A comprehensive evaluation method for plateau freshwater lakes: a case in the Erhai Lake

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ABSTRACT
The study first systematically assessed the ecosystem health status of the plateau freshwater lake of Erhai Lake in Yunnan Province of China, using the revised Freshwater Health Indicator methodology, which comprised three components, i.e., “Ecosystem Vitality,” “Ecosystem Services,” and “Governance and Stakeholders.” To better reflect the real health status of the basin, the cask short board effect was considered during aggregation of the indicators. In addition, analysis of the coupling coordination relationship among the three components was conducted to study the mutual influences among them as well as the comprehensive development level of the studied area. Basically, the ecosystem of the Erhai Lake basin remained healthy during the studied period according to the research due to specific measures and actions taken to manage the environmental problems caused by a former local economic development and urbanization process. However, there were still aspects to improve for more sustainable ecosystem management and utilization in the basin. The “short boards” of the Erhai Lake basin show room for improvement in local freshwater ecosystem management and underline governance problems that need to be addressed. Suggestions are provided for the local stakeholders consequently for the more sustainable development of the studied basin.

Introduction
Considering the benefits that people received from lake ecosystems, it can be concluded that lakes have great influences on the welfare of human society. However, the quality of lake ecosystems is decreasing globally as a result of the growing human disturbance (Groot et al. 2012). Erhai Lake, the second largest plateau freshwater lake of Yunnan Province of China, is the main water supply source for the basin, playing an important part in local residents’ livelihood and social economic development. Meanwhile, the Erhai Lake is an inland fractured lake with typical closure and semi-closure characteristics (Ye et al. 2004) and is easily influenced by the topography and climate of the district, with a relatively smaller recharge coefficient and longer water exchange cycle, resulting in the vulnerability of its ecosystem environment (Yan et al. 2005). Following rapid population growth and urbanization progress, water demand and sewage discharge in the Erhai Lake basin have increased notably in recent decades (Chen et al. 2018), which exerts a severe negative impact on the local ecology and environment, such as water resource shortage (Lin et al. 2018), water quality deterioration (Peng, Wang, and Liu 2005), eutrophication (He et al. 2018), etc.

Numerous studies have been conducted to arouse the stakeholders’ attention to the Erhai Lake and to provide effective measures to address the water pollution and ecology deterioration issues since the 1980s. These studies have been divided into three periods. In the first period (1980–1990), the studies focused on the influence of human activities on the Erhai Lake and the strategic planning of improving environment quality of the lake (Guo et al. 2001; Li, Shi, and Cao 2011). In the second period (2000–2010), the focus of research had been put on comprehensive water pollution prevention and control (Yan, Lu, and Zhao 2008), with emphasis on the treatment and interception of pollution around the lake (Peng, Wang, and Liu 2005), the control of agricultural and rural nonpoint pollution in the watershed combined with the impact of urbanization on the lake (Pang et al. 2015), etc. In the third period (2010–present), apart from the water pollution control of the Erhai Lake, the researchers also focus on habitat improvement (Zhang, Wang, and Imai 2015), sediment pollutant analysis in the lake (Li et al. 2017b), eutrophication governance of the lake (Lin et al. 2020), structure of aquatic ecological community (Zhu et al. 2017), biodiversity conservation (Yang et al. 2018), ecosystem assessment, and sustainability analysis (Zhong et al. 2018) of the lake basin.
Although the above-mentioned studies made efforts to improve the water quality and ecology situation in the Erhai Lake basin, they mainly concentrated on one single aspect, not comprehensively associating the social economic development with water environment and ecology of the basin. There are only a few studies conducted in the perspective of human–environment interactions in the Erhai Lake basin. For instance, Li, Shi, and Cao (2011) assessed the environment-carrying capacity of the Erhai Lake taking consideration of human activities. Zhong et al. (2018) assessed the current sustainability of the Erhai Lake basin through constructing an emergy-based framework, which divided the Erhai Lake basin into five subsystems. Lin et al. (2020) described limitations of sustainable development in the Erhai Lake and proposed green watershed construction (GWC) as well as its relevant effective measures to maintain sustainable development. However, rare research studies consider the Erhai Lake basin as a holistic aquatic ecosystem and study the ecosystem health status comprehensively considering the ecosystem itself, the ecosystem services it provides, and the stakeholders’ management on the ecosystem. Moreover, numerous measures have been taken to improve the Erhai Lake’s ecosystem quality in recent years, but few of the existing research studies have comprehensively assessed the effect of the efforts, consequently making it hard to provide practical suggestions for better governance of the Erhai Lake basin.

The current research is conducted to comprehensively study the ecological health status of the Erhai Lake and aims to examine the former efforts made toward Erhai Lake conservation, providing pragmatic suggestions for more sustainable management of the basin in further steps. A localized methodology of the Freshwater Health Index (FHI) combined with “China Technical guidelines for river and lake health assessment (SL/T793 – 2020)” is first utilized. To better reflect the real health status of the Erhai Lake basin, the cask short board effect is considered during the aggregation of the indicators for the first time, which is the improvement of the FHI methodology used by Vollmer et al. (2018) and Wen, Li, and Li (2020). Furthermore, analysis of the coupling coordination relationship among the key components for the Erhai Lake basin is conducted, as optimizing the key components has become one of the cores in the lake basin management and sustainable development, which is the first trial in the ecological assessment of the basin.

**Methodology**

**The studied area**

The Erhai Lake is located in the Dali Bai Autonomous prefecture of Yunnan Province, southwest China (Figure 1), which is the seventh largest freshwater lake in China and the second largest freshwater lake in the Yunnan-Guizhou Plateau (Cao, Wang, and Li 2014). The elevation of the Erhai Lake Basin ranges from 1478 m to 4081 m with an average elevation of 1796 m (Hu et al. 2018). The deepest point of the Erhai Lake is around 21.0 m, and the average depth is about 10.5 m (Chen et al. 2018). The Erhai Lake Basin is located in the intersection of watersheds of the Lancang River, Jinsha River, and Yuanjiang River, and the total area of the basin is approximately 2565 km². Over the past 10 years, population in the basin has increased by 11.4% and the average GDP growth rate

![Figure 1. Location of Erhai Lake basin (adapted from Lin et al. 2020).](image-url)
of the Erhai Lake basin has reached over 10%, making it one of the fastest growing economic regions in Yunnan Province. Generally speaking, the primary industry of the basin is mainly traditional agriculture and manufacturing, indicating a relatively rough development mode, with prominent pollution problems and low economic benefits.

The water resources of the Erhai Lake primarily come from precipitation (Li et al. 2017b) as well as the three main rivers located north of the Lake, among which the Miju River watershed is the largest sub-basin, covering 61% of the Erhai Lake basin (Wang 2015). The natural outflow of the Erhai Lake is through the Xier River located with the cascade hydropower station, which flows into the tributary of the Lancang River (Wang and Dou 1998). The water from the Erhai Lake was as well introduced into Binchuan through a tunnel from 1995, which is mainly used for agricultural irrigation and domestic water supply in Binchuan County.

**A comprehensive assessment method in Erhai Lake**

**The establishment of the indicator system**

The FHI methodology was initially developed by Vollmer et al. (2018), and it was well used and further revised by Wen, Li, and Li (2020) after jointly conducting the first freshwater ecosystem health assessment on the Lancang River basin in Xishuangbanna of China with Conservation International. The FHI methodology targets to evaluate freshwater resource sustainability, using the conceptual framework consisting of three interacting components, i.e., “Ecosystem Vitality,” “Ecosystem Services,” and “Governance and Stakeholders,” and the indicator system of the methodology has been described (Vollmer et al. 2018; Wen, Li, and Li 2020). The interaction of the three components makes them a holistic system to some extent, and the interactions can be described as: within the constraints and rules set by water governance, stakeholders modify ecosystems through land use change or conservation in order to exploit or manage freshwater ecosystems, and access water-based ecosystem services by developing infrastructure and technologies. Modifications to ecosystems and water withdrawals can alter the flow regime and water quality and affect the delivery of ecosystem services to beneficiaries consequently.

The comprehensive assessment of the Erhai Lake ecological health status is carried out using a localized and revised methodology of FHI. Meanwhile, to ensure the accuracy and universality of the research, some subindicators are chosen and calculated referring to “China Technical guidelines for river and lake health assessment (SL/T793 – 2020)” after discussion with experts and local stakeholders, considering both characteristics of the Erhai Lake and availability of data required during the calculation, as shown in Figures 2–4. In the figures, layer A shows the components, layer B shows the major indicators, and layer C shows the subindicators. Generally speaking, the selection of the major indicators and the corresponding subindicators is carried out based on the principle of whether the indicators are representative and whether empirical data are likely to exist or can otherwise be collected efficiently, based on the specific conditions of the studied area.

**Calculation Methods of the Subindicators**

To quantitatively calculate each subindicator in layer C as shown in Figures 2–4, appropriate methodologies must first be defined. Table 1 shows the calculation methods, reference conditions, and data sources for the subindicators. The subindicator scores are calculated ranging from 0 to 100. The value of 100 indicates that the subindicator is nearly close to nature status and 0 indicates highly interfered by human activities. For the Erhai Lake basin, quantitative information to assess the indicators mainly came from monitored...
water quality and discharge datasets, land cover maps, provincial or prefecture’s statistical yearbooks, IUCN Red List, etc. Some subindicators for the “Govermnance and Stakeholders” component, including “Engagement in decision-making process,” “Public satisfaction,” and “Information access and knowledge,” are obtained by designing and analyzing completed questionnaires.

**Aggregation of the indicators**

After calculation, the subindicator scores are further aggregated to supply an overall score for each major indicator. The major indicators are then aggregated to supply an index value for each component, and the FHI of the Erhai Lake basin is obtained consequently.

Before aggregation, weights need to be assigned to reveal greater or lesser importance of the role of each indicator for evaluating freshwater health of the studied area. AHP is a well-used systematic method that tries to approach decision-making issues using multiple criteria (Saaty 2005). In this paper, we use AHP to decide the weights of components, major indicators, and corresponding subindicators. Fourteen judgment matrices are constructed to obtain the weights in the indicator system, namely, FHI-(A1-A3), A1-(B11-B14), B11-(C11-C12), B12-(C13-C14), B13-(C15-C17), A2-(B21-B23), B21-(C21-C22), B22-(C23-C25), B23-(C26-C27), A3-(B31-B34), B31-(C31-C34), B32-(C35-C36), B33-(C37-C38), and B34-(C39-C310). The reciprocal matrix is formed through pair-wise comparisons of each matrix. Nine stakeholders with different backgrounds are invited to evaluate the relative importance of every indicator to its parent nodes in each group on a scale of 1 to 9. The weights of the indicators are then calculated in the BPMG AHP online system, a web-based tool for using the AHP in group decision making.

The traditional AHP-comprehensive index evaluation method mainly obtains an aggregated value by weighted summation of the indicator scores, and it may ignore the short board effect in the system, failing to reflect the true results. The core idea of cask short board theory is that the water in a cask depends on the shortest board (Chaharbaghi and Lynch 1999). Li, Ding, and Xia (2017a) adapted the logarithmic function to implement the cask short board effect and demonstrated that the logarithmic function-induced values are theoretically more credible than the linearly weighted summation index used in a traditional AHP-comprehensive index evaluation method. In the current study, each component as well as the major indicator of the FHI methodology for the Erhai Lake basin can be regarded as the water contained in a cask. The boards of the cask represent the indicators. The board width shows the weight of an indicator to the ecosystem health and the board height is the status of the indicator.
Table 1. Calculation methods for the sub-indicators.

| Indicator | Calculation methodology | Reference condition/data sources |
|-----------|-------------------------|--------------------------------|
| C11       | The ratio of surface water consumption to total surface water resources in the basin. | China technical guidelines for river and lake health assessment (SL/T793 – 2020)/Dali Bai Autonomous Prefecture Environmental Status Bulletin (2015–2019) |
| C12       | Comparing the annual, multi-day, and daily average water levels with the minimum ecological water level (ML) at which the lake can operate normally. | China technical guidelines for river and lake health assessment (SL/T793 – 2020)/Dali Water Resources Bulletin (2015–2019) |
| C13       | Documents survey from local government website | Environmental Quality Standards for Surface Water of China (GB 3838–2002)/Dali Bai Autonomous Prefecture Environmental Status Bulletin (2015–2019) |
| C14       | Calculation of the comprehensive trophic level index (TLI). | Literature(Wang, Liu, and Zhang 2002)/Dali Bai Autonomous Prefecture Environmental Status Bulletin (2015–2019) |
| C15       | Changes of lake area in the assessment year and benchmark year. | China technical guidelines for river and lake health assessment (SL/T793 – 2020)/Dali Bai Autonomous Prefecture Environmental Status Bulletin (2015–2019) |
| C16       | Proportion of vegetation vertical projection area to the area of the lakeshore zone. | China technical guidelines for river and lake health assessment (SL/T793 – 2020)/Remote sensing analysis combined with field investigation. |
| C17       | The extent to which the lakeshore zone is disturbed by human activities. If there are no human activities considered in the assessment, the score of the sub-indicator is 100, and it is subjected to deduction until zero depending on the presence of the related human activities. | China technical guidelines for river and lake health assessment (SL/T793 – 2020)/expert judgment; field investigation. |
| C18       | The indicator of biodiversity (BIO) consists of Fish biomass loss index (FBLI), as well as invasive and nuisance species (INS), and, \( BIO = \sqrt{FBLI \times INS} \) \( FBLI = (1-F0/FE)\times100 \) INS \( = \min\{NSD_0/NSD \times \Delta SC \times PT, 100\} \) where, \( F0 \) represents number of existing fish species in the assessment year, \( FE \) indicates number of fish species in the benchmark year, \( \Delta SC \) denotes the number of concerned species in the assessment year, \( \Delta SC \) indicates the change in the number of species which are concerned, \( PT \) represents the average population tendency across all species concerned. | Literature (Loh et al. 2005; Wen, Li, and Li 2020)|
| C21-C27   | Dividing the studied area into spatial units, and three dimensions are considered for the assessment of “Ecosystem Services” indicators (ESI), i.e., the number of spatial units in studied area which are unable to meet the specific objective (F1), the frequency with which the specific objectives are not met (F2), and the gap with which the specific objectives are not met (F3). If only F1 can be measured, \( ESI = 100 – F1 \); if F1 and F2 can be measured, \( ESI = \sqrt{(F1^2 + F2^2)/2} \); if all three dimensions can be measured, \( ESI = 100 – \sqrt{(F1^2 + F2^2 + F3^2)/3} \). | Literature (Modarres 2006; Wen, Li, and Li 2020)/Dali Bai Autonomous Prefecture Environmental Status Bulletin (2015–2019); IUCN Red List |
| C31-C310  | Expert symposium, document surveys, field investigation, questionnaire analysis. | Literature (Modarres 2006; Vollmer et al. 2018; Wen, Li, and Li 2020)/Dali Bai Autonomous Prefecture Environmental Status Bulletin (2015–2019); statistical bulletin of national economic and social development of Dali City (2015–2019); questionnaire analysis; stakeholders consultation; field investigation. |

The subindicator scores are therefore reclassified and normalized from scale of 0–100 into five levels indicated by the integers 1, 2, 3, 4, and 5 (defined as “Bad,” “Poor,” “Fair,” “Good,” and “Excellent,” respectively) for better analysis based on regional or national standards and references. The log₃ was utilized as five levels of evaluation results are specified in the present study. The reclassification method of indicator scores are shown in Table 2.

The evaluated value \( R \) of FHI as well as the scores for each component and major-indicator considering cask short board effect can be defined using Equation (1),

\[
R = \sum_{i=1}^{n} \log_j I \cdot w_i
\]

where \( w_i \) is the weight of the \( i \)th indicator, which contributes to the system health, \( I \) is the normalized value of the \( i \)th indicator. Since the normalized values of all the subindicators are integers within the closed interval \([1, 5]\), \( R \) should be within \([0, 1]\) consequently.

Table 2. Reclassification of indicator scores in Erhai Lake basin assessment.

| Levels     | Excellent | Good | Fair | Poor | Bad |
|------------|-----------|------|------|------|-----|
| Original score | ≥95       | ≥90  | ≥80  | ≥70  | <70 |
| Normalized value (I) | 5         | 4    | 3    | 2    | 1   |
| Cask short board effect considered(log₃) | 0.86 0.68 0.43 | 0.43 | 0.2 | 0.86 | 1 |

Coupling coordination degree analysis of three components

Even though the freshwater health index of the Erhai Lake basin can be calculated, how the three components interact and the degree of mutual influence among them are still unclear. To better evaluate the comprehensive development status of the Erhai Lake basin, the coupling coordination degree model is applied to quantitatively measure the interacting and coordination relationships among the three components. The degree of coupling coordination decides the key components’ structure and order, as well as the system’s development trend from disorder to order (Wang et al. 2019).
The coupling coordination degree among the three components is calculated via equations (2)- (4) in the current study.

\[
C = 3 \times \left[ \frac{R_v \cdot R_s \cdot R_g}{(R_v + R_s + R_g)^3} \right]^{1/3} \tag{2}
\]

where C indicates the coupling degree among three components. The value of the coupling degree is within interval of [0, 1], the greater the value is, the stronger interaction among the three components supposed to be, and vice versa. \(R_v\), \(R_s\), and \(R_g\) represent the evaluated values of “Ecosystem Vitality,” “Ecosystem Services,” and “Governance and Stakeholders,” respectively.

\[
T = \alpha \cdot R_v + \beta \cdot R_s + \gamma \cdot R_g \tag{3}
\]

Where T represents the comprehensive evaluation index, \(\alpha\), \(\beta\), and \(\lambda\) represent the contribution proportion of “Ecosystem Vitality,” “Ecosystem Services,” and “Governance and Stakeholders,” respectively, i.e., corresponding weights of these components, and \(\alpha + \beta + \lambda = 1\).

The coupling coordination degree D is then calculated as follows:

\[
D = \sqrt{C \cdot T} \tag{4}
\]

### Results

**Weights and evaluated values of indicators for the Erhai Lake basin**

Evaluating using the FHI methodology with cask short board effect considered during indicator aggregation, the freshwater ecosystem health status of the Erhai Lake basin is between the “Fair” and “Good” level. Among these, the “Ecosystem Vitality” component is close to the “Fair” level, the “Ecosystem Services” component is between the “Fair” and “Good” level, and the “Governance and Stakeholders” component is close to the “Good” level. The weights and evaluated values for the indicators are shown in Figure 5. The results are gathered into three components. The color gradient describes the evaluated value of each indicator, green represents the value of 1, and red represents the value of 0. The size of each wedge reveals the weight of the corresponding indicator.

Weights of components and indicators convey the importance stakeholders place on the corresponding aspects in the basin. Among the three components, “Ecosystem Vitality” is assigned the highest weight of 0.43, followed by “Governance and Stakeholders” and “Ecosystem Services” obtains the lowest weight of 0.21. Within the “Ecosystem Vitality” component, “Water quality” and “Water quantity” are weighted the same and highest at 0.33, followed by “Basin condition” at 0.22. Within the “Ecosystem Services” component, “Provisioning” is weighted the highest at 0.5, “Regulation and support” and “Culture” obtain the same weight. Under the “Governance and Stakeholders” component, “Enabling environment” is weighted the highest at 0.4, followed by “Effectiveness,” whose weight is a bit higher than half of that of “Enabling environment,” and “Stakeholder engagement” is assigned the lowest weight at 0.18.

According to the reclassification, eight of the subindicators belong to the “Excellent” level, including the “Utilization ratio of surface water resources” and “Extent of lake area shrinkage” under the “Ecosystem Vitality” component, “Water supply service,” “Flood regulation” and “Water-related recreation” under the “Ecosystem Services” component, “Water resource management,” “Financial capacity,” and “Technical capacity” under the “Governance and Stakeholders” component. Adversely, there are five indicators assessed in “Poor” or “Bad” levels, i.e., the “short boards” for the local ecosystem health, which will be analyzed below. The “short boards” underline governance as well as conservation problems that need to be resolved for more sustainable development of the studied area and reveal aspects for local government and stakeholders to enhance for more sustainable ecosystem management and utilization of the basin.

**Coupling coordination degree of three components**

The coupling degree of the three components is first calculated to analyze the phenomenon and degree of influence among them through interaction. According to the coupling degree’s variation characteristics, this research separates the coupling relationship among the components into four types, i.e., Low coupling stage, Antagonism stage, Break-in stage, and High coupling stage, as shown in Table 3.

Calculated via Equation (2), the coupling degree of “Ecosystem Vitality,” “Ecosystem Services,” “Governance and Stakeholders” in the Erhai Lake basin is in the high coupling stage currently, indicating that the basin is developed in a sustainable and orderly way.

Although the coupling degree has quantitatively analyzed the degree of mutual influence among the components and development order of the system, it cannot mirror the holistic development level of the studied area. Therefore, coupling coordination degree is further calculated to evaluate the merits and demerits of each component, so as to avoid the situation that the studied area’s sustainable development level is low but the coupling degree of key components is high. The coupling coordination degree is often separated into different levels in
a subjective way (Xing, Xue, and Hu 2019) after calculation. This paper separates the coupling coordination degree into five levels, referring to the existing research (Wang and Tang 2018), i.e., Serious imbalance, Moderate imbalance, Basic coordination, Moderate coordination, and Good coordination, as shown in Table 4.

The coupling coordination degree of the three components is on the brink of “Good coordination” in the current assessment for the Erhai Lake basin. The coupling coordination degree indicates that components of “Ecosystem Vitality,” “Ecosystem Services,” and “Governance and Stakeholders” show the positive relationship and Erhai Lake basin is managed and utilized in a sustainable and orderly way at present. Ecosystem vitality is much improved in recent years and its service products are almost able to meet requirements during the local socioeconomic development as a result of stakeholders’ efforts in the basin governance.
Table 4. Classifications of three components’ coupling coordination degree.

| Coupling coordination degrees (D) | Levels       | Characteristics                                                                 |
|-----------------------------------|--------------|----------------------------------------------------------------------------------|
| D < [0.2]                         | Serious       | Ecosystem vitality of the Erhai Lake basin deteriorates significantly because of human activities, including disorderly discharge of pollutants, excessive exploitation of the ecosystem products, without effective governance and conservation by stakeholders. |
| D ∈ [0.2, 0.4)                    | Moderate      | Ecosystem vitality of the Erhai Lake basin is still deteriorated significantly because of human activities; stakeholders have realized the importance of the Erhai Lake basin governance. |
| D ∈ [0.4, 0.5)                    | Basic         | The three components have coordinately developed. Stakeholders begin to put emphasis on the governance and restoration of deteriorated ecosystem vitality led by human activities. The Erhai Lake basin is gradually developed in an intensive and efficient way. |
| D ∈ [0.5, 0.8)                    | Moderate      | The ecological restoration starts to get achievements. The ecological vitality has been greatly enhanced, and the ecological services have been strengthened continuously. |
| D ∈ [0.8, 1.0)                    | Good          | The three components show the positive relationship, and the Erhai Lake basin is managed and developed orderly. |

Discussion

Ecological health status of the Erhai Lake basin

The study indicates that there is coherent contact among the three components, especially indicators between “Ecosystem Vitality” and “Ecosystem Services,” and it is better to jointly analyze the indicators under these two components. Generally, the Erhai Lake basin is located in the low-latitude plateau area, with a mild climate and abundant rainfall, characterized by a wide variety of plants and animals. “Water quantity,” “Water quality,” and “Biodiversity” are important elements for “Ecosystem Vitality”; besides the indicator of “Basin condition” on the one hand is the expression of “Ecosystem Vitality” status, and affects the “Ecosystem Vitality” on the other hand. With regard to “Ecosystem Services,” the water and aquatic products it provides, the regulation ability of the ecosystem itself and related natural disasters, as well as beautiful scenery and corresponding recreation, are usually concerned.

The water level is an important indicator to indicate the quantity of a lake. The Erhai Lake is a multifunctional plateau freshwater lake with artificially controlled water levels, and local governments have been emphasizing on ecosystem conservation and sustainable utilization of it from various aspects. The statutory minimum ecological water level has been adjusted several times since 1988, and the current one is 1964.30 m according to Regulations on the protection and administration of the Erhai Lake in Dali Bai Autonomous Prefecture of Yunnan Province. Dali water resources bulletins (2015–2019) show that the annual minimum water levels of the Erhai Lake are mostly above 1964.30 m in the past 5 years, except that in 2019, which was 1964.25 m, 0.05 m lower than the statutory one, indicating that water quantity of the Erhai Lake remains a relative steady and satisfying status. As a result of the regulation by the Erhai Lake as well as the cascade hydropower station, the flood did not occur in the basin in recent years, and the water demand in the basin can be met in the studied period; this is in line with the research conducted by Mo et al. (2020). The Erhai Lake’s water quality has changed from a low to moderate nutrient content and failed the Class II water quality standard frequently since 2006, which was specified in Environmental Quality Standards for Surface Water of China (GB 3838–2002), implying preliminary eutrophication in the past few years, particularly in the northern part of the lake, as well as the leeward side where algal blooms occur almost every year (Hu et al. 2018). In the current study, the water quality of the Erhai Lake remains class III during the studied period, but there were 5 months when the water quality was class II in 2018 and 2019, respectively, showing an improvement of the Erhai Lake’s water quality. The dominant water pollution in the Erhai Lake is nitrogen and phosphorus, and the Erhai Lake is mesotrophic in the studied period consequently; this is consistent with the conclusion induced by Li, Bai, and Alatalo (2020). Agricultural planting in the basin has been exhibited to be the main contributor for water consumption and water pollution of the Erhai Lake, with a contribution of around 32% of total nitrogen in the lake water (Hu et al. 2018).

For component of “Ecosystem Vitality,” the “short boards” are “Vegetation coverage of lakeshore zone,” “Level of artificial disturbance in the lakeshore zone,” and “biodiversity.” According to Dali Bai Autonomous Prefecture Environmental Status Bulletin (2019), although the forest coverage of the Prefecture was 62.86% in 2019, it was only 39.32% in the Erhai Lake basin. The research is in accordance with a conclusion induced by Chen, Guo, and He (2021) that vegetation...
coverage in Erhai Lake Basin shows a fluctuating upward trend, and the areas with an obvious decrease are concentrated around the Erhai Lake because of the land use increase brought by urbanization. Li, Bai, and Alatalo (2020) also proposed that area dedicated to planting economic crops has extended with continuing increase of the population in the Erhai Lake basin, which has consequently led to vegetation degradation. Based on remote sensing data analysis combined with field investigation, artificial disturbance around the Erhai Lake is identified with distance measured, such as lakeshore buildings, roads, pipelines, agricultural cultivation, and hard embankments, which contribute to a low score for the “level of artificial disturbance in the lakeshore zone” subindicator. This is also illustrated by Li, Bai, and Alatalo (2020) that constructed area in the Erhai Lake basin, especially in the lakeshore zone, increased significantly from 2000 to 2015 due to a boom in tourism, at the expense of forest, grassland, and farmland. Furthermore, the local economic development and infrastructure construction have resulted in declining biodiversity. According to the local documentation, there were a total of 17 species of fish in the Erhai Lake in the 1950s, all of which are indigenous species. In the 1960s and 1970s, fish species like grass carp and silver carp were artificially stocked into the Erhai Lake and the fish species increased from 17 to 30, which broke the original ecological balance and impeded the proliferation and development of indigenous fish species to some extent. Furthermore, the happening of eutrophication in the Erhai Lake had a strong influence on aquatic organisms and their related communities (Wu and Wang 1999). There was an evident fluctuation in the quantity of zooplankton (Dong 2015), and some indigenous fish have become threatened or even extinct. In the meanwhile, the invasive species of Pomacea canaliculata was discovered in 2008 in the basin. Although the population of Pomacea canaliculata has decreased as a result of Dali City’s unremitting efforts to eradicate them, the invasive species has caused incalculable economic losses and ecological safety problems in Dali city and surrounding areas (Su et al. 2016).

For the component of “Ecosystem Services,” the “short board” is the “Aquatic product yield.” According to the Statistical bulletin of national economic and social development of Dali City (2015–2019), the aquatic product yield of the Erhai Lake deceased every year except the year of 2019 in the past 5 years, especially in 2017 and 2018, the deceased ratio reached 56.9% and 36.94%, respectively. The decreasing aquatic product yield is probably attributed to two reasons. First, forbidden fishing period is set in Erhai Lake for the past 15 years to effectively protect and restore the ecological environment, optimize the ecological structure, and realize the sustainable development of fishery economy of the Lake. Generally, the forbidden fishing period lasts from six to nine months, and it was prolonged for a whole year from 2017 to 2019. Second, the eutrophication of the Erhai Lake leads to a lower aquatic product yield to some extent. Wu et al. (2021) determined the relationship between the diversity and productivity of submerged plants in the mesotrophic Erhai Lake and found that the community productivity was remarkably negatively correlated with the biodiversity of plants due to intense competition effects among submerged species. The lower submerged plants’ productivity because of microreplication in the Erhai Lake accordingly induces a decrease in the aquatic product yield.

The “Governance and Stakeholders” indicators were determined qualitatively and were elicited by an approximate 60 question survey in the previous studies of the Dongjiang and Lancang River in Xishuangbanna (Vollmer et al. 2018; Wen, Li, and Li 2020), which used methodology of FHI as well, and it was found that the design of the questionnaire was complex and covered too many fields for stakeholders to answer all the questions effectively. In the current study, we adopted the stakeholders and experts’ suggestions to adjust indicators for the “Governance and Stakeholders” component and simplified the questionnaires to make it more suitable and flexible for the Erhai Lake assessment. Most of the indicators are calculated quantitatively by surveying local documentations as well as websites. The indicators of “Engagement in decision-making process,” “Public satisfaction,” and Information access and knowledge are determined through designing a 14-question questionnaire as there is few related data resource.

For component of “Governance and Stakeholders,” the “short board” is “Engagement in decision-making process.” A total of 70 copies of the questionnaire above-mentioned were distributed and collected from related stakeholders. Among these, 35.71% of the interviewers are satisfied with the Erhai Lake ecological environment, 11.43% are very satisfied, and 5.71% are dissatisfied. Most of the representatives who are not satisfied or hard to say whether satisfied or not gave low scores for “Information access and knowledge” and “Engagement in decision-making process” indicators, especially “Engagement in decision-making process.” To enhance stakeholders’ engagement in decision-making process in the Erhai Lake basin, it is recommended that the government starts by promoting school education on environment and ecology management to promote public participation. Furthermore, public participation in data collection, decision making, and performance appraisal is necessary to be encouraged, and the public’s rights to participation need to be clearly stated in relevant laws and regulations.
Analysis of coupling coordination degree of the Erhai Lake basin development

The Erhai Lake basin is rich in resources and beautiful scenery. It is not only the domestic water source of Dali City but also has many functions, such as regulating climate, providing water for industrial and agricultural production, tourism, shipping, power generation, etc. However, with the increase of population, the development of industrial and agricultural production and the intensification of people’s unreasonable development activities in the Erhai Lake basin in recent decades, the ecological environment in the basin had been seriously disturbed and deteriorated, the ecological function was seriously weakened accordingly. There was a serious imbalance in the development of production, life, and ecological protection in the basin. For instance, the Erhai Lake’s water quality has showed a downward trend since 1990. Three severe algae blooms have occurred in 1996, 2003, and 2013, even though the water quality standard in 1996 was at Class II (Wang 2015). In addition, the increasing water demand as population and social economic development, combined with successive years of drought in the basin, has led to a gradual downward trend of the Erhai Lake water resources since the 1990s (Lin et al. 2018).

The severe water pollution and ecological deterioration in the Erhai Lake attracted stakeholders’ attention and caused them to take actions to reverse the situation. Numerous policies have been made to guide the protection of the Erhai Lake water and ecology quality. For instance, Regulations on the protection and administration of the Erhai Lake in Dali Bai Autonomous Prefecture of Yunnan Province firstly released in 1988, which has been revised four times, is the basic regulation for the Erhai Lake conservation. To further enhance the conservation of the Erhai Lake ecosystem and to make the lake more sustainable, projects related to lakeshore belt restoration and aquatic ecological protection have been effectively carried out, of which, the most famous one is the “Seven Actions” for the protection of the Erhai Lake, which was launched in 2017. Besides, Dali City delineated the “three lines” of the Erhai Lake ecological environment protection in 2018, i.e., the blue line represents the boundary of the Erhai lake area, the green line represents the protection boundary of the Erhai lakeshore zone, and the red line represents the boundary of the core area of the Erhai water ecological protection zone. The program contains strict regulations on the activities that can be carried out within the scope of the “three lines.” Meanwhile, a technical service system has been established and related research has been conducted to provide technical support for the Erhai Lake protection in recent years. According to the Statistical bulletin of national economic and social development of Dali City (2019), the sewage treatment rate of lake-dependent tourism in the studied area is 100%, and the domestic garbage in Dali city has been completely treated in an eco-friendly way. All these measurements and efforts contribute to a more coordinated and sustainable development of the Erhai Lake basin.

Conclusion

A comprehensive evaluation of the Erhai Lake ecological health status is conducted using a localized and revised methodology of Freshwater Health Index (FHI), some subindicators are chosen and calculated referring to “China Technical guidelines for river and lake health assessment (SL/T793 – 2020).” Cask short board effect is considered during the aggregation of the indicators to better indicate the real health status of the components, i.e., “Ecosystem Vitality,” “Ecosystem Services,” and “Governance and Stakeholders.” Basically, the ecosystem of the Erhai Lake basin remains healthy in the studied period according to the research, thanks for specific measures and actions taken to deal with the ecological environmental issues caused by a previous local economic development and urbanization process. The coupling degree of the components is first calculated to analyze the mutual interaction among them, and the coupling degree is currently in a high coupling stage, revealing that the Erhai Lake basin is developed in a sustainable and orderly way. The coupling coordination degree of the three components is analyzed to further reflect the comprehensive development level of the studied area, and it’s “Good coordination” in the current assessment for the lake basin, indicating that the three components are in the positive relationship.

Although the Erhai Lake basin presents a relatively healthy ecological status, there are still some aspects for local government and stakeholders to enhance in order to achieve more sustainable ecosystem management and utilization in the studied area. The “short boards” of the Erhai Lake basin show room for improvement in local freshwater ecosystem conservation and restoration and underline governance issues that need to be resolved for more sustainable development of the studied basin. Suggestions are provided for the Erhai Lake basin sustainable management and conservation: First, more effective measurements and stricter enforcement need to be taken to reduce human disturbance, such as increasing vegetation coverage to promote biodiversity conservation, prolonging forbidden fishing period, etc., so as to restore the ecology of the Erhai Lake basin.

Second, greener agriculture with less fertilizer or chemicals is recommended to reduce nitrogen and phosphorus non-point source pollution, in order to relieve the eutrophication of the Erhai Lake.
Third, to increase stakeholder engagement and awareness in the basin conservation-related decision making to strengthen freshwater ecosystem management by stepwise manners, such as school education, public propagation, stated in regulations etc. 

Furthermore, even though water supply can meet water demand in the Erhai Lake basin currently, the increasing water demand as population and social economic development, combined with gradual downward trend of the Erhai lake water resources and prominent water pollution caused by agricultural planting, has been exerting pressure on the local water resources management. Improvement of water efficiency and adjustment of economic structure should also be significantly considered for more sustainable development of the Erhai Lake basin.

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