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RESEARCH ARTICLE

Construction of Ecological Security Evaluation Index System for Hengshui Lake National Nature Reserve Based on the Pressure-State-Response Model

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ABSTRACT

Ecological security is crucial for national security, human survival, and sustainable development. Thus, this study aims to establish an Ecological Security Evaluation Index System for Hengshui Lake National Nature Reserve in China based on the Pressure-State-Response (PSR) model. This reserve is a critical habitat for various wildlife species and provides essential ecosystem services to surrounding communities facing ecological issues, such as transitional development and accelerated urbanisation. The PSR model was chosen in this study because this tool provides a comprehensive and complex framework for assessing ecological security by considering three key components: Pressure, State, and Response. Three pressure components have been selected as indicators: Population, population density, and natural population growth rate. Meanwhile, eight condition parameters were included as the state indicator: Precipitation, precipitation pH, eutrophication, comprehensive water quality pollution index, chemical oxygen demand (COD), total phosphorus, fluoride, and permanganate index. Finally, the proportion of the tertiary industry, residents' per capita disposable income, energy conservation and environmental protection expenditures, education expenditure, social security expenditures, and wetland environmental protection awareness were the response indicators considered in this study. The findings indicated that the ecological security evaluation index of Hengshui Lake between 2016 and 2022 increased from 0.203 to 0.756, whereas the ecological security level transitioned from unsafe to safe.

1. INTRODUCTION

A wetland is formed through the interaction of terrestrial and aquatic ecosystems. Dubbed as the "kidney of the earth", this unique ecosystem is known for the significant environmental and ecological function, and socioeconomic value. Since ancient times, humans have a special love for water and often choose to reside near water bodies. History has shown how cities thrived because of water, and wetlands are no exception. (Das et al., 2020; Liu et al., 2020; Zhou et al., 2020).

Wetlands are critical for climate regulation, the mitigation of rising sea levels, and the protection of migratory water birds (Duarte et al., 2013; Wang et al., 2019; Yang et al., 2020). Nevertheless, there has been a rapid loss of coastal wetlands over the past 50 years due to global changes. Human activities have jeopardised the key ecological service functions of wetland ecosystems. Therefore, researchers have increased their attention and efforts towards the ecological restoration of wetlands (Hu et al., 2017; Murray, 2023). Common wetland restoration methods include hydrological connectivity and vegetation restoration (Zhao et al., 2016). Countries such as Mexico, the United States of America (US), and the Netherlands have developed strategies to restore wetland ecosystems by dredging tidal channels and constructing breakwaters in mangrove forests and salt marsh (Bashan et al., 2013; Jarzemsky et al., 2013). Other researchers have also attempted vegetation transplantation and seed broadcasting to restore wetlands (Silliman et al., 2015; Suykerbuyk et al., 2016; Valdez et al., 2020).

The intrinsically vulnerable wetland ecosystems are subject to external pressures from natural environmental factors and anthropogenic activities (Han et al., 2024). For example, natural disturbances such as fluctuations in temperature and precipitation significantly influence wetland ecological processes, while human activities further exacerbate stress on their ecological functions. Moreover, the spatial extent, structural characteristics, and functional attributes of wetlands intensify makes this ecosystem highly susceptible to ecological risks. Effective management of these risks necessitates an integrated approach that addresses the interplay between internal wetland properties and external stressors, enabling the development of robust conservation and management strategies (Mao et al., 2018). Therefore, conducting ecological risk assessments is essential for systematically identifying multifaceted risk disturbances, evaluating the ecological consequences, and optimising frameworks for wetland protection and sustainability.

Hengshui Lake is a famous freshwater lake at the centre of Hebei Province of the North China Plain. This lake is one of the largest in the North China region. Renowned for the beautiful natural scenery and abundant biological resources, Hengshui Lake is one of the key tourist attractions in Hebei Province. In recent years, the ecosystem of Hengshui Lake has faced mounting anthropogenic disturbances and environmental pressures. The accelerating pace of urbanisation in the surrounding areas has led to the encroachment of construction land into the wetland margins of the lake, altering traditional land use patterns and damaging vital ecological buffer zones. Concurrently, uneven water resource allocation and declining water levels have diminished the hydrological connectivity and weakened the natural self-purification capacity of the lake.

Agricultural intensification further exacerbates these pressures, as excessive application of fertilisers and pesticides result in nutrient-rich runoff (nitrogen, phosphorus) into the lake, thereby triggering eutrophication and threatening aquatic biodiversity. These compounded stresses have substantially reduced the ecosystem stability and resilience, posing significant risks to regional ecological security and sustainable development of the wetland. Thus, a comprehensive ecological security assessment is essential to identify critical risk factors and ecological vulnerabilities, thereby informing targeted restoration strategies and evidence-based environmental management across the Hengshui Lake basin. In this study, an integrated indicator is adopted to assess the ecological security of Hengshui Lake from 2016 to 2022 based on the PSR model. The comprehensive weights of the indicators are determined using the Analytic Hierarchy Process (AHP) and entropy methods (Li et al., 2021).

2. MATERIALS AND METHODS

2.1. Study area

Hengshui Lake is located in Hengshui City, southern-central of Hebei Province (37°25'–37°40' N and 115°30'–115°45' E). Known as the “Kidney of North China”, this inland freshwater lake is the largest in the North China Plain. The terrain is generally flat, with elevations ranging from 31 to 105 m. The lake and surrounding wetlands are low-lying, while the edges are slightly higher, forming a typical plain lake–wetland ecosystem (see Fig 1).

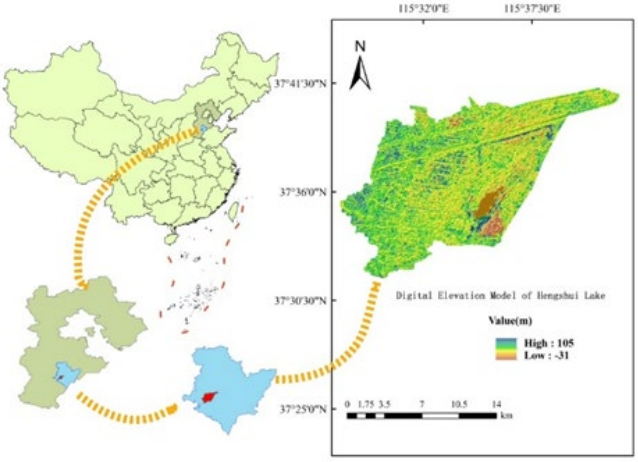

Figure 1: Map of Hengshui Lake, China

2.2. Ecological Security Evaluation Model

Since the dawn of the 21st century, ecological security has emerged as the focus of scholarly inquiry, domestically and internationally. Notably, the areas of investigation have been ecological security assessment (Wang et al., 2003) and the establishment of ecological security frameworks (Yi et al., 2022). Nevertheless, it is imperative to underscore that ecological security assessment serves as the foundational pillar of ecological security research. The meticulous evaluation of ecological security within a designated area allows researchers to gain insights into the stability and integrity of the ecosystem, thus furnishing the requisite groundwork for sound judgments regarding subsequent sustainable development endeavours. Executing an ecological security assessment hinges upon the utilisation of evaluation models and methodologies. Presently, such models encompass a spectrum of methodologies, including mathematical models, ecological models, and digital elevation models.

2.2.1. Pressure-State-Response (PSR) model

In the realm of digital modelling, the PSR framework stands out as the most prevalent, embodying elements of pressure, state, and response. This model adeptly elucidates the intricate cause-and-effect dynamics between external pressures, societal factors, and the ecological environment (Ma et al., 2019). Building upon this foundation, scholars have undertaken further refinements by introducing additional dimensions, notably Drivers (D) and Impacts (I). Such enhancements aim to bolster the logical coherence of the model. As a result, the DPSIR model has found application across diverse domains, including urban ecological security assessment, protected area evaluation, and marine ecosystem appraisal (Gao et al., 2022; Liu et al., 2021; Zhao et al., 2021).

2.2.2. Ecological model

The ecological footprint serves as a straightforward ecological model to evaluate ecological security. This model has distinguishing characteristics from the PSR model, boasting simplified principles and convenient operationality (Wiedmann & Barrett, 2010). The ecological footprint delineates the discrepancy between human reliance on nature and the biocapacity of ecosystems (Wang et al., 2020; Yang & Cai, 2020). A higher ecological footprint denotes a heightened impact of human activities on the ecological environment; conversely, a lower footprint indicates reduced influence (Chu et al., 2017).

2.2.3. Landscape ecological model

The landscape ecological model, born from the realms of landscape ecology and the advancement of ecological security, serves as a cornerstone in evaluating landscape ecological security. As landscape patterns evolve, spatial structures also shift, directly impacting the composition and arrangement of ecosystems, thereby exerting a profound influence on ecological security. Central to this methodology is the construction of landscape ecological models facilitated by the application of landscape pattern indices. This approach is commonly utilised to scrutinise the spatiotemporal dynamics within a defined research domain (Li et al., 2010; Sun et al., 2020).

2.2.4. Digital terrain model

As technology continues to advance, remote sensing (RS) and geographic information systems (GIS) technologies have become integral to ecological security assessments. Leveraging raster data types, these tools enable seamless overlay and offer straightforward logic. The application of this technology extends across diverse research domains, encompassing urban areas, watersheds, mountainous regions, and scenic areas (Cao et al., 2022; Li et al., 2010; Liu et al., 2021). The PSR model is chosen for this study to systematically reflect the relationship between human activities and the ecological environment through three dimensions (pressure, state, and response), with a clear structure suitable for ecological security evaluation.

2.3. Evaluation Index

The core of the PSR model lies in scientifically and reasonably selecting various indicators to accurately reflect the environmental conditions and changes. Stress indicators are used to measure the pressure exerted by human activities on the environment, mainly including industrial emissions, agricultural activities, transportation, energy consumption, and land use changes. Status indicators reflect the current state of the environment, such as air quality, water quality, soil health, and biodiversity. Response indicators are used to measure societal response to environmental issues, including policy implementation, governance measures, and public participation (Liu et al., 2020; Lu et al., 2022; Wang et al., 2021).

In recent years, more studies have utilised the PSR model while combining social indicators (population density and urbanisation rate), economic indicators (gross domestic product (GDP) and industrial added value), and GIS indicators [land use change and normalised difference vegetation index (NDVI)] when selecting evaluation indicators (Hasan et al., 2020; Zhang et al., 2022).

2.4. Data source

The data utilised in this study are obtained from authoritative local government publications and statistical reports to ensure accuracy and reliability. Specifically, data spanning the years 2016 to 2022 were retrieved from the Hengshui Municipal People's Government Statistical Bulletin, which provides comprehensive insights into the socio-economic development of the region. Meanwhile, environmental data crucial for assessing ecological health and trends were sourced from the Hengshui City Environmental Quality Bulletin (2016–2022). This bulletin offers detailed information on air, water, and soil quality, which are vital for evaluating the ecological security of Hengshui Lake. Additionally, the Hengshui Statistical Yearbook (2020) provided supplemental data, offering a broader context for understanding demographic, economic, and environmental conditions in the area. These documents collectively form the backbone of the dataset, allowing for a systematic and quantitative evaluation of the ecological security of the lake over the study period. Integrating these resources ensured a holistic approach to this study in analysing the pressures, states, and responses affecting Hengshui Lake.

2.5. Establishment of evaluation index

The PSR model was adopted as the research framework, establishing a hierarchical structure consisting of an objective layer, system layer, and indicator layer. Based on the data availability, it is necessary to consider using the PSR model to comprehensively and accurately reflect the ecological security of Hengshui Lake. Combining social, economic, and ecological indicators, a total of 17 evaluation indicators were selected for this study (see Table 1). These indicators were selected based on the ecological significance and the availability of continuous, high-quality data at the regional scale. The final indicator set emphasises water quality risk, anthropogenic pressure, and institutional response, which were relevant for the Hengshui Lake ecosystem as a sensitive urban-wetland composite system.

Different from other ecological security evaluations that often incorporate natural ecological indicators (NDVI, LUCC, water level variation) (Zhang et al., 2022; Song et al., 2024)this study employed a policy-oriented and management-responsive approach. The NDVI and LUCC were not included in this study due to the limited temporal resolution and spatial granularity of remote sensing data at the municipal or county level. Additionally, long-term hydrological monitoring data (water level) were unavailable or inconsistent across the study period. These constraints necessitated a focus on publicly available statistical indicators that reflect environmental risks and institutional responses.

Table 1: The Ecoweights Security Index System of Hengshui Lake (Bai & Tang, 2010; Li et al., 2023)

Objective layer	System layer	Indicator layer
Ecological security evaluation of Hengshui Lake	Pressure	Population
		Population density
		Natural population growth rate
	State	Precipitation
		Precipitation ph
		Eutrophication
		Comprehensive water quality pollution index
		Chemical oxygen demand (COD)
		Total phosphorus
		Fluoride
		Permanganate index
	Response	Proportion of the tertiary industry
		Per capita disposable income of residents
		Energy conservation and environmental protection expenditures
		Education expenditure
		Social security expenditures
		Wetland environmental protection awareness

The weights of the selected indicators were determined using the AHP and the entropy method to reconcile the differences between the two methods and leverage subjective expert opinion and objective data characteristics. The AHP method, developed by Saaty, is a structured technique for organising and analysing complex decisions, based on mathematics and psychology. This method involves structuring the decision problem into a hierarchy, making pairwise comparisons, and synthesising the results to determine the weights of criteria and alternatives. Meanwhile, the entropy method is an objective weighting method that originated from information theory. This method is used to determine the weight of an indicator by calculating the entropy value, which represents the magnitude of information the value contains. A smaller entropy value indicates greater variation in the indicator and thus a greater weight in the evaluation. Based on these weights, a comprehensive ecological security evaluation model was developed.

2.6. Establishment of evaluation index

(1) AHP method

The AHP method is widely used in environmental decision-making and ecological security assessments. First, the pairwise comparison judgment matrices were constructed to quantify the decision-making (see Table 2). Subsequently, 15 experts in environmental science, ecology, social economics, and other related fields were invited to consult on the calculation of the indicator weights at each level (Zhu et al., 2021). Comparing the pairwise matrices and calculating expert weights aids in determining the relative importance of each indicator systematically and quantitatively, thereby improving the scientific measure and objectivity of the results (Du & Gao, 2020).

The social, economic, and ecological data collected by the research institute were quantitative data, while the expert opinions and scores collected through face-to-face discussions, phone calls, and online conferences with experts were qualitative data. A pairwise comparison matrix was constructed using the "1-9 scale method" to allow experts to compare each indicator in pairs and determine the relative importance. The AHP and entropy weights were then calculated using the formula in Microsoft Excel.

Table 2: Factor of relative importance index

Number	Comparison of Relative Importance between Two Factors	Calibration value
1	Most important	9
2	More important	7
3	Significantly important	5
4	Slightly important	3
5	Equally important	1
6	Slightly less important	1/3
7	Clearly unimportant	1/5
8	Much less important	1/7
9	Least important	1/9

Judgment matrix formula:

$$A=\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{24} \\ \dots & \dots & \dots & \dots \\ a_{41} & a_{42} & \dots & a_{44} \end{bmatrix} \quad (1)$$

The judgment matrix was normalised using the following formula:

$$\overline{A_{ij}}=\frac{A_{ij}}{\sum_{\lambda=1}^{n} A_{ij}},i,j=1,\ 2,\ \dots n \quad (2)$$

Rows of the processed judgment matrix were added according to the formula:

$$\overline{N_i} = \sum_{ij}^{n} \overline{A_{ij}}, \quad i, \ j = 1, 2, \ \ldots n \tag{3}$$

Upon normalising the vector $\overline{N_i}$ the weight values of the desired indicators were obtained.

$$N_i = \frac{\overline{N_i}}{(\overline{N_1} + \overline{N_2} + \cdots \overline{N_x})}, i = 1, 2, \ \ldots n \tag{4}$$

(2) Entropy method

The entropy method is an objective weighting technique grounded in information theory, effectively capturing the intrinsic information of indicator data. Given the diverse dimensions and units of the evaluation indicators, it becomes imperative to counteract the impact of disparate dimensions on data analysis, thereby ensuring a more scientifically robust assessment outcome (Jing et al., 2024). In this study, the entropy method was incorporated to validate the objectivity of the data and mitigate the subjective influence introduced by AHP.

This study employs deviation standardisation to linearly transform the raw data, enhancing data comparability (Han et al., 2015). Several indicators contributed positively to the evaluation outcome during the standardisation process (wetland environmental awareness), while others contributed negatively (population density). Therefore, data processing is conducted differently based on these two scenarios. The specific calculation formulae are as follows:

$$Ci' = \frac{Ci - Cmin}{Cmax - Cmin} \tag{5}$$

$$Ci' = \frac{Cmax - Ci}{Cmax - Cmin} \tag{6}$$

When Ci is a positively oriented indicator, formula (5) was applied. Conversely, formula (6) was utilised when the Ci is a negatively oriented indicator. To the standardised value of indicator Ci, where $0 < Ci < 1$; Ci is the statistical value or raw data of a single indicator; and is the maximum and minimum value of a single indicator.

After standardising the data indicators, the entropy method was utilised for weight calculation. The specific steps and formulas are as follows:

$$fij = \frac{cij}{\sum_{j=1}^{n} cij} \tag{7}$$

$$ei = -\frac{1}{\ln n} \sum_{j}^{n} fij \ln fij \tag{8}$$

$$Wi = \frac{1 - ei}{m - \sum_{i=1}^{m} e_i} \tag{9}$$

In the equation, *fij* represents the characteristic weight of the *i*th indicator in the *j*th year, ei denotes the entropy of the *i*th indicator, *Wi* represents the weight of the ith indicator, n is the number of years, and m is the number of indicators.

3. RESULT

3.1 Determination of combined weight

The weights obtained from the two calculation methods are combined to derive the comprehensive weights via formula (10) (see Table 3). This combined approach mitigated the subjectivity of AHD and the potential neglect of strategic importance by the entropy method, providing a more balanced and robust weighing scheme.

$$W_i' = \frac{N_i \times W_i}{\sum N_i \times W_i} \tag{10}$$

Table 3：Ecological security index system weight of Hengshui Lake

Index	AHP weight	Entropy weight	Combined weight
Population	0.054	0.049	0.044
Population density	0.036	0.062	0.037
Natural population growth rate	0.036	0.056	0.034
Precipitation	0.042	0.037	0.026
Precipitation ph	0.021	0.053	0.019
Eutrophication	0.105	0.063	0.111
Comprehensive water quality pollution index	0.105	0.103	0.181
Chemical oxygen demand (COD)	0.084	0.030	0.042
Total phosphorus	0.084	0.050	0.071
Fluoride	0.084	0.067	0.095
Permanganate index	0.084	0.044	0.062
Proportion of the tertiary industry	0.036	0.043	0.026
Per capita disposable income of residents	0.036	0.052	0.031
Energy conservation and environmental protection expenditures	0.054	0.082	0.073
Education expenditure	0.036	0.072	0.043
Social security expenditures	0.036	0.094	0.056
Wetland environmental protection awareness	0.071	0.043	0.051

After computing the comprehensive weights for each indicator, the comprehensive value of the evaluation result was determined via the multi-level weighted sum method.

$$Z_i = \sum_{i=1}^{n} W_i' \times e_i \tag{11}$$

Z denotes the comprehensive ecological evaluation index, *Wi'* represents the comprehensive weight of the indicator, *Ci* stands for the standardised value of the original data, and *n* indicates the total number of indicators. The comprehensive index Z fell within the range of [0, 1], with higher values indicating better ecological health.

Table 4: Hengshui Lake ecological security grade standard

Composite index	Ecological security level	Ecological security status
0.9–1.0	V	Ideal safety
0.6– 0.9	IV	Safe
0.4– 0.6	III	Relatively safe
0.2– 0.4	II	Relatively unsafe
0.0–0.2	I	Unsafe

3.2 Calculation Procedure

"Population Density" and "Total Phosphorus Concentration" were taken as examples to clearly illustrate the process of calculating the comprehensive weights of each indicator. The data used for this purpose spanned seven years (2016–2022).

(1) AHP

Step 1: Construction of the judgment matrix

Based on the expert scores and the literature review, the score for population density was 2, and the total phosphorus concentration was 3. Together with the remaining 15 evaluation indicators (N = 17), a judgment matrix was constructed according to Equation (1).

Step 2: Normalisation of the matrix

The judgment matrix was normalised using Equation (2) to eliminate the influence of differing dimensions.

Step 3: Calculation of the row average to obtain the weights

According to Equations (3) and (4), the normalised matrix was averaged by row to obtain the corresponding feature vector for each indicator (weight). The results are presented in Table 5.

Table 5: AHP-based weights of population density and total phosphorus concentration

Indicators	Construction of the judgment matrix	Column sum of the judgment matrix	Normalisation of the judgment matrix	Calculate weights based on the row average	Overall weight
Population density	1, 1/4.27 ≈ 0.2342	5.27，1.2342	0.1897, 0.1898	0.1898	0.3571
Total phosphorus	4.27, 1	5.27，1.2342	0.8103, 0.8102	0.8102	0.0837

Note: Population density: λmax = 3.000, CI = 0.000, CR = 0.000； Total phosphorus concentration: λmax = 8.000, CI = 0.000, CR = 0.000
As CR = 0 (< 0.1), the judgment matrices are perfectly consistent.

(2) Entropy method

Step 1: Data Standardisation

Given that both indicators are negative, the min-max reverse normalisation method was applied for standardisation. The specific calculation is shown in Equation (6), and the resulting normalised values are as follows:

Table 6: Standardised results of population density and total phosphorus from 2016 to 2022

Indicators	2016	2017	2018	2019	2020	2021	2022
Population density	0.2100	0.2205	0.2676	0.9637	1.0000	0.7763	0.000
Total phosphorus	0.0293	0.7647	0.7647	0.76470	0.7895	0.8947	1.000

Note: This study uniformly corrected the 0 value in all standardised results to 0.0001 to avoid the occurrence of ln0 in subsequent calculations.

Step 2: Computation of the characteristic proportion, *fij*

The standardised data were normalised using Equation (7), and the feature proportion for each year was subsequently calculated (see Table 7).

Table 7: The fij values of population density and total phosphorus from 2016 to 2022

Indicators	2016	2017	2018	2019	2020	2021	2022
Population density	0.06109	0.06414	0.07785	0.28000	0.29002	0.22586	2.9×10^{-5}
Total phosphorus	0.00583	0.15213	0.15213	0.15213	0.15701	0.17787	0.20390

Step 3: Calculation of information entropy

The information entropy of each indicator was calculated using Equation (8), with n = 7. The resulting entropy values for population density and total phosphorus are presented in Table 8.

Step 4: Calculation of the degree of diversification and the weights

Based on the information entropy, the diversification coefficient was calculated as $di=1-ei$ and normalised using Equation (9) to obtain the final weights (see Table 8).

Table 8: Entropy, difference coefficient, and entropy weight for population density and total phosphorus

Indicators	*Ei*	*di*	*Wi*
Population Density	0.06109	0.06414	0.07785
Total Phosphorus	0.00583	0.15213	0.15213

(3) Determination of combined weight

Based on the weights obtained from the AHP (see Table 5) and the entropy (see Table 8) methods, the comprehensive weights were calculated using Equation (10). The results are presented in Table 3.

4. DISCUSSION

After standardising the original data and applying the AHP and the entropy method, comprehensive weights for each indicator were computed. As depicted in Table 3, water quality pollution index, eutrophication, and fluoride significantly impacted ecological security, as evidenced by the higher weight values. This finding is consistent with studies on other lake ecosystems, such as Taihu Lake and Huama Lake in China, which indicated water quality parameters as important indicators of ecological health (Dong et al., 2024; Zhao et al., 2025). The dominance of the comprehensive water quality pollution index (0.181) highlighted this indicator as a holistic measure of aquatic degradation, integrating multiple stressors. Similarly, the high weights for eutrophication (0.111) and fluoride (0.095) emphasised specific pollution threats. Eutrophication, often driven by nutrient loading from agricultural runoff, is a critical issue for freshwater lakes globally, leading to algal blooms and oxygen depletion (Paerl & Huisman, 2008). Elevated fluoride, potentially from industrial discharges, can have toxic effects on aquatic life and human health (Canadian Council of Ministers of the Environment, 2017).

Factors such as precipitation pH, the proportion of the tertiary industry, and the impact of precipitation on ecological security demonstrated relatively minor effects, as reflected in the lower weight values. The low weight of precipitation pH suggested the indicator as a stable parameter in this region. For instance, the pH value of precipitation in China's Taihu Lake Basin remained stable at 5.5–6.5 from 1990 to 2018, with low acid rain frequency (averaging 5.89 in 2018 with little variation). Studies in the Shiyang River Basin and Taihu Lake Basin reported that the impact of precipitation pH on ecological security was only 0.01–0.02, indicating that the minor effects of pH on ecological security (Chen et al., 2025; Dai et al., 2022; Zhao et al., 2019).

The modest weight of the tertiary industry proportion indicated the potential indirect and slower-acting influence on the immediate ecological state of the lake compared to direct pollution indicators. On the one hand, upgrading the industrial structure affects the water environment through reductions in energy intensity and technological substitution, and is often transmitted along the chain from environmental regulation to industrial structure and then to water pollution. Therefore, this indicator tends to receive a smaller weight in comprehensive evaluations. On the other hand, land-use patterns and seasonal non-point-source loads exert an immediate, direct influence on water-quality parameters, such as total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD). Thus, the corresponding pollution indicators carry higher weights (Hou et al., 2021; Liu & Gan, 2024; Sun et al., 2023; Wang et al., 2024; Wang et al., 2020). Computing the Z value can aid in ascertaining the ecological security level and status of Hengshui Lake from 2016 to 2022, as depicted in Table 9 and Figure 2.

Table 9: Temporal dynamics of ecological security indices of Hengshui Lake (2016–2022)

Year	P	S	R	Z	Security Level
2016	0.041	0.162	0.000	0.203	Relatively unsafe
2017	0.066	0.174	0.026	0.266	Relatively unsafe
2018	0.057	0.229	0.084	0.371	Relatively unsafe
2019	0.082	0.295	0.153	0.530	Relatively safe
2020	0.115	0.351	0.214	0.679	Safe
2021	0.045	0.319	0.221	0.584	Relatively safe
2022	0.012	0.467	0.277	0.756	Safe

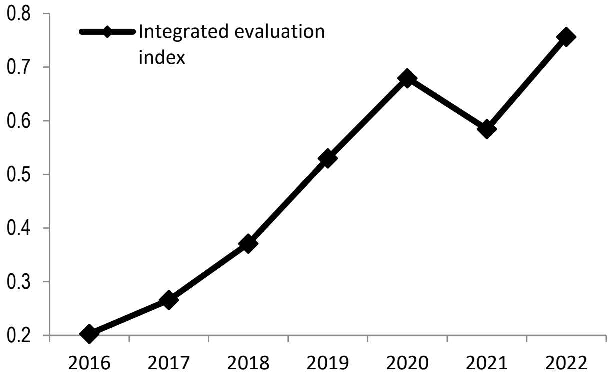

Figure 2: Temporal variation of the integrated ecological security index for Hengshui Lake (2016–2022)

Figure 2 illustrates that the ecological security index of Hengshui Lake experienced a consistent upward trend from 2016 to 2022. Back in 2016 to 2018, the ecological security composite index of Hengshui Lake was 0.203, 0.266, and 0.371, respectively, all falling within the "relatively unsafe" category. In 2019, the ecological security composite index increased to 0.530, marking entry into a "relatively safe" level. This positive trajectory continued, with the composite index ascending to 0.679 by 2020. Notably, the composite index continues to surge in 2021 and 2022, reaching 0.684 and 0.756 (safe level), respectively. This overall improvement is a significant positive outcome, suggesting that management and conservation efforts in the Hengshui Lake basin have been effective. Furthermore, this trend mirrors successful restoration initiatives in other Chinese wetlands, such as Taihu Lake and Baiyangdian, where integrated water quality management and policy interventions have led to measurable ecological outcomes (Dong et al., 2024; Li et al., 2024).

The lowest ecological security composite index of Hengshui Lake was recorded in 2016, which corresponded to relatively low-pressure index, state index, and response index values. This phenomenon was potentially attributed to water pollution challenges reported in China during that period. Since then, various protective and remedial measures have been implemented, and public awareness regarding wetland conservation has also increased, resulting in the “safe” index level in 2022. The strengthening of national environmental policies, such as the Water Ten Plan, and increased local investment in ecological restoration, demonstrate the critical role of policy response (R) in driving ecological improvement (Hengshui Municipal People’s Government Office., 2017).

As depicted in Figure 3, the ecological security of Hengshui Lake has improved substantially between 2016 and 2022, as reflected by the continuous rise in the State and Response subsystem indices. Specifically, the State (S) index increased from 0.161 in 2016 to 0.467 in 2022, indicating a steady enhancement in ecological conditions and environmental quality. This improvement in the subsystem, particularly driven by water quality indicators, is the most direct evidence of successful ecological management, such as reducing pollution inputs and restoring the natural functions of the lake. In addition, these improvements in the "state subsystem" index are consistent with existing evidence, including the significant rise in surface water quality at the national level since 2003. These enhancements were contributed by emissions reduction, the decline in total phosphorus in lakes since 2006, as urban and rural sewage treatment levels have improved, and the steady improvement in water quality after 2007 under continuous treatment, as recorded in the Taihu Lake Thirty-Year Research Review (Ma et al., 2020; Tong et al., 2017; Yan et al., 2024).

The Response (R) index rose sharply from 0.000 in 2016 to 0.277 in 2022, suggesting progressively stronger policy support and ecological interventions. This rapid growth in Response (R) highlights a significant increase in societal and governmental action, including financial investment in environmental protection and public education, which are crucial drivers for long-term ecological security (Du et al., 2018; Zhou et al., 2021). In contrast, the Pressure (P) index displayed more fluctuation, rising from 0.041 in 2016 to a peak in 2020 at 0.115, followed by a decline to 0.012 in 2022. This trend implies that anthropogenic and environmental pressures on the lake system were initially increasing, but have been effectively mitigated in recent years (Zhang, Y. et al., 2022). The initial increase in Pressure (P) could be linked to ongoing regional development and population growth. The sharp decline after 2020 is a promising sign, potentially resulting from effective policy interventions that decoupled economic activity from environmental pressure, such as stricter regulations on pollution discharge and more sustainable land-use planning (Hebei Ecology and Environment Bureau., 2023).

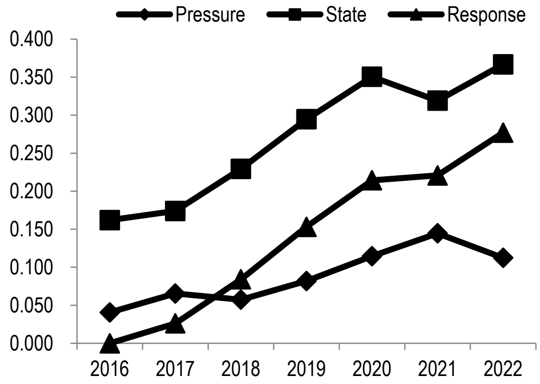

Figure 3: Temporal evolution of the PSR subsystem indices for Hengshui Lake (2016–2022)

Figure 4 presents the changing proportional contributions of the Pressure, State, and Response subsystems to the overall ecological security index of Hengshui Lake from 2016 to 2022. The State subsystem consistently accounted for the largest share throughout the period, although the proportion decreased from 79.95% in 2016 to 61.72% in 2022. This decline reflected a relative balancing among the subsystems rather than deterioration, as both Pressure and Response proportions experienced dynamic shifts. Notably, the Response subsystem contribution increased markedly from 0.00% in 2016 to 36.64% in 2022, indicating a growing emphasis on policy interventions, ecological restoration, and societal actions.

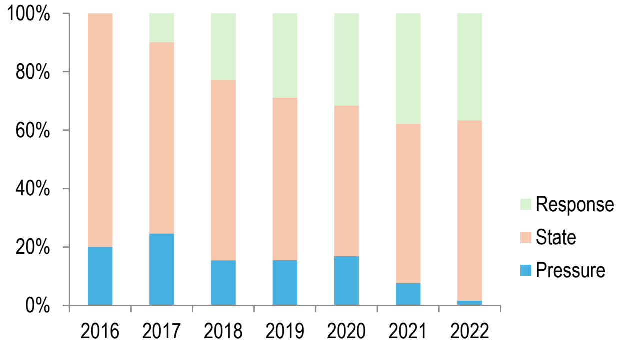

Figure 4: Proportional contribution of Pressure, State, and Response subsystems to the ecological security index of Hengshui Lake (2016–2022)

This shift signifies a transition from a passive state of degradation to an active phase of management and recovery, which is a common pattern observed in ecosystems under successful restorative governance (Zhou et al., 2021). In contrast, the Pressure subsystem exhibited a sharp decline, peaking at 20.05% in 2016 and plunging to 1.64% in 2022. This trajectory suggested that environmental pressures have been substantially mitigated or the relative impact was diminished through effective management. The drastic reduction in the Pressure component is an encouraging outcome. The positive impact indicates that the sources of environmental stress have been effectively managed, allowing the improved State and proactive Response to become the dominant factors determining ecological security (Ma et al., 2020).

Analysing the long-term trend of ecological security in Hengshui Lake from 2016 to 2022 revealed the changes in ecological security levels in different periods, reflecting the temporal dynamics of ecological security in Hengshui Lake.

5. CONCLUSION

This study has developed an ecological security assessment model for Hengshui Lake spanning from 2016 to 2022, based on the PSR framework. The results indicated an overall improvement in the ecological security and sustainable development capacity of the lake during this period. This upward trend aligns with findings from global research on wetland ecosystems, which suggest that targeted management interventions can enhance ecological resilience (Zedler & Kercher, 2005).

The progressive enhancement of ecological responsiveness in Hengshui Lake mirrors the concept of "adaptive governance", as reflected by the rising tertiary industry proportions, increased environmental protection expenditures, and improved wetland conservation awareness (Folke et al., 2005). Societal responses, which include policy adjustments, financial investment, and public participation, are critical for reversing ecological degradation. In this case, the growth in energy conservation and environmental protection expenditures for Hengshui Lake (a core response indicator) aligns with the findings of Canning et al. (2021), who demonstrated that sustained investment in wetland restoration directly enhanced ecosystem stability. Additionally, the elevation of wetland protection awareness echoes the study conducted by Zhou et al. (2017), which highlights public engagement as a key driver of long-term ecological management success of nature reserves in China.

The Pressure index experienced an initial increase, a brief decline in 2018, and resumed the upward trajectory up to 2022. This finding indicated that human disturbances have not been fundamentally curbed despite ongoing conservation efforts. Moreover, this trend aligns with the "pressure threshold" model, which suggests that rapid urban expansion and population growth exert sustained and cumulative stress on ecosystems, often exceeding the capacity of short-term mitigation measures (Hillebrand et al., 2020). In the case of Hengshui Lake, the continuous rise in population density, a core pressure variable, highlights the persistent tension between regional economic development and ecological conservation. Similar challenges have been observed in other urban wetlands, such as Baiyangdian (Zhao et al., 2021).

The overall improvement in the State Index, driven by better water quality metrics (reduced COD and total phosphorus) and stable precipitation patterns, indicated effective environmental governance. This outcome aligns with studies by Qu & Fan (2010), who linked targeted pollution control measures in Chinese lakes to measurable improvements in ecological state. The marginal decline in 2021, however, may reflect transient factors such as extreme weather events or short-term policy gaps; a phenomenon also reported in the Taihu Lake basin, where annual fluctuations in ecological state are attributed to climate variability and enforcement lags (Wang et al., 2019). Thus, there is a need for adaptive management strategies to buffer against such uncertainties.

Data accessibility constrained the indicator selection of this study, a common challenge in ecological assessments (Carignan & Villard, 2002). While the absence of a standardised methodology for choosing ecological indicators justified the current framework, the use of a structured conceptual foundation is equally important (Niemeijer & De Groot, 2008). Future research could integrate more granular data, such as biodiversity metrics (avian species richness) or soil quality parameters, to enhance evaluation precision.

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