governance using the WECC index system, which has had different degrees of improvement, but, for the Taihu Basin, the upper reaches of the lake district, namely, Zhenjiang, Changzhou, and Wuxi areas, need to focus on the control and management of pollution emission because the WECC of downstream areas is low, and it has a great impact on the lake [59]. Meanwhile, the influence degree of the Taihu Lake has been relatively increased. For eutrophication control, the inflow of nutrients in the upper reaches of Taihu Lake is still an important means of control.

4.3. More Attention Should Be Paid to Water Ecology in the Future Management of the Watershed

The assessment of the WECC barriers in the past decade shows that water ecology has replaced water quality as the biggest obstacle preventing the achievement of WECC standards in lake basins. Over the past ten years, continuous investment in water pollution control in the Taihu Basin has played a great role in reducing the total amount of pollutants in the rivers and lakes of the basin and improving the water quality; however, resistance to water quality improvement has gradually emerged. According to the water quality monitoring results of total nitrogen (TN) and TP in Taihu Lake in 2017 and 2018, the TP and TN in the main rivers flowing into the lake improved every year with increasing pollutant control measures in the land area, and the abnormal phenomenon of TP has increased, and TN has decreased in Taihu Lake [60,61]. Studies have shown that this may be due to the increase in pollution flux into lake caused by water with high P content transported by the many water diversion systems created in recent years, or by the release of TP in sediments, as well as by the abnormal denitrification process induced by phytoplankton activities in Taihu Lake [62,63]. However, the water quality monitoring value of Taihu Lake showed a gradually improving trend in the past ten years, and the bloom area of the lake body was not effectively controlled. This indicates that the factors affecting the ecological environment of the lake basin are complex, and it is difficult to achieve comprehensive management of the lake basin by controlling a single aspect, such as nutrient salt control.

In the past, the Taihu Basin focused on source control, but the pollution control has now reached the stage of refinement and precision, and continuous capital investment may not achieve the same significant improvement. In the future, watershed management should consider how to comprehensively study water resources, water environment, and water ecology from the ecosystem perspective and gradually realize the ecological environment restoration of the watershed [64]. Therefore, various indicators should be included in the management and assessment system, and water quality assessment should be progressively transformed into a comprehensive analysis of the ecological environment of the basin. Ecological restoration and river and lake remediation and other supporting engineering measures should be continuously promoted to restore the WECC of the Taihu Basin to a healthy level.

5. Conclusions

Based on the PSR assessment framework, this study selected 26 WECC evaluation index systems that reflect the ecological environment characteristics of the Taihu Basin. The

AHP method was used to determine the index weights, and the ecological environment status of the Taihu Basin was evaluated from 2007 to 2019. The main research conclusions are as follows:

(1) The corresponding weights of water resources, pollution discharge, land use, water environmental quality, and water ecology in the WECC evaluation index system of the Taihu Basin were 6.5%, 21.8%, 27.9%, 11.1% and 32.9%, respectively; among them, the three indices with the highest weight proportion were the total pollution emission into the lake (9.2%), water quality exceeding multiples of the lake (9.1%), and bloom outbreak (9.0%).

(2) The WECC of the Taihu Basin changed from a severe overload grade in 2007 to mild overload in 2019. The WECC of the river network area was better than that of the lake body, while the WECC of the lake outlet area was better than that of the lake inlet area on average. The reduction in the pollution flux into the lake and the improvement of the water quality were the main factors contributing to the improvement of the WECC of the Taihu Basin in recent years.

(3) The major obstacles to WECC in the Taihu Basin changed between 2015 and 2017, with water ecology becoming the most important factor restricting the improvement of the WECC in the Taihu Basin. In addition to reducing the amount of pollution sources and improving the water quality of rivers and lakes, the overall restoration of the water ecosystem must receive more attention in the future.

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