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RESEARCH ARTICLE

SPATIOTEMPORAL VARIATION OF WATER QUALITY AND ALGAL BIOMASS IN ERHAI LAKE AND ITS ENVIRONMENTAL MANAGEMENT IMPLICATIONS

Xiaofei LIU*[1,2], Yue WU*[1,2,3], Zhaokui NI[1], Shengrui WANG (✉)[1,2,4]

1 Guangdong-Hong Kong Joint Laboratory for Water Security, Center of Water Research, Beijing Normal University at Zhuhai, Zhuhai 519087, China.

2 Engineering Research Center of Ministry of Education on Groundwater Pollution Control and Remediation, College of Water Sciences, Beijing Normal University, Beijing 100875, China.

3 National Engineering Laboratory for Lake Pollution Control and Ecological Restoration, Chinese Research Academy of Environmental Sciences, Beijing 100012, China.

4 Yunnan Key Laboratory of Pollution Process and Management of Plateau Lake Watershed, Kunming 650034, China.

*These authors contribute equally to the work

KEYWORDS

Erhai Lake, control measures, water environment, water quality index (WQI)

HIGHLIGHTS

- The water environment of Erhai Lake has shown satisfactory, declining and improving.
- Total N and P, and chemical oxygen demand as key water environment indicators.
- Pollution load distribution and control measures are key to Erhai Lake management.

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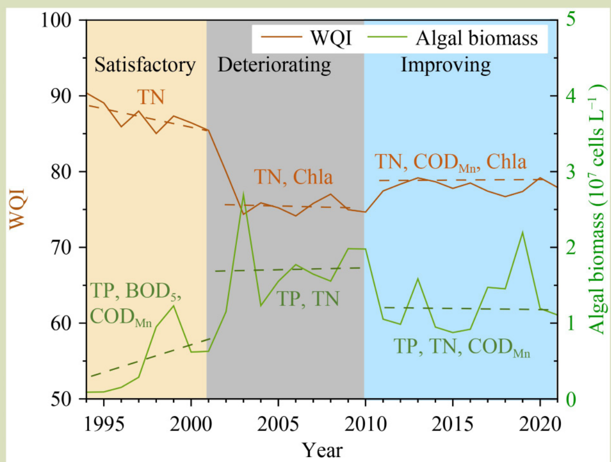
Correspondence: wangsr@bnu.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

Elucidating the spatiotemporal pattern of water quality and algal biomass is crucial for accurately tracing pollution sources and reducing the risk of algal blooms in lake systems. This study analyzed the spatiotemporal variability of water quality and algal biomass in Erhai Lake from 1994 to 2021 using water quality index (WQI), Mann-Kendall test and Sen's slope combined methods. The potential causes of water quality deterioration and algal biomass dynamics were also elucidated. The results showed that the historical changes in the water environment of Erhai Lake mainly had three stages: satisfactory (1994–2001), deteriorating (2002–2010) and improving (2011–2021). The changes in water quality and algal biomass were primarily affected by total nitrogen, total phosphorus and chemical oxygen demand in different stages. The water environment of Erhai Lake is currently improving significantly, starting in the southern area that is furthest from the sources of agricultural pollution, especially in summer and autumn. This is attributed to the implementation of control measures resulting in lower pollutant loads at particular times and places. Therefore, it is necessary to continue to promote standardized livestock farming, to strengthen rural wastewater collection and to investigate measures such as the interruption of the endogenous cycle.

1 INTRODUCTION

In recent decades, lake eutrophication has become a widespread concern and area of research interest worldwide. Much research is concerned with the degradation of water quality and the ecological and toxicological effects of eutrophication in aquatic ecosystems caused[1,2]. Overall improvement of the lake environment involves regulating water quality within permissible ranges and preventing algal blooms[3]. However, with the escalation of human activities in watersheds due to population and economic growth, the aquatic environment of lakes has been degraded by excessive inputs of pollutants such as nitrogen and phosphorus[4]. Such degradation of the aquatic environment has detrimental impacts on the services and functions of lake ecosystems[5]. Thus, understanding the variation and trends of water quality caused by pollutant inputs and their control measures are major challenges for improving water quality and sustainable lake management.

Water quality index (WQI) is an efficient method for assessing water quality. It integrates several physical, chemical and biological parameters into a single value, and has been widely used in water quality assessment[6,7]. Combined with methods such as the Mann-Kendall (M-K) test, it helps to comprehensively examine the historical changes and characteristics of water quality indicators and algal biomass[8–10]. Diamantini et al.[11] assessed water quality and drivers of change in three large European river basins at the inter-annual scale, using many individual water quality indicators. Li et al.[12] studied the multi-decadal trend of water quality and hydroclimatic conditions in Lake Poyang using single indicators such as total nitrogen (TN) and total phosphorus (TP). Wang et al.[6] used trophic level index and WQI methods to assess the eutrophication levels and water quality status in the Wuli Lake estuary. However, these studies rarely link water quality and algal biomass to watershed pollutant discharges and control measures at refined spatial and temporal scales. Water quality parameter data collected from many sites in multiple seasons would provide a comprehensive data set for applying the above methods to assess the overall water quality status and spatiotemporal patterns.

Erhai Lake is one of the nine largest plateau lakes in Yunnan Province in south-western China. It provides indispensable water resources for irrigation, human consumption, tourism and fishing for the people of Dali City, which is crucial for the local socioeconomic development[13]. Due to the massive influx of pollutants, the lake water quality experienced a sharp deterioration in 2002–2003 and a shift from a macrophyte-dominated state to a phytoplankton-dominated state[14]. Since 2011, the authorities have made considerable efforts to protect Erhai Lake. The overall water quality of Erhai Lake has improved in recent years, but incidents of localized and time-delayed algal blooms are common[15]. Current fine-scale spatiotemporal evaluations of water quality and algal biomass are limited and largely rely on single parameters such as TN, TP and ammonia-nitrogen, which hampers the comprehensive understanding and assessment of the ecological environment of Erhai Lake.

Therefore, this study attempted to comprehensively analyze the monthly data of Erhai Lake over 28 years using WQI, M-K test and Sen’s slope trend test to evaluate the comprehensive temporal and spatial distribution pattern of water quality and algal biomass. The main objectives were: (1) to analyze spatiotemporal variations and characteristics of water quality and algal biomass in Erhai Lake, (2) to identify the main parameters affecting water quality and algal biomass at each stage and the causes, and (3) to illustrate the current problems and insights for the management of Erhai Lake.

2 MATERIALS AND METHODS

2.1 Study area and sampling sites

Erhai Lake (99°32′ to 100°27′ E, 25°25′ to 26°16′ N) is located in Dali Bai Autonomous Prefecture, Yunnan Province (Fig. 1). It is the second largest freshwater lake in Yunnan Province, with an average elevation of 1796 m. The lake has a total water surface area of about 250 km^2, and mean and maximum water depths of 10.8 and 21.3 m, respectively. The lake watershed covers an area of 2565 km^2 and includes 10 towns in Dali City and 6 towns in Eryuan County[16].

Regional and seasonal water pollution problems and algal blooms persist in Erhai Lake due to spatial and temporal differences in pollutant loads. Eleven sampling sites within the National Control Sections of the lake have been grouped into northern, central and southern areas, according to the characteristics of their pollutant load sources. The northern watershed of Erhai Lake (sampling sites S1–S3, Fig. 1) is characterized by extensive agriculture and livestock farming[13]. In the central watershed (sampling sites S4–S8, Fig. 1), the main sources of pollution are villages, farmland and tourism. The southern watershed (sampling sites S9–S11, Fig. 1), adjacent to the central area of Dali City, is mainly affected by urban pollution.

2.2 Data sources

This study presents an analysis of monthly surface water quality and algal biomass data collected from the 11 nationally controlled sites in Erhai Lake from 1994 to 2021 (Fig. 1). From 1994 to 2000, data are only available only for March, August and November, while other years had 12 months of data. The parameters collected include water temperature (WT, °C), pH, electrical conductivity (EC, μs·cm^{-1}), dissolved oxygen (DO, mg·L^{-1}), total nitrogen (TN, mg·L^{-1}), ammonia nitrogen (NH_4^+-N, mg·L^{-1}), total phosphorus (TP, mg·L^{-1}), permanganate-based chemical oxygen demand (COD_{Mn}, mg·L^{-1}), five-day biochemical oxygen demand (BOD_5, mg·L^{-1}),

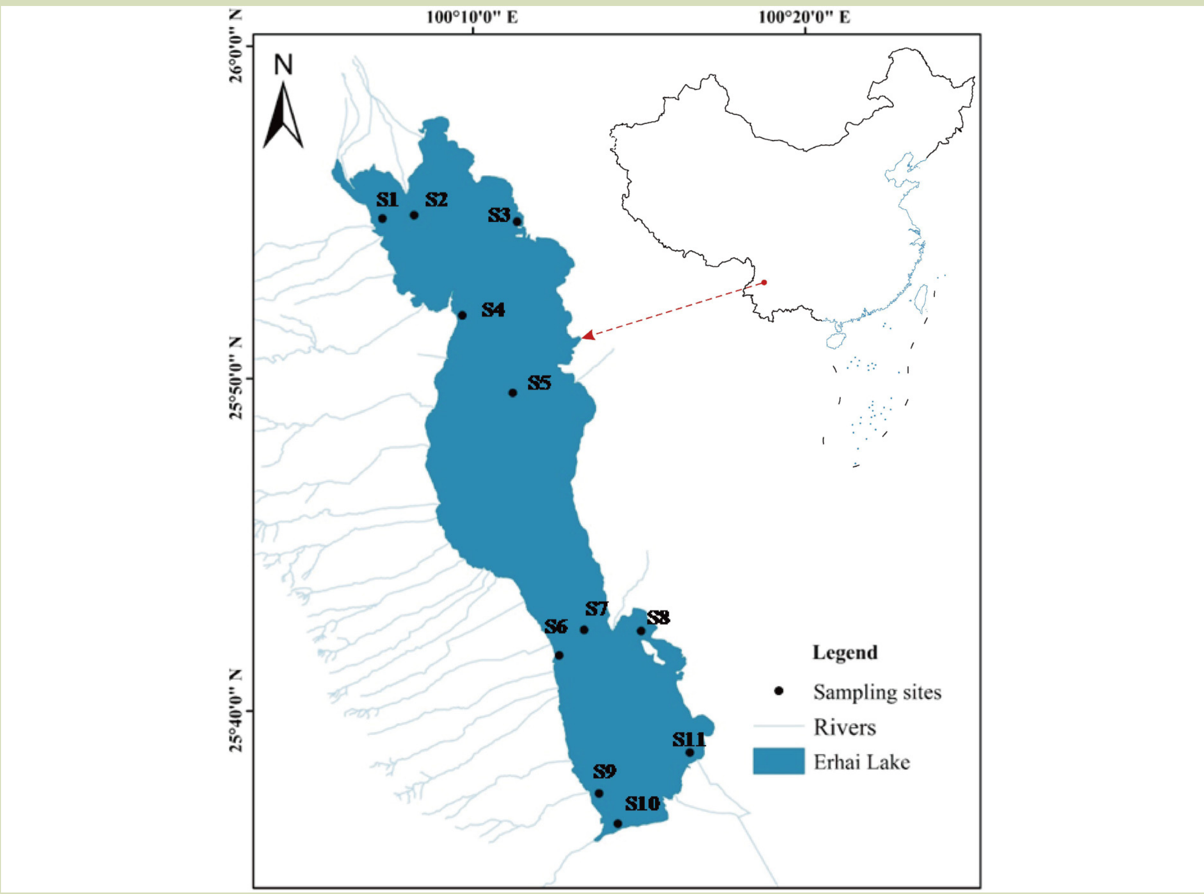


Fig. 1 Location of Erhai Lake and distribution of sampling sites (审图号: GS 京 (2023) 2266 号).

chlorophyll a (Chla, μg·L^{-1}) and algal biomass represented by algal density (10^7 cells L^{-1}). Data were collected from the Dali Prefecture Environmental Monitoring Centre Station and the Hydrological Bureau.

In addition, annual data on gross regional production (GRP) for Dali City, population, total central and local financial investment in Erhai Lake protection were obtained from open data sources such as the Yunnan Provincial People's Government website, the National Bureau of Statistics of China website and the Chinese government website (Table S1). TN, TP and COD loads to the lake were calculated from river quality data entering the lake[17].

2.3 Statistical analysis

2.3.1 WQI

The WQI was developed by integrating several parameters into a single value representing the overall water quality[18], which was calculated from 10 parameters, including WT, pH, EC, DO, TN, TP, NH_4^+-N, COD_{Mn}, BOD_5 and Chla. Lower and higher WQI indicate poorer and better water quality, respectively. The normalization method of the parameters as shown in Table S2. The WQI was calculated as:

$$\mathrm{WQI} = \sum_{i=1}^{n}(P_i \times W_i) \Big/ \sum_{i=1}^{n} W_i \quad (1)$$

where, P_i is the normalized value of factor i and W_i is the weight of factor i. WQI ranges from 0 to 100, with values of 90–100, 0–90, 50–70, 25–50, and 0–25 considered to be represent excellent, good, fair, poor, and very poor water quality, respectively.

2.3.2 M-K test

To identify the changing trends and mutations of water quality and algal biomass in Erhai Lake, M-K tests were conducted[6]. For a time series x with a capacity of n samples, each value of the series is compared with the remaining values, and count the total number of remaining values greater than this value is counted as the order column s_k. Assuming random independence of the time series, the statistics are defined as:

$$\mathrm{UF}_k = \frac{[s_k - \mathrm{E}(s_k)]}{\sqrt{\mathrm{Var}(s_k)}} (k = 1, 2, \ldots, n) \quad (2)$$

where, UF_1 is equal to 0, $\mathrm{E}(s_k)$ and $\mathrm{Var}(s_k)$ are the mean and variance of the cumulative number s_k, which are independent of each other at x_1, x_2, …, x_n. UF_i obeys the standard normal distribution, which is a sequence of statistics calculated according to the time series x order x_1, x_2, …, x_n. Under the condition of significance level α (α = 0.05, U_α = ±1.96), if $|\mathrm{UF}_i| > \mathrm{U}_\alpha$, the sequence has a significant trend change. According to the inverse sequence x_n, x_{n-1}, …, x_1 of the time series x, the above process is repeated again, making $\mathrm{UB}_k = -\mathrm{UF}_k$, $k = n, n-1, \ldots, 1$, and $\mathrm{UB}_1 = 0$. If the intersection of the two curves of UB and UF lies between the critical lines, the corresponding moment of the intersection is the starting time of the sudden change.

2.3.3 Sen's slope test

In addition to M-K test, the magnitude of the trend was determined by using Sen's slope test[19] calculated as:

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, 2, \ldots, N \quad (3)$$

where, x_j and x_k are the data values at time j and k ($j > k$), respectively. Q_i is sorted from the smallest to the largest, and the median Q_{med} is taken as the Sen's slope. A positive Sen's slope indicates an upward trend, while a negative value indicates a downward trend. The magnitude of the slope determines the magnitude of the increase or decrease.

All statistical analyses were performed within the package 'trend' in R 4.0.2, and graphs were generated using Origin 9.0 and Microsoft PowerPoint 2019.

3 RESULTS AND ANALYSIS

3.1 Inter-annual changes and stage characteristics of water quality and algal biomass in Erhai Lake

As shown in Fig. 2, TN (0.241–0.649 mg·L^{-1}, mean 0.482 mg·L^{-1}) and TP (0.015–0.033 mg·L^{-1}, mean 0.024 mg·L^{-1}) are generally in Classes II to III of the Chinese surface water standard (Table S3). NH_4^+-N (0.023–0.168 mg·L^{-1}, mean 0.089 mg·L^{-1}) is mainly in Class I standard, with some years in Class II. BOD_5 (0.462–2.77 mg·L^{-1}, mean 1.76 mg·L^{-1}) is at Class I standard. COD_{Mn} (1.26–3.98 mg·L^{-1}, mean 2.83 mg·L^{-1}) is generally at Class II standard, but has been increasing in recent years, with a trend toward Class III standard. Chla (0.584–22.8 μg·L^{-1}, mean 9.28 μg·L^{-1}) is in the critical range for algal blooms in most years. Therefore, TN, TP and COD_{Mn} are the main parameters affecting the water quality status of Erhai Lake.

Trend analysis was performed on the forward series UF and the backward series UB of the M-K test statistic for annual average series of water quality parameters. The results revealed significant differences in the trends and abrupt change points of different water quality parameters, as illustrated in

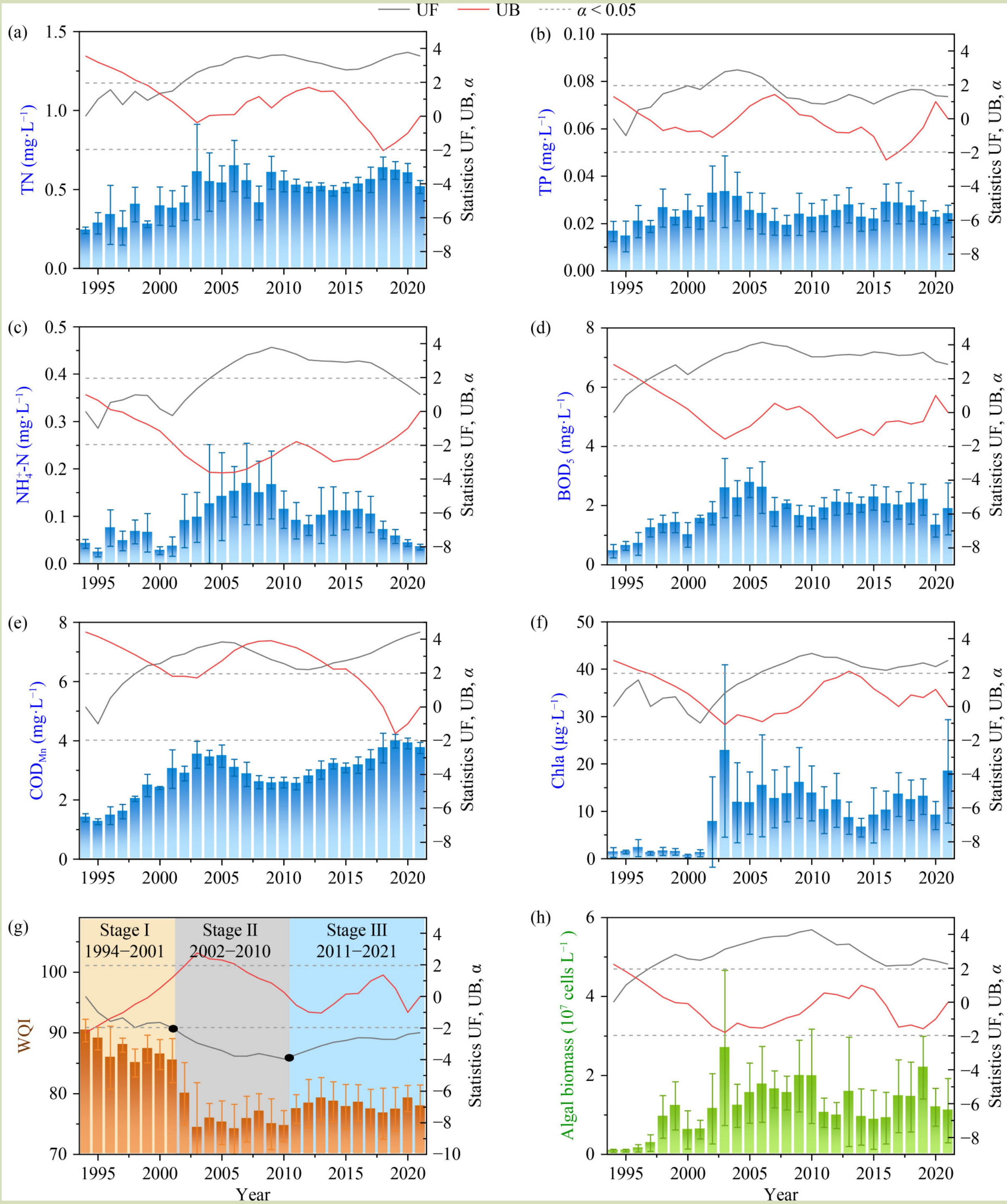


Fig. 2 Annual variation of water quality parameters, water quality index (WQI) and algal biomass in Erhai Lake and Mann-Kendall trend analysis (1994–2021).

Fig. 2(a–f). The UF of TN had an overall upward trend, with the UF and UB curves intersecting within the confidence interval in 2000, indicating an abrupt change point for TN in that year. The UF crossed the confidence line in 2002, indicating a significant upward trend in TN, followed by fluctuating changes after 2010. TP had a general upward trend, with an abrupt change point in 1996, followed by a significant increase from 2002 and then relative stability after 2005.

NH_4^+-N had a generally upward trend, with an abrupt change point in 1996, a significant increase from 2004 and a fluctuating downward trend from 2009. BOD_5 had an overall upward trend, with a change point in 1997 and a significant upward trend starting when the UF curve crossed the confidence line. BOD_5 started to decrease from 2006 and then remained relatively stable. COD_{Mn} had a general upward trend from 1998, with no significant change point detected, followed by a short decrease in 2006 and a continuous increase from 2012 to 2021. Chla had an overall upward trend, with an abrupt change point in 2002, followed by a significant upward trend after 2006 and then stabilizing at a high level. In summary, TN, TP, NH_4^+-N, BOD_5, $COD_{Mn,}$ and Chla had upward trends, with significant upward trends starting in 2002, 2002, 2004, 1997, 1998 and 2002, respectively. The abrupt change points for these upward trends also showed significant differences.

As presented in Fig. 2(g), WQI ranged from 74.2 to 90.4, with a mean of 79.9, indicating good water quality. However, UF for WQI was negative, indicating a decline in the water quality of Erhai Lake over the past 28 years, with a significant change point in 1996. In 2001, the UF curve broke through the lower confidence limit, indicating a significant decline in water quality. After 2010, the UF curve started to rise, indicating an improvement in water quality. Based on these results, the changes in the water quality of Erhai Lake can be divided into three stages: satisfactory (1994–2001), deteriorating (2002–2010) and improving (2011–2021).

The algal biomass ranged from 0.089 to 2.70 (10^7 cells L^{-1}) with an average of 1.19 (10^7 cells L^{-1}), with an increasing trend over time (Fig. 2(h)). Based on the UF and UB curves, there was an abrupt change point in 1996 and a significant upward trend in 1997. After a short decrease in 2000, an upward trend was observed from 2001 onwards, followed by a downward trend after 2010. In general, the overall variation of algal biomass was consistent with WQI and could also be divided into the same three stages. However, algal biomass was more unstable, with sudden increases observed in 2003, 2013 and 2019.

3.2 Intra-annual variations in WQI and algal biomass in Erhai Lake

In addition to the inter-annual trends, the intra-annual variation of water quality and algal biomass in Erhai Lake were investigated as well. WQI and algal biomass were collected monthly, and Sen's slope was calculated to assess the trend change and slope within each stage. In all three stages, WQI was lowest in July–October (Fig. 3(a)), which corresponded to

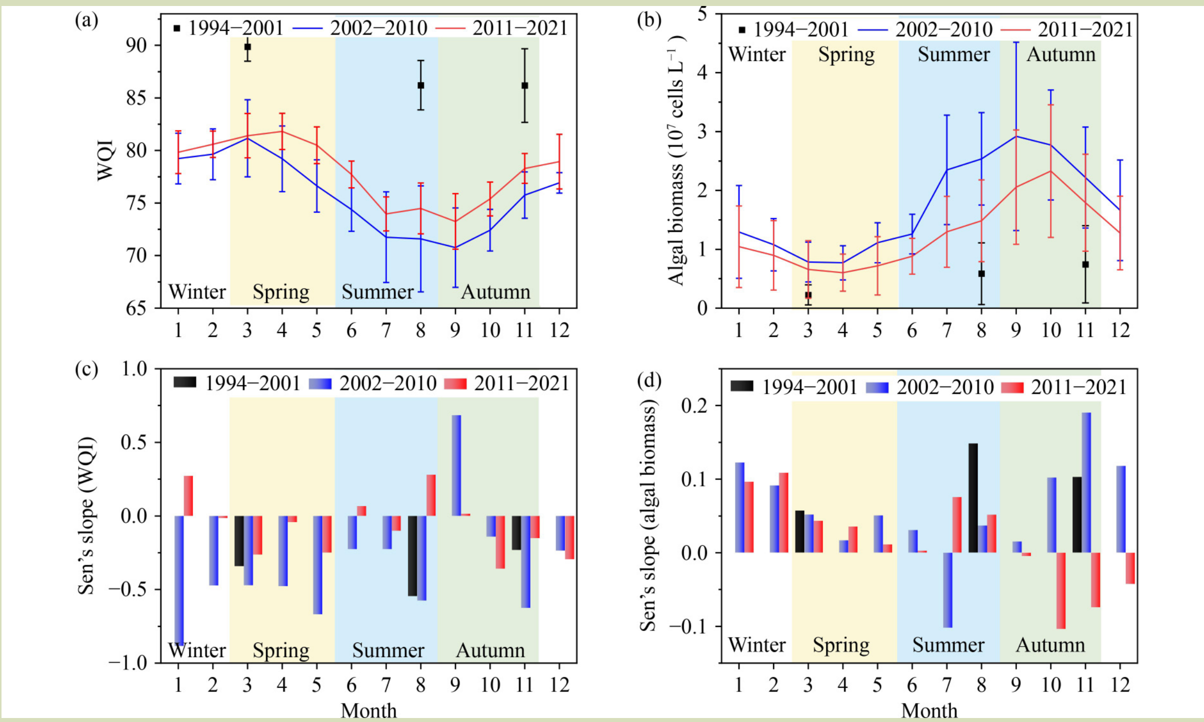


Fig. 3 Seasonal variation and trend characteristics of water quality index (WQI) and algal biomass in Erhai Lake at different stages.

the highest algal biomass at the same time (Fig. 3(b)). It is noteworthy that the lowest WQI and the highest algal biomass occurred in September prior to 2010, while the highest algal biomass in 2011–2021 occurred in October. The seasonal characteristics of the stages showed that from Stage I (1994–2001) to Stage II (2002–2010), water quality decreased, and algal biomass increased throughout the year. From Stage II to Stage III (2011–2021), water quality improved and algal biomass decreased throughout the year, but the improvement was better in summer and autumn.

The Sen's slope for WQI was positive in September (Stage II), January, June, August and September (Stage III), and negative the rest of the year (Fig. 3(c)). The Sen's slope for algal biomass was negative in July (Stage II), September to December (Stage III), and positive the rest of the time (Fig. 3(d)). This indicates a significant improvement in the water environment in summer and autumn in Erhai Lake from 2011 to 2021 with trend toward better water quality and lower algal biomass.

3.3 Spatial variations in WQI and algal biomass in Erhai Lake

The spatial variation and trend characteristics of WQI and algal biomass in Erhai Lake at three stages are presented in Fig. 4. There was only minor variation in WQI between sites (Stage I: 87.2 ± 0.58, Stage II: 75.6 ± 0.74, Stage III: 78.0 ± 0.41), and WQI in the northern area of Erhai Lake was slightly lower than in the central and southern areas (Fig. 4(a)). Algal biomass was 0.505 ± 0.076 (10^7 cells L^{-1}) in Stage I, 1.75 ± 0.084 (10^7 cells L^{-1}) in Stage II, and 1.26 ± 0.168 (10^7 cells L^{-1}) in Stage III, indicating that spatial variability was greater in Stage III, and algal biomass in the northern area was significantly higher than in the other areas (Fig. 4(b)).

The Sen's slope for WQI was positive at sampling sites S10 (Stage II) and S9 (Stage III) and negative at the remaining sites (Fig. 4(c)). The Sen's slope for algal biomass was negative at sampling sites S7, S9, S10 and S11 (Stage III) and positive at the remaining sites (Fig. 4(d)). This indicates a clear trend of improvement in water quality and algal biomass in the southern area of the lake during 2011–2021.

4 DISCUSSION

4.1 Analysis of the causes of stage-specific variation in water quality and algal biomass in Erhai Lake

The factors influencing the water environment in lakes are

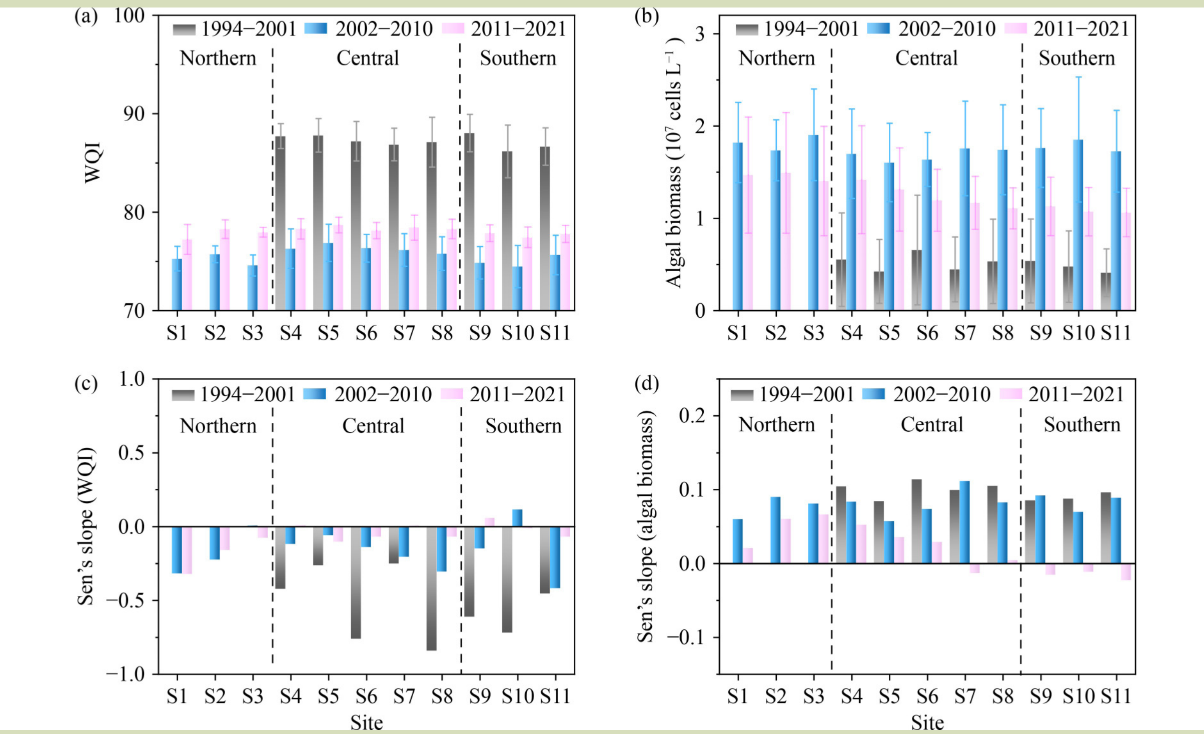


Fig. 4 Spatial variation and trend characteristics of water quality index (WQI) and algal biomass in Erhai Lake at different stages.

complex and include hydrological, hydrodynamic and meteorological factors[20,21]. In general, the emission of pollutants is the key determinant of the water environment condition as well as an important basis for the implementation of control measures to improve the water environment condition. Therefore, this study focused on the changes of human-induced disturbances in Erhai Lake, including economic development in the watershed, investment in pollution control and pollutant loads (Fig. 5).

From 1994 to 2001, the relatively slow economic and social development of Dali City resulted in minimal pollution (Fig. 5(a)). In 1996, there was a turning point in the WQI (Fig. 2(g)), with a discernible deterioration in water quality and a *Herba houttuynia* bloom occurred[22], albeit the overall aquatic environment remained satisfactory. From 2002 to 2010, the further socioeconomic development of the basin led to a large amount discharge of point and non-point source pollutant loads (peaking in 2010) and caused a significant decline in water quality and the outbreak of a *Microcystis aeruginosa* bloom in 2003. From 2001 to 2010, pollution control in the watershed was in the early stages, with the central and local governments investing 86.9 × 10^8 yuan in pollution control. From 2011 to 2020, the investment raised to 233.5 × 10^8 yuan (Fig. 5(b)). These funds facilitated the implementation of various measures including controlling pollution sources, intercepting pollution around the lake and supplementing clean water sources[15]. These measures shifted the focus of treatment from lake management to watershed management and protection of the lake ecology. Enhanced treatment efficiently counterbalanced the pressures imposed by economic and population growth, basically controlled the influx of TN, TP and COD (Fig. 5(c)), and significantly improved the water environment of Erhai Lake in Stage III.

To further interpret the changes in the water quality and algal biomass of Erhai Lake, the main influencing factors at each stage were identified and the control measures implemented

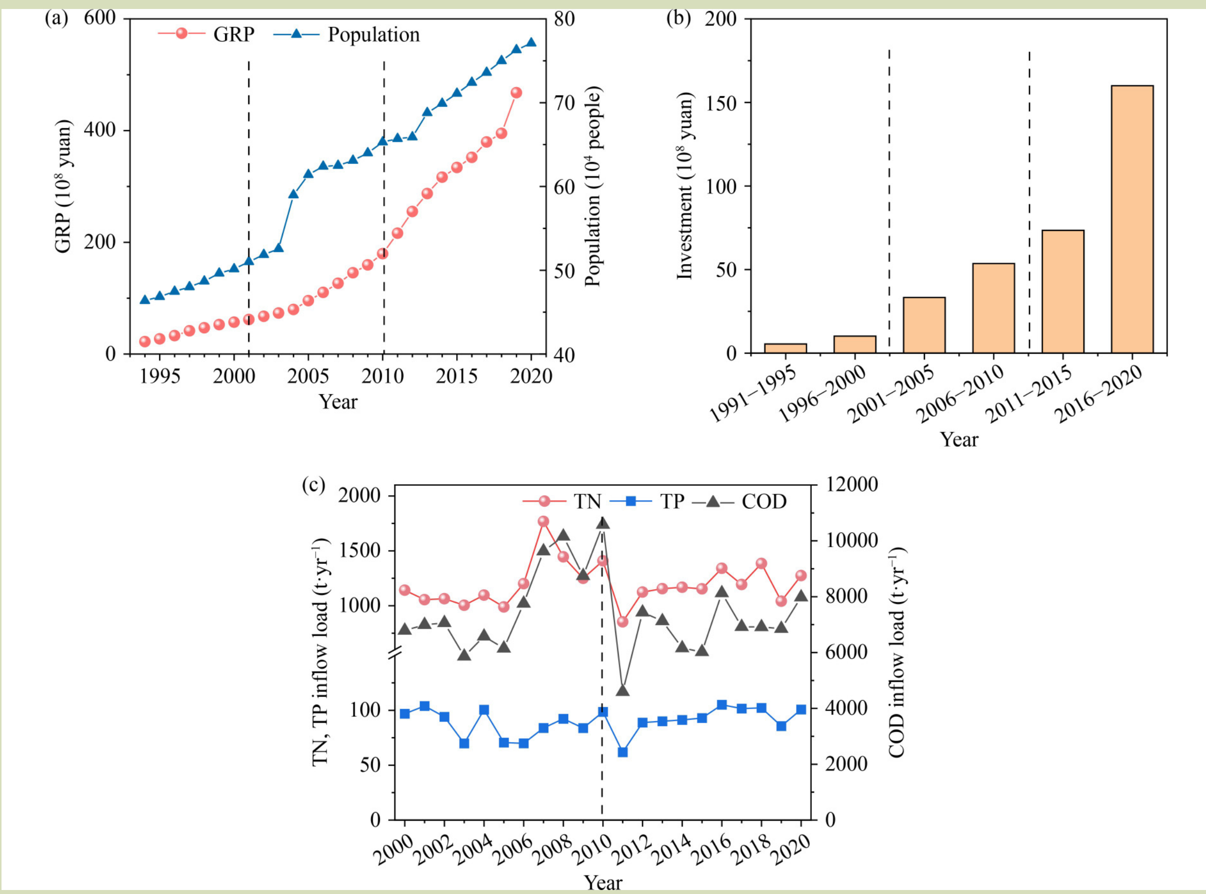


Fig. 5 Historical changes of gross regional production (GRP) and population in Dali City (a), central and local financial investment in Erhai Lake treatment (b), and total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD) in Erhai Lake (c).

are discussed. The parameters that determined WQI in the three stages were identified by lower standardized WQI, namely TN (1994–2001); TN and Chla (2002–2010); TN, Chla and COD_{Mn} (2011–2021) (Fig. 6(a–c)). TN is the main indicator of deteriorating water quality in Erhai Lake. Erhai Lake is subject to non-point source pollution. The most serious non-point source pollution in the watershed is agricultural pollution[16]. Since the 21 century, fertilizers from agricultural runoff, livestock breeding and poultry farming have caused significant nitrogen and phosphorus loads into the lake, increasing the concentration of TN and TP in the water body of Erhai Lake[23]. Figure 7 shows that the management of agricultural surface pollution in the Erhai Lake basin has received attention since 2006, and systematic measures were initiated in 2010 to mitigate pollution sources, including the promotion of organic fertilizer, adjustment of planting structure, collection of livestock and poultry manure, and a ban on the sale of highly toxic and high-residue pesticides. In addition, a 128-km buffer zone around the lake was implemented in 2018–2020, which has contribute greatly to intercepting pollutants that would have otherwise entering the lake (Fig. 7). All these measures have effectively reduced the TN and TP loads and concentrations in Erhai Lake over recent years (Fig. 2(a, b)). Therefore, the water quality of Erhai Lake primarily depends on the discharge and interception of surface source pollution in the watershed. Since the *M. aeruginosa* bloom in 2003, cyanobacteria have gradually taken over the dominant position, and Chla, representing algal biomass, has gradually become an important factor affecting water quality[24]. In addition, high algal biomass was always associated with low alkaline water, so a lower pH-normalized value, $pH_{(WQI)}$, also contributed to the reduction in WQI. BOD_5, NH_4^+-N and DO had higher normalized values, which had less impact on the water quality of the Erhai Lake. In general, the main factors affecting the WQI of Erhai Lake were TN and Chla, and COD has also become an important factor over the past 10 years.

From 1994 to 2001, there was a significant positive correlation between algal biomass and TP, BOD_5 and COD_{Mn} (Fig. 6(d)). From 2002 to 2010, algal biomass was positively correlated with TN and TP (Fig. 6(e)). From 2011 to 2021, algal biomass was

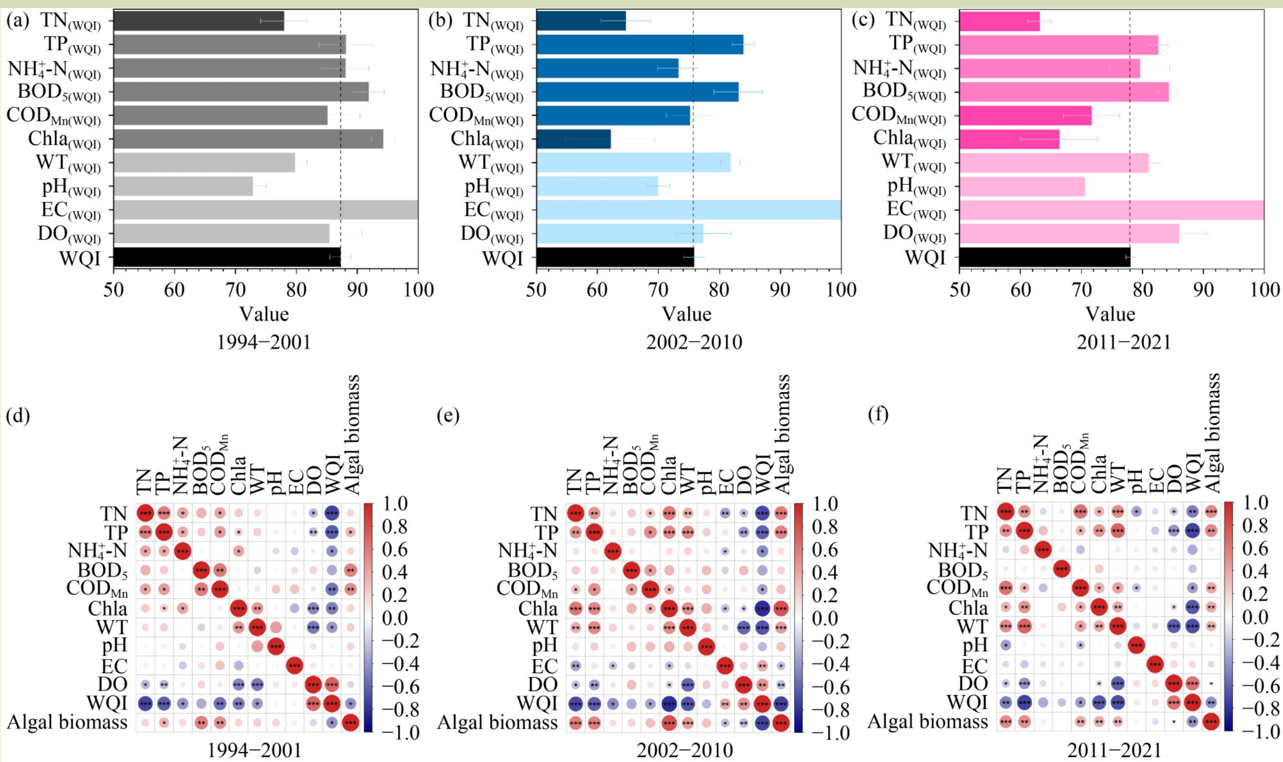


Fig. 6 Normalized water quality index (WQI) for each parameter (a–c) and Pearson correlation analysis of each parameter with algal biomass (d–f) at different stages. In (a–c), the importance of the parameter for the WQI increases with deeper color. In the correlation matrices, * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

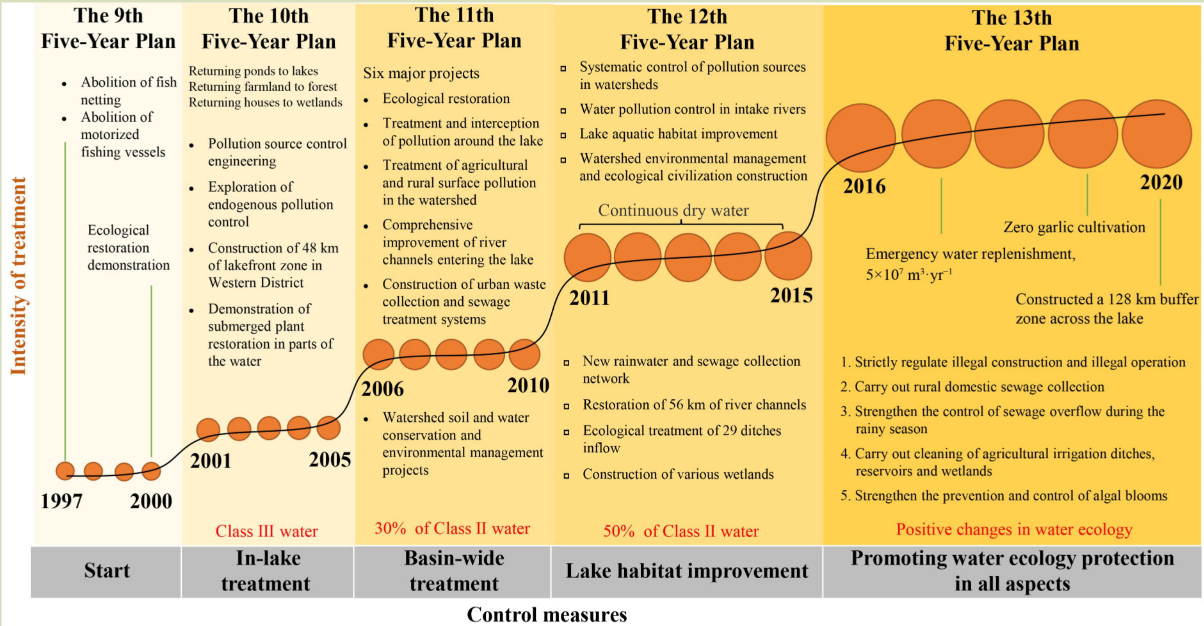


Fig. 7 Control measures of Erhai Lake in recent decades.

positively correlated with TN, TP and COD_{Mn} (Fig. 6(f)). In addition, WT was positively correlated with algal biomass during Stages II and III. Therefore, TP is always the most important indicator of algal biomass, followed by TN. Over recent years, the control of non-point source pollution in the Erhai Lake basin has facilitated the control of the phosphorus load in the lake, and endogenous pollution has become the key to the phosphorus supply for algal growth. Endogenous phosphorus pollution is mainly due to effective phosphorus turnover caused by phosphorus release from lake sediments and degradation by algal mortality[25,26]. As shown in Fig. 7, since 2016, authorities have vigorously implemented algal bloom prevention and control measures, including the establishment of algal water separation stations and cyanobacteria rescue teams to quickly capture aggregated cyanobacteria and control the occurrence of large-scale algal blooms. These measures have prevented the internal cycling of phosphorus to some extent, resulting in a significant reduction in TP concentration and algal biomass in the Erhai Lake after 2016, and a great improvement in overall water quality. However, it is suggested that increased efficiency of phosphorus use by algae may have offset the effects of reduced external loading on algae[27]. The problem of endogenous phosphorus loading supply is far more complex for algal bloom prevention and control. In addition, warmer temperatures in recent years have provided optimal growth conditions for cyanobacteria, increasing their growth rate and sensitivity to changes in the external environment[28].

4.2 Current situation and treatment insights of the Erhai Lake

For improving the water environment of Erhai Lake, the basin-wide control of pollution sources, the retention of pollutants in the buffer zone along the lake and the timely salvage of algae have been effective. However, despite the progress made in water quality and algal biomass management through the above measures, some new issues and phenomena have been observed during the water environment improvement stage (2011–2021), which need to be considered in the future management of the lake. These issues include understanding why the water environment improvement is more effective in summer and autumn than in other seasons, why the improvement of the water environment in southern lakes is more successful than in others, and why COD elevation is so common. These phenomena highlight the importance of continued efforts to enhance the water environment of Erhai Lake.

Erhai Lake receives 85% of its annual precipitation during the summer and autumn, the period when pollution inputs to the lake are particularly concentrated[29]. Comprehensive control measures, such as the management of agricultural and rural surface pollution, the implementation of urban and rural waste collection, and sewage treatment systems, have resulted in a reduction of pollution sources in summer and autumn[16]. The water quality of Erhai Lake in summer and autumn has been greatly improved by the construction of the shoreline ecological zone, which acts as a barrier to ingress of pollution[30]. The Sen's slope suggests that with successful watershed management, the water quality and algal biomass in Erhai Lake during the summer and autumn seasons can be expected to improve sustainably. As of 2018, sewage collection from villages around the lake has increased to full coverage and is connected to the lake-wide interceptor system. However, the problem of rainwater and sewage mixing has not been fully resolved due to different construction batches of the lake-wide interceptor system, resulting in sewage overflows into the environment during the rainy season[30,31]. In the future, the management of Erhai Lake basin should focus more on rainwater treatment and sewage separation in the summer and autumn seasons.

According to the above analysis, the water environment in the northern area of Erhai Lake are sensitive to the intensive agricultural activities in the area. Over the years, the rapid agricultural development in the northern catchment area has led to a large amount of nitrogen and phosphorus pollutants entering the lake along with runoff, laying the foundation for continued eutrophication in the northern area[14,15]. As phosphorus cannot exist in a gaseous form, most of the high phosphorus load in the northern area is deposited in the sediment, forming an endogenous load. Phosphorus from the sediments could return to the lake water under appropriate conditions. Studies have shown that algal degradation and mineralization processes mediated by microorganisms lead to a rapid decrease in dissolved oxygen concentration at the water-sediment interface, inducing the release of stabilized phosphorus from the sediments into the water for algal utilization, resulting in an anaerobically driven nutrient cycle[32]. The contribution of phosphorus released from sediments in the northern area of Erhai Lake to the overlying water body was significantly higher than that in other areas[33]. In the central area of the lake, due to the west to east degressive terrain, nitrogen and phosphorus pollution is rapidly washed into the lake during rainfall. If the self-purification capacity of Erhai Lake is not sufficient to absorb this pollution shortly, a temporary accumulation of algae will occur[15]. Collectively, the northern area is responsible for a substantial volume of pollution, while the central area has a high concentration of pollutants, hence, the enhancement of water quality has commenced from the southern area of the lake.

In recent years, increasing COD has emerged as a critical factor affecting the water quality and algal biomass of Erhai Lake. COD is an indicator of organic pollution, which mainly comes from livestock breeding and poultry farming, rural life and industrial activities in the watershed[30]. After 2010, the COD load to the lake was basically maintained at about 7000 $t \cdot yr^{-1}$ (Fig. 5(c)), which was significantly higher than the load of nitrogen and phosphorus to the lake, indicating that it is necessary to further strengthen the targeted measures for external COD reduction. In addition, the growth, death and decomposition of algae are also important sources of COD in lakes[34]. The death and deposition of algae releases large amounts of organic matter, which can be recycled by the algae through decomposition and mineralization by heterotrophic bacteria, which in turn maintains the biomass of the algae[35]. The sustained increase in COD concentration in Erhai Lake over the past 10 years (Fig. 2(e)) is also partly attributed to the strength of the cycling process in the lake. To solve the problem of high COD in Erhai Lake, in addition to further promoting non-point source pollution control measures, such as standardized concentrated aquaculture in the watershed, and increasing the means of livestock and poultry waste treatment and resource utilization, endogenous pollution cycle blocking measures should be further strengthened.

Overall, the water environment of Erhai Lake has greatly improved through the implementation of various management measures. The further improvement of the water environment in Erhai Lake requires equal attention to the control of water pollution and algal biomass, which is reflected in the simultaneous implementation of exogenous and endogenous pollution control. For external pollution control, it is necessary to focus on the treatment in particular time periods and areas. The pollution in the northern area of Erhai Lake basin is massive and dispersed, while the western area has a high pollution intensity, and the pollution entering the lake is concentrated in high temperature seasons such as summer and autumn. In the future, the centralized control of agricultural and rural sewage in the north should be strengthened, and the intensity of pollution entering the lake in the west in summer and autumn should be reduced, especially to solve the problem of rainwater and sewage spills. For endogenous pollution control, it is necessary to remove the internal pollution load in time, to intensify research on blocking mechanisms for the endogenous cycle, and to quantify in detail the relationship between the self-purification capacity of the water body and the exogenous pollution load.

5 CONCLUSIONS

This study evaluated the spatiotemporal variability of water quality and algal biomass in Erhai Lake as well as the underlying reasons at each stage, while summarizing the problems at the current stage and the future management priorities. The water environment of Erhai Lake has had three stages: satisfactory (1994–2001), deteriorating (2002–2010) and improving (2011–2021). TN is the most critical indicator of water quality whereas TP is the most critical indicator of algal biomass. Economic development in the basin, investment in environmental pollution control, pollution load to the lake and other anthropogenic disturbances have greatly affected the environmental conditions of Erhai Lake influencing the discharge/interception of pollutants in the basin.

After the implementation of a series of control measures, water quality in Erhai Lake in 2011–2021 improved during summer and autumn (predominantly in the south) while COD levels remained significant. The high pollution load in summer and autumn, the large non-point pollution source in the northern area of the basin and the topographically induced rapid pollution in the west have greatly influenced the seasonal and spatial characteristics of the pollution load. For the future, control of COD within Erhai Lake must be reinforced through standardized animal husbandry and rural wastewater collection. Additionally, research efforts to mitigate endogenous pollution release merit further encouraged.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2023520 contains supplementary materials (Tables S1–S3).

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Compliance with ethics guidelines

Xiaofei Liu, Yue Wu, Zhaokui Ni, and Shengrui Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Kim H G, Hong S, Chon T-S, Joo G-J. Spatial patterning of chlorophyll a and water-quality measurements for determining environmental thresholds for local eutrophication in the Nakdong River basin. *Environmental Pollution*, 2021, 268(Part A): 115701
2. Paerl H W, Havens K E, Xu H, Zhu G, Mccarthy M J, Newell S E, Scott J T, Hall N S, Otten T G, Qin B. Mitigating eutrophication and toxic cyanobacterial blooms in large lakes: the evolution of a dual nutrient (N and P) reduction paradigm. *Hydrobiologia*, 2020, **847**(21): 4359–4375
3. Huang J, Zhang Y, Arhonditsis G B, Gao J, Chen Q, Wu N, Dong F, Shi W. How successful are the restoration efforts of China's lakes and reservoirs. *Environment International*, 2019, **123**: 96–103
4. Zou W, Zhu G, Xu H, Zhu M, Zhang Y, Qin B. Temporal dependence of chlorophyll *a*-nutrient relationships in Lake Taihu: drivers and management implications. *Journal of Environmental Management*, 2022, **306**: 114476
5. Monchamp M E, Spaak P, Domaizon I, Dubois N, Bouffard D, Pomati F. Homogenization of lake cyanobacterial communities over a century of climate change and eutrophication. *Nature Ecology & Evolution*, 2018, **2**(2): 317–324
6. Wang J, Fu Z, Qiao H, Liu F. Assessment of eutrophication and water quality in the estuarine area of Lake Wuli, Lake Taihu, China. *Science of the Total Environment*, 2019, **650**(Part 1): 1392−1402
7. Qu X, Chen Y, Liu H, Xia W, Lu Y, Gang D D, Lin L S. A holistic assessment of water quality condition and spatio-temporal patterns in impounded lakes along the eastern route of China's South-to-North water diversion project. *Water Research*, 2020, **185**: 116275
8. Wang J H, Yang C, He L Q S, Dao G H, Du J S, Han Y P, Wu G X, Wu Q Y, Hu H Y. Meteorological factors and water quality changes of Plateau Lake Dianchi in China (1990–2015) and their joint influences on cyanobacterial blooms. *Science of the Total Environment*, 2019, **665**: 406–418
9. Tian Y, Jiang Y, Liu Q, Dong M, Xu D, Liu Y, Xu X. Using a water quality index to assess the water quality of the upper and middle streams of the Luanhe River, northern China. *Science of the Total Environment*, 2019, **667**: 142–151
10. Nong X, Shao D, Zhong H, Liang J. Evaluation of water quality in the South-to-North Water Diversion Project of China using the water quality index (WQI) method. *Water Research*, 2020, **178**: 115781
11. Diamantini E, Lutz S R, Mallucci S, Majone B, Merz R, Bellin A. Driver detection of water quality trends in three large

European river basins. *Science of the Total Environment*, 2018, **612**: 49–62
12. Li B, Yang G, Wan R. Multidecadal water quality deterioration in the largest freshwater lake in China (Poyang Lake): Implications on eutrophication management. *Environmental Pollution*, 2020, **260**: 114033
13. Ni Z, Wang S, Zhang M. Sediment amino acids as indicators of anthropogenic activities and potential environmental risk in Erhai Lake, Southwest China. *Science of the Total Environment*, 2016, **551–552**: 217–227
14. Wang S, Zhang L, Ni L, Zhao H, Jiao L, Yang S, Guo L, Shen J. Ecological degeneration of the Erhai Lake and prevention measures. *Environmental Earth Sciences*, 2015, **74**(5): 3839–3847
15. Lin S S, Shen S L, Zhou A, Lyu H M. Sustainable development and environmental restoration in Erhai Lake, China. *Journal of Cleaner Production*, 2020, **258**: 120758
16. Zhong S, Geng Y, Kong H, Liu B, Tian X, Chen W, Qian Y, Ulgiati S. Emergy-based sustainability evaluation of Erhai Lake basin in China. *Journal of Cleaner Production*, 2018, **178**: 142–153
17. Guo Y, Dong Y, Chen Q, Wang S, Ni Z, Liu X. Water inflow and endogenous factors drove the changes in the buffering capacity of biogenic elements in Erhai Lake, China. *Science of the Total Environment*, 2022, **806**(Part 1): 150343
18. Uddin M G, Nash S, Olbert A I. A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators*, 2021, **122**: 107218
19. Chen J, Lyu Y, Zhao Z, Liu H, Zhao H, Li Z. Using the multidimensional synthesis methods with non-parameter test, multiple time scales analysis to assess water quality trend and its characteristics over the past 25 years in the Fuxian Lake, China. *Science of the Total Environment*, 2019, **655**: 242–254
20. Chen Q, Ni Z, Wang S, Guo Y, Liu S. Climate change and human activities reduced the burial efficiency of nitrogen and phosphorus in sediment from Dianchi Lake, China. *Journal of Cleaner Production*, 2020, **274**: 122839
21. Ji D, Wells S A, Yang Z, Liu D, Huang Y, Ma J, Berger C J. Impacts of water level rise on algal bloom prevention in the tributary of Three Gorges Reservoir, China. *Ecological Engineering*, 2017, **98**: 70–81
22. Liu Y, Yang S, Liu X F. Ecological risk assessment of Microcystis blooms in Erhai Lake. *Acta Hydrobiologica Sinica*, 2018, **42**(5): 1066–1074 (in Chinese)
23. Geng B, Luo L G. Farmers' willingness to reduce fertilizer input and adopt organic fertilizer—Based on the perspective of non-point source pollution prevention and control in the upper reaches of Erhai watershed. *Chinese Journal of Agricultural Resources and Regional Planning*, 2018, **39**(4): 74–82 (in Chinese)
24. Quinlan R, Filazzola A, Mahdiyan O, Shuvo A, Blagrave K, Ewins C, Moslenko L, Gray D K, O'reilly C M, Sharma S. Relationships of total phosphorus and chlorophyll in lakes worldwide. *Limnology and Oceanography*, 2021, **66**(2): 392–404
25. Pu J, Wang S, Fan F, Zhou C, Liu Z. Recognizing the variation of bioavailable organic phosphorus in sediment and its significance between high and low risk periods for algal blooms in Erhai Lake. *Water Research*, 2023, **229**: 119514
26. Ni Z, Wang S, Cai J, Li H, Jenkins A, Maberly S C, May L. The potential role of sediment organic phosphorus in algal growth in a low nutrient lake. *Environmental Pollution*, 2019, **255**(Part 2): 113235
27. Chen Q, Wang S, Ni Z, Guo Y, Liu X, Wang G, Li H. No-linear dynamics of lake ecosystem in responding to changes of nutrient regimes and climate factors: Case study on Dianchi and Erhai lakes, China. *Science of the Total Environment*, 2021, **781**: 146761
28. Deng J, Qin B, Paerl H W, Zhang Y, Wu P, Ma J, Chen Y. Effects of nutrients, temperature and their interactions on spring phytoplankton community succession in Lake Taihu, China. *PLoS One*, 2014, **9**(12): e113960
29. Liu Y, Qu X, Elser J J, Peng W, Zhang M, Ren Z, Zhang H, Zhang Y, Yang H. Impact of nutrient and stoichiometry gradients on microbial assemblages in Erhai Lake and its input streams. *Water*, 2019, **11**(8): 1711
30. Xiang S, Wu Y, Lü X, Gao S, Chu Z, Pang Y. Characteristics and spatial distribution of agricultural non-point source pollution in Erhai Lake basin and its classified control strategy. *Research of Environmental Sciences*, 2020, **33**(11): 2474–2483 (in Chinese)
31. Lu Z, Yu B, Zhang H, Yang Z. Correlation analysis of agricultural non-point source pollution and water environment change in Erhai Lake watershed. *Journal of Central China Normal University (Natural Sciences)*, 2017, **51**(2): 215–223
32. Li H, Xing P, Wu Q. Characterization of the bacterial community composition in a hypoxic zone induced by *Microcystis* blooms in Lake Taihu, China. *FEMS Microbiology Ecology*, 2012, **79**(3): 773–784
33. Liu W, Wang S, Zhang L, Ni Z, Zhao H, Jiao L. Phosphorus release characteristics of sediments in Erhai Lake and their impact on water quality. *Environmental Earth Sciences*, 2015, **74**(5): 3753–3766
34. Yin Y, Zhang Y, Liu X, Zhu G, Qin B, Shi Z, Feng L. Temporal and spatial variations of chemical oxygen demand in Lake Taihu, China, from 2005 to 2009. *Hydrobiologia*, 2011, **665**(1): 129–141
35. Tang X, Gao G, Chao J, Wang X, Zhu G, Qin B. Dynamics of organic-aggregate-associated bacterial communities and related environmental factors in Lake Taihu, a large eutrophic shallow lake in China. *Limnology and Oceanography*, 2010, **55**(2): 469–480