Research Article

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Water quality assessment and spatial–temporal variation analysis in Erhai lake, southwest China

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Abstract: For the implementation of lake ecological protection, understanding the water pollution status and spatio–temporal variation of water quality has become the most important thing for water safety in the basin. To analyze the water quality in recent years, water quality data in Erhai lake from 2013 to 2017 were first collected from typical nine monitoring stations. Based on the comprehensive water quality index (WQI) method, the temporal and spatial variation characteristics of water quality in Erhai lake were analyzed, and the main factors affecting water quality in Erhai lake were explored. The results indicated that the water quality of Erhai lake was worse than its target water quality, and total nitrogen (TN) and total phosphorus (TP) exceeded the Class II standards (TN: 0.5 mg L^{-1} , TP: 0.025 mg L^{-1}) of China's Environmental Quality Standard for Surface Water (GB3838-2002). In terms of changes across seasons, the overall lake water quality in the dry season was better than that in the wet season, and TN and TP reached the peak value in September. In terms of spatial distribution, water quality

of the northern area was better than that of the southern area in the dry season, whereas water quality of the southern area was better than that of the northern area in the wet season. At present, Erhai lake is at a critical turning point of water eutrophication, and its nutrition status is mainly affected by both nitrogen and phosphorus. The pollution load from the land area is the main factor affecting the deterioration of Erhai lake. Our results can provide a scientific basis for the treatment of the water environment of Erhai lake.

Keywords: water quality, Erhai lake, WQI, spatio–temporal distribution characteristics

1 Introduction

Being one of the important resources that is closely associated with human activities, river and lake water resources play an important role in human and biological health [1,2]. Due to the increase in human activities, a large amount of tourist, industrial, and agricultural nonpoint pollution and domestic sewage flow along with surface runoff into river and lake systems, directly resulting in a sharp deterioration of the water quality of the corresponding water ecosystems [3]. To protect the water quality of river and lake systems and maintain their healthy and sustainable development, the selection of a fast and efficient water quality assessment method is important. This can enable regulatory bodies to comprehensively master the water quality of river and lake systems, identify the main factors affecting the water quality, and implement appropriate treatment measures [4,5].

Water quality assessment is a qualitative or quantitative assessment of the water quality of river and lake systems by calculating the measured data of the physical, chemical, nutrient, and biological indicators of such systems according to certain evaluation standards [6]. Among the various water quality assessment methods, the water quality index (WQI) plays an important role in aiding water resource management and has been widely applied in the water quality assessment research of the surface and

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ground water [7–9]. The use of WQI was initially proposed by Horton [10] and Brown *et al.* [11]. This method takes into account the degree of influence of various water quality indicators on the water environment quality and assigns weight coefficients to different water quality indicators in order to reasonably reflect the comprehensive status of the water body [12,13]. From a global perspective, many water quality assessment methods are based on the WQI method, such as the Canadian Council of Ministers of the Environment Water Quality Index [14], the British Columbia Water Quality Index [15], and the Oregon Water Quality Index [16]. These indices were established based on the US National Sanitation Foundation Water Quality Index [17]. At present, WQI is widely used in the field of water environment worldwide, for example, Lumb *et al.* [18], Nong *et al.* [19], Karunanidhi *et al.* [20], Ma *et al.* [21], and Lin *et al.* [22] used the WQI method to identify the main water pollution factors of different water bodies from a number of indicators, providing a direction for local water environment management and treatment. It can be observed that the WQI method is highly representative and can be promoted in the evaluation of river and lake water systems.

In recent years, on the one hand, how to quickly and accurately obtain a calculation method that better reflects water quality based on WQI has become a study hotspot [23]. It is more typical to use mathematical methods to identify key water quality parameters to establish a WQI_{min} model, which makes it possible to reduce the cost of water quality testing and reduce environmental pollution caused by chemical reagents in the water quality evaluation process. Studies have shown that WQI_{min} and WQI show a high degree of linear correlation, which can better reflect the changes in the WQI. This method has been widely used in China's South-to-North Water Diversion Project [19], Taihu lake [24], and Chaohu lake [25]. On the other hand, with the development of machine learning algorithms, many scholars combine the algorithms with WQI to evaluate and analyze the water quality change characteristics. Hatvani *et al.* used combined cluster and discriminant analyses to study the nutritional status and driving factors of the largest shallow lake in Central Europe at different periods [26]. Granata *et al.* evaluated the trend of the wastewater quality indicators based on support vector regression and regression trees [27]. Oladipo *et al.* combined fuzzy logic and WQI to assess the water quality in a zone of Nigeria [28]. In general, water quality evaluation and analysis based on WQI is an important method for basin water environment management.

Erhai lake is the second largest freshwater lake in the Yunnan Province of China and undoubtedly has significant importance for the aerial hydrological cycle, ecosystem

stability, and socioeconomic development. Research shows that the Erhai lake water quality has changed from the stable Class I–II standards of China's Environmental Quality Standard for Surface Water (GB3838-2002) in 1980s to Class III status at present. Besides, Class IV status and even Class V status are speculated to appear locally in the lake area during the year. Thus, the Erhai lake water quality tends to decrease significantly [29]. According to the monitoring records, Erhai lake experienced large-scale outbreak of algal blooms in 1996, 2003, and 2013. Particularly, in 2013, the blooms evolved from local algal blooms in the bay to algal blooms in the whole lake, with an area of close to 60% of the whole lake [30]. Notably, being a lake in the early stage of eutrophication, it is at the critical turning point of the transformation of water eutrophication state. It would therefore be of significance to study the water quality and the main controlling factors of eutrophication in the lake area for exploring the trend of lake eutrophication [31]. Some studies have been conducted to explore and verify the water quality status of Erhai lake from a single water quality indicator [29,32]. Nevertheless, further study is still necessary for the following reasons: In the face of the rapid socioeconomic development of the Erhai lake basin, the temporal and spatial variation characteristics of the lake's comprehensive water quality should be further studied. At the same time, the key factors affecting the fluctuation of the lake's water quality should be further clarified.

Based on the water quality monitoring data of Erhai lake, this study has the following objectives: (i) It seeks to understand the variation characteristics of the water quality at different temporal and spatial scales, and reveal the variation law of the water quality in Erhai lake. (ii) We have attempted to find the important factors affecting the development of lake eutrophication. (iii) The variation of water quality in Erhai lake has been explained from two perspectives: the variation characteristics of pollution load into the lake and the variation characteristics of lake hydrodynamics.

2 Materials and methods

2.1 Study area

The Erhai lake basin is located in Dali City and Eryuan County, Yunnan Province of China and belongs to the Lancang River Basin (Figure 1). It has an area of 2,565 km² and a population of 400 per km² and is situated on an altitude of 1,960–4,040 m. At the normal water level of 1,974 m (Yellow Sea elevation), the lake has an area of 249.8 km², average water depth of 10.5 m, and storage

capacity of $28.8 \times 10^8 \text{ m}^3$. The meteorological conditions of the basin include an annual average temperature of 16.4°C , the annual average precipitation and evaporation are 928.7 and 1099.3 mm, respectively, and the annual sunshine percentage is 48.80% [33]. In terms of the hydrological conditions, there are 28 main rivers flowing into the lake: Miju, Yongan, and Luoshi in the north; 18 creeks of Cangshan in the west; Fengweijing, Yulong, Nancun, and Xiahejing in the east; and Boluo and Baitai in the south of the basin [34].

2.2 Sample collection and laboratory analysis

Considering the integrity of water quality monitoring data of the lake area, TY and SL in the northern part of Erhai lake, GS, HX, HY, and CC in the middle, and HD, CY, and TS in the south were selected, and their spatial distribution is shown in Figure 1. The research was conducted from 2013 to 2017, and water samples were collected in February, April, August, and October that represent the water quality of winter, spring, summer, and autumn, respectively. Water temperature (WT), pH, dissolved oxygen (DO), Secchi depth (SD), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD_{Mn}), and chlorophyll a

(Chla) were selected as the parameters to evaluate the water environment in the lake area.

Water samples were collected in sunny or cloudy weather conditions to minimize the impact of rainfall on the water quality. YSI EXO2 (USA) was used to monitor WT, pH, DO, and SD *in situ*. According to the water quality sampling technical regulations (SL 187–96), water samples of 50 cm under water were collected in plastic buckets flushed with water samples and washed with acid. During collection and transportation, water samples were stored at $2\text{--}5^\circ\text{C}$. Based on the specifications of HJ636-2012, GB/T11893-1989, and HJ897-2017 standards, TN, TP, COD_{Mn} , and Chla were analyzed.

2.3 Calculation of WQI

The WQI was deduced as follows: Initially, each water quality parameter was given a different absolute weight (w_i). The absolute weights were set at levels 1–4, representing low-to-high categories, indicating the impact of a certain water quality parameter on the water quality in the study area. Weight level 4 is assigned to the most sensitive water quality parameter that can characterize the water quality of the lake [35]. In this study, the

Figure 1: Geographical location and water quality monitoring points of Erhai lake.

highest absolute weight 4 was assigned to TN and TP. The main reasons are as follows: First, for plateau inland lakes, nitrogen and phosphorus nutrients are important factors affecting the nutritional status of lakes; second, for Erhai lake, TN and TP are over-standard items relative to the target water quality. COD_{Mn} was assigned the absolute weight of 3, mainly considering the impact of the different forms of nitrogen on the algae and the impact of organic matter content on the water quality. The DO level of Erhai lake is always at a high level, so it was given an absolute weight of 2. Relative weight (W_i) indicates the importance of water quality parameters relative to other indicators and is calculated as shown by equation (1).

$$W_i = w_i / \sum_{i=1}^n w_i, \quad (1)$$

where W_i is the relative weight, w_i is the absolute weight of each water quality parameter, and n is the total number of water quality parameters.

q_i is defined as the quality rating of each water quality parameter, whose essence is the ratio between the measured concentration value and the corresponding standard limit value of the water quality parameter in the surface water quality standard (GB3838-2002). It is calculated from equation (2).

$$q_i = \frac{C_i}{S_i} \times 100, \quad (2)$$

where C_i is the concentration (mg L^{-1}) of a certain water quality parameter monitored at each water quality sampling point and S_i is the limits for water quality concentration in lakes. Erhai lake is the Cangshan-Erhai National

Table 1: Target standard limits of surface water quality (Class II)

WQI	TN (mg L^{-1})	TP (mg L^{-1})	COD_{Mn} (mg L^{-1})	DO (mg L^{-1})
Target standard limits	0.5	0.025	4	6

Nature Reserve according to the water function zoning of Dali Prefecture, and its water quality target is Class II. The corresponding standard limits of water quality parameters are presented in Table 1 as the China Environmental Quality Standard for Surface Water (GB3838-2002).

In order to calculate WQI, SC_i was defined as the sub-score of each water quality parameter, and then SC_i and WQI were calculated from equations (3) and (4).

$$SC_i = W_i \times q_i, \quad (3)$$

$$\text{WQI} = \sum_{i=1}^n SC_i. \quad (4)$$

The calculated WQI was divided into three levels [17]: $\text{WQI} < 0.7$, good water quality; $0.7 \leq \text{WQI} < 0.8$, moderate water pollution; and $\text{WQI} \geq 0.8$, high water pollution.

MS Excel 2016 was used to process the water quality monitoring data and SPSS 17.0 for Pearson correlation analysis [36]. In addition, in this study, based on the water quality data of the monitoring points, the Kriging interpolation method [37] in ArcGIS 10.2 was used to realize the conversion of point data to surface data. Based on the research objectives, the research framework of this study is shown in Figure 2.

Figure 2: Study framework.

3 Results

3.1 Time variation law

The change in the WT within the year showed an initial increase and a subsequent decrease (Figure 3(a)). The average WT within a year was 17.9°C, the highest value in August was 23.6°C, and the lowest value appeared in February to be 11.1°C. The annual average WT difference was 12.5°C. WT is suitable for algal growth, whether it is the fluctuation range of WT during the year or the average temperature difference during the year.

The pH value ranged between 8.46 and 8.58 in the course of the study (Figure 3(b)). With the period of January–July, the pH value change was relatively stable. Within August–October, the pH value decreased slightly, and an increase in the pH value was seen in November–December. This was mainly

affected by the algal respiration in the lake area and the water from the basin. In August–October, the WT in the lake area was relatively high. A large number of nitrogen and phosphorus pollutants brought by the basin runoff provided nutrients for algal growth, and the HCO_3 formed by CO_2 during the algae respiration caused a reduction in the pH value of the lake water. In addition, August–October coincided with the wet season in the Erhai lake basin, and the inflow of water from the land area played a role in diluting the pH of the lake water body.

DO showed a trend of an initial decrease, followed by a subsequent increase, which was relatively high in the dry season and less in the wet season (Figure 3(c)). The minimum appeared in June at 7.83 mg L^{-1} , and the maximum appeared in January at 10.5 mg L^{-1} . The reason for this phenomenon is that during the wet season, as the inflow of water increases, the pollutants carried by the river also increase, and so does the oxygen consumption

Figure 3: Trend of WT (a), pH (b), DO (c), SD (d), TN (e), TP (f), COD (g) and Chla (h) of Erhai lake during the year. Each point represents the average value of the water quality monitoring data of all stations in the lake, and the error bars represent the maximum, minimum, and average values of the monitoring data.

of the water. The DO minimum values were observed in June and September. In the dry season, the pollution load of the lake from the basin was smaller, and the oxygen consumption of the water in the lake area also decreased, so the water DO in the lake area was correspondingly higher coupled with the disturbance of the wind field.

The SD change in the year was divided into three stages (Figure 3(d)). In the first stage, during January–April, SD showed an upward trend, which was mainly due to the lower pollution load in the lake, low algal abundance in the lake area, relatively low wind speed in the lake area, and a smaller disturbance to the bottom sediments. The maximum SD was observed in April, being 2.34 m. The second stage was in the period of May–September. During this period, the basin water increased gradually and correspondingly the quantity of sediment and pollutants into the lake. Besides, the large quantity of output of nitrogen, phosphorus, and other nutrients also improved the abundance of algae. All these factors contributed to the decrease in the lake SD, and the annual minimum SD was observed in September, which was 1.66 m. The third stage was in the period October–December. With a decrease in the base precipitation, the sediment and pollution load into the lake also decreased, and the decrease of temperature led to the decrease in the algal activity intensity, thereby leading to a rise in the SD. The average value of Erhai lake water transparency for many years was 1.98 m, which is already in the state of lake eutrophication.

The TN change in the year showed an initial decreasing trend, followed by an increasing trend and then being stable (Figure 3(e)). Specifically, in the first stage of January–May, TN showed a downward trend, and a small peak appeared in April. In this period, the maximum value of TN appeared in January, whereas the minimum value appeared in May, with a value between 0.47 and 0.63 mg L⁻¹. The second stage was in the period July–September, wherein TN showed an upward trend, and the double peak value appeared in July and September. In this period, the maximum value of TN appeared in September, whereas the minimum value appeared in June, with a value between 0.44 and 0.68 mg L⁻¹. The third stage was in the period October–December when TN changed the trends to be stable, and the maximum value of TN appeared in November, whereas the minimum value appeared in December, with a value between 0.57 and 0.59 mg L⁻¹. Considering the TN alone, the concentration of TN in months except for May and June did not reach the Class II water standard, which indicated that the TN load in the lake exceeded the standard seriously. Generally, in January–June, there is less basin pollution, less active

aquatic biological activities due to lower temperature, and smaller disturbance of wind field to sediment, which together cause the decrease of the TN concentration in Erhai lake water. Notably, middle to end of March and the first 20 days of April are the time for crop harvesting, crop planting, and large area application of base fertilizers in the Erhai lake basin. Although the volume of the basin water is relatively low, the pollution load into the lake is relatively large, which resulted in a small peak of TN concentration in the lake water in April. With the advent of the rainy season, the pollution from the basin gradually increased, and the increase of temperature led to the strengthening of nitrogen fixation and ammoniation of aquatic plants, which resulted in the increasing trend of TN concentration in this period. In October–December, the TN concentration of this period was always at a high level due to the decomposition of algae and resuspension of sediment disturbed by the wind field.

TP change in the year showed a trend of an initial increase and a subsequent decrease, and the concentration fluctuated within 0.018–0.043 mg L⁻¹ (Figure 3(f)). The first peak was observed in September, 0.43 mg L⁻¹, the second peak in June, 0.032 mg L⁻¹, and the third peak in March, 0.024 mg L⁻¹. In March, due to the loosening of farmland soil caused by crop harvesting, microorganisms in the soil release a lot of nutrients from the decomposition of crop residues. Although the precipitation was less in this period, the deposition of farmland soil close to both sides of the river was larger, and the decomposition of algal residues released a large amount of phosphorus. In June, the precipitation increased, and phosphorus pollutants carried by the basin water went into the lake water, resulting in a higher concentration of TP. In September, a large amount of nutrients is needed for algal growth, forming a “pumping” effect on the sediment, and thus a large amount of phosphorus in the sediment was released.

The concentration of COD_{Mn} varied between 3.97 and 3.57 mg L⁻¹ (Figure 3(g)). The first peak was observed in May, 3.97 mg L⁻¹, and the second peak in September, 3.87 mg L⁻¹. The concentration change of COD_{Mn} was mainly affected by the organic matter and algal abundance in the lake area. May is the peak period of agricultural planting and fertilization in the Erhai lake basin, and the short period of rainfall flushed the fertilizer residues on the surface of the soil into Erhai lake. With the increase of organic matter into the lake and algal biomass in July, the COD_{Mn} showed a rapid increasing trend. After October, organic pollutants entering the lake and algal biomass decreased, and the COD_{Mn} decreased accordingly. The decomposition of aquatic plant residues in

December increased the content of organic pollutants, and the COD_{Mn} increased slightly.

The annual average value of Chla was $8.98 \mu\text{g L}^{-1}$. In January–June, the Chla concentration fluctuated with no significant difference between months ($P > 0.01$). In July–September, the Chla concentration showed a significant upward trend. The main peak value of Chla concentration was observed in September, $14.33 \mu\text{g L}^{-1}$, and the second peak value was observed in July, $12.10 \mu\text{g L}^{-1}$. In October–December, the Chla concentration showed a downward trend. The time change process is shown in Figure 3(h).

3.2 Spatial characteristics

In February (winter), the spatial distribution of WT followed the sequence northern area > central area > southern area. In April (spring), the spatial distribution of WT followed the sequence central area > northern area > southern area. In August (summer), the spatial distribution of WT followed the sequence northern area > central area > southern area. In October (autumn), the spatial distribution of WT followed the sequence northern area > central area > southern area. Generally, there was no significant difference in the WT among different areas of Erhai lake, and the relatively high-temperature area was concentrated in the northern and central areas, which was mainly affected by the water from the basin and the disturbance of dynamic conditions of the lake water. In the northern area, human activities are concentrated and there is huge amount of water entering the lake, which exhibited a greater impact on WT. Affected by the wind field in the southern region, the circulation phenomenon is obvious, and the lake water body is more disturbed, resulting in relatively low WT. See Supplementary Material A for the spatial distribution of WT in different seasons.

In February (winter), the spatial distribution of pH followed the sequence central area > northern area > southern area. In April (spring), the spatial distribution of pH followed the sequence northern area > central area > southern area. In August (summer), the spatial distribution of pH followed the sequence northern area > southern area > central area. In October (autumn), the spatial distribution of pH followed the sequence northern area > southern area > central area. Besides, the pH value of water in the northern part of the Erhai lake is relatively high, which could be affected by the water from the basin. The pH value of water in the central part is relatively low, which is mainly due to the spatial distribution of the

aquatic plants. Emergent and submerged plants are concentrated in the western part of Erhai lake. See Supplementary Material A for the spatial distribution of pH in different seasons.

In February (winter), the spatial distribution of DO followed the sequence southern area > northern area > central area. In April (spring), the spatial distribution of DO follows the sequence central area > southern area > northern area. In August (summer), the spatial distribution of DO followed the sequence northern area > central area > southern area. In October (autumn), the spatial distribution of DO followed the sequence northern area > southern area > central area. Generally, DO was mainly affected by the pollution from the basin and the hydrodynamic conditions of the lake. In the dry season (February, April), due to the relatively large inflow of water in the north area of the basin, the pollution load into the lake increased significantly, and the oxygen consumption of pollutants resulted in a relatively low DO content in the north area of the lake. In the wet season (August, October), there was an increase in the pollution load into the lake. In the western part of basin, pollutants accumulated in the river flow into the water body along with the surface runoff, and the DO concentration in the water body was relatively low in the southern part, where the lake outlet was located. In addition, due to the algal growth in the central part of the lake and the influence of the southwest dominant wind direction, a large quantity of phytoplankton accumulates in the west bank of the lake, resulting in a relatively low DO content in the central part of the lake. See Supplementary Material A for the spatial distribution of DO in different seasons.

In February (winter), the spatial distribution of SD followed the sequence southern area > central area > northern area. In April (spring), the spatial distribution of SD followed the sequence central area > northern area > southern area. In August (summer), the spatial distribution of SD followed the sequence northern area > central area > southern area. In October (autumn), the spatial distribution of SD followed the sequence southern area > central area > northern area. Generally, in February, SD in the north part of the lake area was mainly affected by the nutrients such as nitrogen and phosphorus and sediment from the watershed. In April, the south of the lake area was disturbed by the wind field, and the water transparency was low. In August, under the influence of hydrodynamic conditions of the lake, phytoplankton was concentrated in the middle and south of the lake area, resulting in low SD. In October, with the decrease of basin precipitation, the pollution load in the northern part of the basin was gradually highlighted. Meanwhile,

the decomposition of the submerged plants also aggravated the lower SD in the northern part of the lake. See Supplementary Material A for the spatial distribution of SD in different seasons.

In February (winter), the spatial distribution of TN followed the sequence southern area > central area > northern area. In April (spring), the spatial distribution of TN followed the sequence southern area > northern area > central area. In August (summer), the spatial distribution of TN followed the sequence northern area > central area > southern area. In October (autumn), the spatial distribution of TN followed the sequence northern area > central area > southern area. Generally, in the wet season (August, October), the northern part and the central part of Erhai lake consists of a high concentration of TN. In the dry season (February, April), the southern area of Erhai lake possessed a high concentration area of TN. Two factors contribute to this phenomenon. One is that in the dry season, the southern part of Erhai lake was greatly affected by the wind field. The disturbance of water body promoted the sediment resuspension, and a large amount of dissolved nitrogen was diffused into the water body. During this period, because of the relatively small amount of pollution from the basin, the endogenous release had a greater influence on the change of the TN concentration in the lake water. Second, in the wet season, the amount of pollution from the basin increased gradually, along with the concentration of TN in the north and middle of the lake. In this period, the input of basin pollution load greatly affected the change of TN concentration in the lake. Generally, the annual high concentration area of TN in Erhai lake shifted from the south to the north. See Supplementary Material A for the spatial distribution of TN in different seasons.

Like the spatial distribution of TN, in February (winter), the spatial distribution of TP followed the sequence southern area > central area > northern area. In April (spring), the spatial distribution of TP followed the sequence southern area > central area > northern area. In August (summer), the spatial distribution of TP followed the sequence northern area > central area > southern area. In October (autumn), the spatial distribution of TP followed the sequence northern area > central area > southern area. Generally, in the dry season (February, April), the southern area of the Erhai lake consisted of a high concentration area of TP, and in the wet season (August, October), the northern area of Erhai lake consisted of a high concentration of TP. Two factors contribute to this phenomenon. First, in the dry season, due to the influence of the wind field, the water disturbance in the southern area resulted in the release of phosphorus from the sediments. Second, in the wet season, with the

increase of pollution load from the north bank of the basin, the “pumping” effect of huge algal growth on sediment gradually increased, resulting in the relatively high concentration of TP in the northern area of the lake. Generally, the annual high concentration area of TP shifted from the south to the north. See Supplementary Material A for the spatial distribution of TP in different seasons.

In February (winter), the spatial distribution of COD_{Mn} followed the sequence southern area > central area > northern area. In April (spring), the spatial distribution of COD_{Mn} followed the sequence southern area > northern area > central area. In August (summer), the spatial distribution of COD_{Mn} followed the sequence northern area > southern area > central area. In October (autumn), the spatial distribution of COD_{Mn} followed the sequence northern area > southern area > central area. The high value area of COD_{Mn} concentration in Erhai lake was similar to that of TN and TP concentration in different seasons. Generally, the annual high value area of COD_{Mn} concentration in the Erhai lake gradually moved from the south to the north. See Supplementary Material A for the spatial distribution of COD_{Mn} in different seasons.

In February (winter), the spatial distribution of Chla followed the sequence northern area > central area > southern area. In April (spring), the spatial distribution of Chla followed the sequence central area > northern area > southern area. In August (summer), the spatial distribution of Chla followed the sequence southern area > central area > northern area. In October (autumn), the spatial distribution of Chla followed the sequence southern area > central area > northern area. Generally, the annual high value area of Chla concentration gradually shifted from the northern area to the southern area, which was mainly because the growth of algae was not only affected by the nutrient concentration but also closely related to the hydrodynamic conditions of the lake. See Supplementary Material A for the spatial distribution of Chla in different seasons.

3.3 Comprehensive evaluation of lake water quality

3.3.1 Characteristics of monthly variation

From equations (1)–(4), the average WQI of Erhai lake in each month was calculated. The monthly variation characteristics are shown in Figure 4. As observed, in February and April, the Erhai lake water quality was in good status; in March, May, June, and August, the Erhai lake water quality was moderately polluted; in January, July

Figure 4: Monthly WQI values of Erhai lake water quality.

and September–December, the Erhai lake water quality was highly polluted. Generally, there was a good correspondence between the comprehensive water quality and the variation characteristics of Chla concentration in the lake area, which shows that the change of nitrogen and phosphorus and other nutrients affected the water quality by changing the algal abundance. However, transformation of nutrients by algae, release of nutrients in the sediment, and decomposition of algae in turn affected the concentration of nitrogen and phosphorus in the lake. The overall water quality of Erhai lake is determined by this two-way influence mechanism.

3.3.2 Identification of factors affecting lake eutrophication

The results of correlation analysis between Chla and WQI in Erhai lake in different seasons are shown in Table 2. It was observed that in February (winter), the algal activities were less active, and there was a significant positive correlation between the Chla, $\text{NH}_3\text{-N}$, and pH values, which was due to the fact that algal growth mainly occurs from the $\text{NH}_4^+\text{-N}$ in the water. In April (spring), there was a significant positive correlation between Chla and TP, which indicates that during this period, the TP was the limiting factor of algal growth. In August (summer), there

was a significant positive correlation between the Chla and TN, which indicates that TN was the limiting factor of algal growth in this period. In October (autumn), Chla was significantly positively correlated with the WT, and negatively correlated with the transparency, which indicates that temperature and light were the key factors affecting the algal growth during this period.

4 Discussion

Wind is the main driving force for the lake current of lake Erhai. The pollutants to the lake participate in the material circulation and exchange of the whole lake under the joint impact of the wind-driven current and the throughput current. The characteristics of the migration and transformation of pollution in the lake and the temporal and spatial distribution of water quality are not only closely related to the temporal and spatial distribution of pollutants to the lake but are also affected and controlled by the lake current.

4.1 The influence of pollutants to the lake on the water quality

The nitrogen, phosphorus, and organic pollutants of Erhai lake mainly come from agricultural nonpoint source pollution discharged into the lake through rivers and ditches. Figure 5 shows the variation characteristics of COD, TN, and TP of Erhai lake in 2017 (normal flow year). The pollution load into the lake during the rainy season (June–October) accounted for about 59.22–74.99%, and the non-rainy season only accounted for 25.01–40.78%. In terms of spatial distribution characteristics, the pollution load into the lake in the north accounts for about 61.72–77.32%, the pollution load into the lake in the west accounts for about 15.09–30.63%, and the pollution load into the lake in the south and east accounts for about 7.59–9.36%. Therefore,

Table 2: Correlation analysis of Chla and different WQIs of Erhai lake

	TN	TP	$\text{NH}_3\text{-N}$	COD_{Mn}	WT	pH	DO	SD
February	−0.37	0.42	0.53*	0.36	0.21	0.53*	0.06	−0.03
April	0.18	0.61**	−0.13	0.63**	−0.18	−0.19	−0.04	−0.37
August	0.57**	0.12	0.11	−0.12	−0.05	0.04	−0.04	−0.12
October	0.23	−0.15	0.31	0.38	−0.48*	0.15	0.10	−0.58**

Note: *, **, and *** represent the significance level exceeds $\alpha = 0.05$, $\alpha = 0.01$ and $\alpha = 0.001$, respectively.

Figure 5: The distribution process of the pollution load into the lake during 2017. East, South, West, and North represent the rivers entering the lake in different areas of the Erhai lake basin. The pollution load into the lake is calculated by multiplying the flow and the concentration. The flow and concentration are derived from the actual observation values of the river entering the lake. (a) COD, (b) TN, and (c) TP.

the concentration of a large amount of pollution load from the north and west into the lake along with precipitation runoff is a key environmental factor in recent years that the water quality of lake Erhai has exceeded the water quality standard, and it is also a decisive factor affecting the distribution of the water quality of the Erhai lake area during the year. Zheng *et al.*'s [38] research results showed that agricultural nonpoint source pollution was the main factor affecting water quality in the northern part of the lake whereas in the southern part of the lake, economic development, accelerated urbanization, and tourism were the main factors affecting water quality. Sun and Liu [39] established the correlation between changes in the water quality of the West lake and tourism, and the study found that human activities are the main reason for the deterioration of the water quality of the West lake. Shang *et al.* [40] used the soil water assessment tool (SWAT) model to establish the response relationship between pollution source input and river water quality, and found 37% of the watershed area contributed 56% of the TN pollution load. Furthermore, most of these critical source areas were concentrated in the north and west of the watershed.

The total amount of pollutants entering the lake and its distribution process within the year are key factors that affect whether the water quality of lake Erhai meets the water quality standard. At the same time, the spatial distribution characteristics of pollutants entering the lake will also have an important impact on the spatial distribution of water quality in the lake. Figure 6 shows the comparison of the water quality concentration of the northern, western, and southern areas of lake Erhai in 2017. The results show that the COD concentration in the north and south is higher than that in the west. However, the concentration of TN and TP in the west and south are worse than that in the north, which is closely related to the relatively short degradation distance and passage through large agricultural areas before entering the lake in the west and south. Yurista *et al.* [41] used towed electronic instrumentation to analyze water quality changes and influencing factors in the lake Michigan nearshore, and the research results showed agricultural land was a key factor affecting coastal water quality. Nielsen *et al.* [42] established the correlation between the water quality of 414 Danish lakes and the land use of the watershed. The results of the study

Figure 6: The distribution process of the water quality into the lake during 2017. South, West, and North represent the rivers entering the lake in different areas of the Erhai lake basin. The pollution concentrations are derived from the actual observation values of the river entering the lake. (a) COD, (b) TN, and (c) TP.

found that lake water quality agreed better with the proportion of agricultural land use in the entire watershed. By integrating InVEST models and socioeconomic data, Li et al. [43] performed a comprehensive temporal and spatial assessment of the impact of land use change on lake Erhai ecosystem. The results showed that the nitrogen and soil exports caused by tourism development and changes in land use types were impairing water quality in Erhai lake and causing severe environmental problems.

4.2 The influence of lake hydrodynamics on the water quality

According to Chen's research results [44], driven by the dominant wind field, that is, the southwest wind, the wind-driven current of Erhai lake formed six circulations from north to south (Figure 7a). Under calm winds, the throughput current of the lake flows from north to south overall due to the influence of the topography of the valley (Figure 7b). There is a large angle between the wind-driven current and the throughput current of lake Erhai. Affected by the wind field, the lake Erhai current forms relatively independently in the north, middle and south lake areas. A weak current area is formed at the narrowest part of the east and west banks of the lake, which is very unfavorable to the transportation and diffusion of pollutants from north to south. This reveals that the water quality in the northern lake area is the worst, followed by the southern lake area and the middle lake area has relatively good water quality.

Figure 7: Hydrodynamic characteristics of lake Erhai. Wind-driven current in Erhai Lake dominated by southwest wind (a) and gravity current in Erhai Lake influenced by lake topography (b).

The north lake bay is an area with relatively large nutrient input, relatively poor water quality, and relatively static hydrodynamics. The rich nutrient and static lake hydrodynamic provide a material basis and dynamic environment for the growth of algae. At the same time, under the influence of the wind-driven current, planktonic algae gradually accumulate in the north lake bay. Therefore, a large amount of nutrient input and relatively unfavorable static hydrodynamic environment are important driving factors for algal accumulation in the north lake bay of lake Erhai. Like lake Erhai, lake Egirdir in Turkey and lake Fuxian in China also belong to the narrow and long lake types. Kaçikoç and Beyhan [45] and Zhao et al. [46] found that the hydrodynamic factors were very important for the spatial distribution of water quality in the lake area.

5 Conclusion

This work demonstrates the spatial-temporal variation characteristics of Erhai Lake water quality based on WQI and the identification of the influencing factors of water quality. The main conclusions are as follows:

- (1) Currently, the water quality of Erhai lake is generally Class III standard, and TN and TP were found to exceed the standard limits.
- (2) In terms of change with time, the water quality in the dry season was better than that in the wet season. In terms of spatial distribution, the water quality in the north was better than that in the south in the dry season. In contrast, during the wet season, the water quality in the south was better than that in the north. This phenomenon is mainly affected by the watershed precipitation runoff and lake hydrodynamic conditions.
- (3) It is worth noting that during the period of high risk of algal bloom outbreak (July–October), TN, TP, WT, pH, DO, and SD of the water in the lake area were higher, which provided the necessary nutrient basis and the physical and chemical environment for an algal bloom outbreak.
- (4) With the accumulation of nutrients in the lake and degradation of aquatic ecosystem, Erhai lake has become a double-control lake for nitrogen and phosphorus, and there is an urgent necessity to address the issue of the eutrophication treatment of Erhai lake, considering increased human activity.
- (5) Overall, the physical and chemical parameters of each water body are considered to be definite values.

However, in reality, subjective factors such as sampling errors, measurement errors, environmental factor errors, and methodological errors introduce uncertainty. For objective factors such as the spatial heterogeneity of parameter indicators, the parameter value is actually a range rather than a fixed value. Therefore, more extensive monitoring is needed to make up for the uncertainty caused by monitoring.

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