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Water Quality of Lake Erhai in Southwest China and Its Projected Status in the near Future

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Abstract: The water quality of Lake Erhai has deteriorated in recent decades due to socioeconomic development in the lake basin. After the massive implementation of water environmental protection measures in Lake Erhai in 2016, the trend of water quality deterioration has been curbed and the intensity and frequency of algal blooms has decreased. However, water quality monitoring data show that pollutant concentrations in Lake Erhai still exceed acceptable values, and there is a risk of water quality standard limits being further exceeded in the future. Therefore, it is urgent to systematically study the variability characteristics of water quality in Lake Erhai to provide practical methods to predict the future evolution of water quality. Based on water quality monitoring data from 2009 to 2019, the current water quality characteristics of Lake Erhai were analyzed, and a two-dimensional hydrodynamic and water quality mathematical model was built to predict the water quality in 2025. The results showed that the total phosphorus (TP) concentration declined after 2016, mainly due to the significant reduction of TP entering the lake due to pollution interception. However, the concentrations of the potassium permanganate index (COD_{Mn}) and total nitrogen (TN) increased after 2016, demonstrating that the pollution control measures have had little effect on the improvement of COD_{Mn} and TN. The spatial and temporal distribution of pollutants showed that the water quality in winter and spring was better than in summer and autumn, and the water quality in the southern lake was better than in the northern lake. This analysis indicates that non-point source pollution remains the main source of pollution in Lake Erhai, and that rainfall is the main driving force of pollutants exceeding the water quality standard. According to the water quality predictions, without additional pollution control measures, pollutant concentrations in Lake Erhai will exceed the Class II water quality standard by 2025. This study analyzes the water quality characteristics, predicts the direction of future water quality changes, and provides a theoretical basis for the future water quality protection of Lake Erhai.

Keywords: Lake Erhai; water quality; water quality characteristics; water quality prediction

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1. Introduction

The Erhai basin belongs to the Lancang River in the Mekong River system, and it covers an area of 2565 km^2. Lake Erhai is located at 25°36′–25°58′ N, 100°05′–100°17′ E (Figure 1). Lake Erhai is located in the center of the basin at its lowest point, and it is the second largest plateau freshwater lake in Yunnan Province. Climate change and human activities have affected the Erhai River basin for a long time [1,2]. Lake Erhai is not only the water source for local production and daily life, but also constantly receives wastewater produced by these things, as well as farmland non-point source pollutants in the basin. In the past decade, with rapid socioeconomic development and the vigorous development of tourism in the basin, problems such as the overuse of water resources, the gradual degradation of the lake water ecosystem [3], accelerated eutrophication [4–6], and the continuous decline of water quality [7,8] have become increasingly prominent. Since the implementation of the "seven actions" and "eight key battles" for comprehensive water pollution control in the Erhai basin in 2016 [9,10], the protection and treatment of Lake Erhai have achieved phased results, and the trend in water quality decline has been alleviated. The protection of Lake Erhai has shifted from the rescue management stage to the conservation management and ecological restoration stage. According to the water quality monitoring data, the concentration of TP has declined, which is beneficial for reducing the eutrophication of lakes [11–13], but the concentrations of COD_{Mn} and TN have increased. This indicates that the factors affecting the water quality of Lake Erhai are extremely complicated, so it is necessary to systematically study the characteristics of the variation in water quality in Lake Erhai.

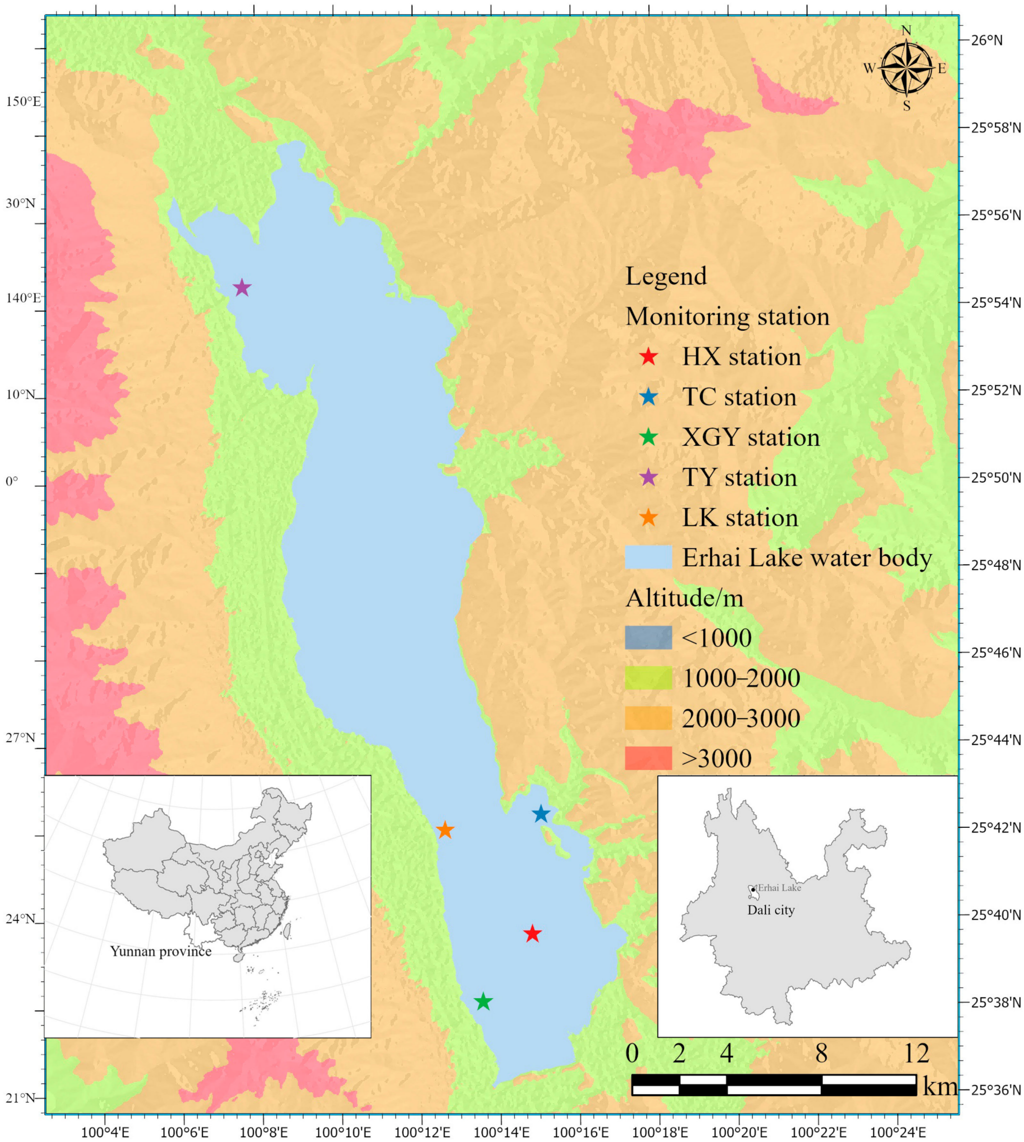

Figure 1. Location of Lake Erhai and monitoring stations (Digital Elevation Model (DEM) data were obtained from the website https://www.gscloud.cn/ and accessed on 30 October 2022).

Many scholars have studied the water quality of Lake Erhai using different methods. Some scholars directly compared the changes of water quality monitoring data. For example, Shen [14] analyzed the water quality monitoring data of Lake Erhai from 1971 to 1985 and concluded that the water level of Lake Erhai had a direct influence on the water quality. According to the water quality monitoring data of Lake Erhai from 1985 to 2019, Zhang et al. [15] stated that the TN of Lake Erhai was mainly affected by the inflow of rivers. Ma et al. [16] believed that agricultural non-point source pollution was the key environmental factor causing the water quality of Lake Erhai to exceed the Class II water quality standard during the rainy season. Other scholars used statistical analysis in their research. Using the absolute principal component score-multiple linear regression (APCS-MLR) and correlation analysis methods, Shi et al. [17] concluded that pollutants enter Lake Erhai mainly through surface runoff and atmospheric dry and wet deposition. Based on grey relational analysis, Wang et al. [18] concluded that the pollutants in Lake Erhai mainly originate from non-point source pollution. An et al. [19] used the linear regression method to study the relationship between climate factors and water quality and showed that climate change was related to the water quality of Lake Erhai. Zheng et al. [20] analyzed changes in the water volume and quality in Lake Erhai based on statistical data from 2000 to 2019 combined with climate, land-use type, and socioeconomic data. Huang [21] studied the correlation between water quality and rainfall in Lake Erhai using the correlation analysis method. Jin et al. [22] researched the characteristics of nitrogen and phosphorus pollution in surface runoff and the impacts of land use on the water quality of the runoff during the rainy season in the plains area of the Yunnan plateau. Using spatial and statistical analysis, Pang et al. [23] studied the relationship between agricultural land and the water quality of the inflow river in the Erhai Basin. Peng et al. [24] analyzed the water quality characteristics of irrigation and drainage ditches in western Lake Erhai under rainy conditions, as well as the impact of land use on water quality.

Although the above two methods can reflect and reveal the correlations between water quality and its influencing factors and deeply analyze the main factors affecting water quality, these methods cannot accurately predict the future water quality evolution of Lake Erhai. In order to solve this problem, scholars have also constructed mathematical models of the hydrodynamics and water quality of Lake Erhai based on hydrodynamic and water quality equations to simulate the future of Lake Erhai. Wang et al. [25] built a two-dimensional unsteady model to study what the influence of diverting the Jinsha River into Lake Erhai would be on its water quality. Wei et al. [26] and Zhang [27] established a hydrodynamics and water quality model of Lake Erhai by using EFDC to study the hydrodynamic characteristics and water quality of Lake Erhai.

Based on the operation and management of the water level of Lake Erhai, considering the changes of pollution sources after the implementation of water pollution control measures in 2016, this research predicted the changes in the water quality of Lake Erhai in different hydrological years based on hydrodynamic and water quality mathematics models and provided a theoretical approach for the scientific protection of Lake Erhai.

2. Data and Model

2.1. Study Area and Data Sources

The research area is shown in Figure 1. Three water quality indicators, COD_{Mn}, TP, and TN, were selected as the representative indicators of water quality. The water quality monitoring data of Lake Erhai were obtained from the Dali Bai Autonomous Prefecture Monitoring Station and the Dali City Environmental Monitoring Station. The years these monitoring data were collected was from 2009 to 2019. There were five monitoring sites, as shown in Figure 1: Longkan, Tacun, Xiaoguanyi, Huxin, and Taoyuan. Longkan is located in the western lake, Tacun in the eastern lake, Xiaoguanyi in the southern lake, Huxin in the center of the southern lake, and Taoyuan in the northern lake. Meteorological data for 2009–2019 were obtained from the Dali Meteorological Station, which was monitored daily and then averaged monthly. The Dali Meteorological Station is located near Lake Erhai. The data were obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA) and the National Center for Environmental Information (NCEI)

(NOAA—National Centers for Environmental Information, https://www.ncei.noaa.gov (accessed on 28 September 2022)). The pollution sources data were obtained from the Dali Prefecture Ecology and Environment Bureau. The gross domestic product (GDP) data and population data were obtained from the Yunnan Statistical Yearbook (2009–2019).

2.2. Methods and Models

Lake Erhai faces Yuling Mountain in the east and Diancang Mountain in the west and is located in a northeast–west–southeast valley. The wind field on the lake surface is affected by the surrounding mountains, and the airflow movement has obvious directionality; moreover, there are no mountains in the middle of the valley, allowing uniform wind conditions can be used in the model. According to the research on numerous shallow lakes in China and internationally, in shallow lakes, water flow is mainly driven by wind flow, and the pollutants are transported and diffused under the combined action of wind-generated flow and throughput flow. It is assumed that the water body of Lake Erhai is uniformly mixed in a vertical direction. The study mainly reflects the overall change in water flow and quality in the study area; therefore, the transport and diffusion of pollutants in Lake Erhai can be described mathematically using a two-dimensional flow equation and diffusion equation. The hydrodynamic model built in this study is shown in Equation (1) as follows:

$$\begin{array}{l} \frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q \\ \frac{\partial (uh)}{\partial t} + \frac{\partial (u^2 h)}{\partial x} + \frac{\partial (uvh)}{\partial y} + gh\frac{\partial z}{\partial x} - fv = \frac{\tau_{wx}}{\rho} - \frac{\tau_{bx}}{\rho} \\ \frac{\partial (vh)}{\partial t} + \frac{\partial (uvh)}{\partial x} + \frac{\partial (v^2 h)}{\partial y} + gh\frac{\partial z}{\partial y} + fu = \frac{\tau_{wy}}{\rho} - \frac{\tau_{by}}{\rho} \end{array}, \tag{1}$$

where h is the water depth that is equal to the water level minus the elevation of the lake bottom; q is the discharge to and from the lake per unit area, where entering the lake is "+", leaving the lake is "−"; u and v are the velocity components in the x and y directions; Z is the water level of Lake Erhai; g is the acceleration of gravity; ρ is the density of water; f is the Coriolis parameter, where according to the longitude and latitude of Erhai, f is 6.1×10^{-5} 1/s; τ_{bx} and τ_{by} are friction components at the bottom of the lake in the x and y directions, respectively; and τ_{wx} and τ_{wy} are wind stress components on the lake surface in the x and y directions, respectively.

The water quality model constructed in this study is shown in Equation (2) as follows:

$$\frac{\partial (hC)}{\partial t} + \frac{\partial (MC)}{\partial x} + \frac{\partial (NC)}{\partial y} = \frac{\partial}{\partial x}\left(E_x h\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y h\frac{\partial C}{\partial y}\right) + S + F(C) \tag{2}$$

where C is the concentration of COD_{Mn}, TP, and TN; M is the discharge per unit width in the x direction, $M = u \times h$; N is the discharge per unit width in the y direction, $N = v \times h$; E_x is the transverse diffusion coefficient; E_y is the longitudinal diffusion coefficient; S is the source or sink; and $F(C)$ is the biochemical response term.

The biochemical response term of COD_{Mn} is shown in Equation (3) as follows:

$$F(C) = -K_C \times C \times h, \tag{3}$$

where K_C is the decay coefficient of COD_{Mn}.

The biochemical response term of TP or TN is shown in Equation (4) as follows:

$$F(C) = S_T - K_T \times C \times h, \tag{4}$$

where S_T is the sediment release rate of TP or TN; K_T is the decay coefficient of TP or TN.

A rectangular mesh 250 m × 250 m in size was used to divide the calculation units of Lake Erhai. There were a total of 3969 computational mesh elements. The model equations were discretized by the finite difference method with the physical parameters arranged on a staggered grid. The convective terms and diffusion terms were treated with the upwind scheme and central difference scheme, respectively.

2.3. Parameter Calibration and Model Verification

Using the water quality monitoring data, water level, flow, water quality, and meteorological data of Lake Erhai in 2016 and 2018, the parameter calibration and model verification of Lake Erhai's hydrodynamic characteristics and water quality model were performed. The parameter values of the model are shown in Table 1.

Table 1. Parameter values of the hydrodynamic characteristics and water quality model of Lake Erhai.

Parameters	Value	Unit
Transverse/longitudinal diffusion coefficient	4	m^2/s
Decay coefficient of COD_{Mn}	0.001	d^{-1}
Sediment release rate of COD_{Mn}	0–200	$mg/(m^2{\cdot}d)$
Decay coefficient of TP	0.005	d^{-1}
Sediment release rate of TP	0–5	$mg/(m^2{\cdot}d)$
Decay coefficient of TN	0.004	d^{-1}
Sediment release rate of TN	0–50	$mg/(m^2{\cdot}d)$

According to the results, the relative errors of the simulation of five monitoring sites in the study area are less than 10%, as shown in Table 2. The comparison of the simulated and measured water quality results at the Huxin site in 2018 is shown in Figure 2. The simulation results show with strong accuracy that the hydrodynamic characteristics and water quality model of Lake Erhai can reflect the circulation pattern of Lake Erhai and the spatiotemporal variation characteristics of pollutants entering the lake. This model can also provide a scientific prediction tool for simulating the temporal and spatial distribution of water flow and quality in Lake Erhai under the conditions of water resources and pollution change. Because the difference between the velocity components in the x and y direction is small in the lake, the same values are used for the transverse and longitudinal diffusion coefficient.

Table 2. Simulation errors of water quality monitoring site in Lake Erhai in 2018.

Pollutant	Monitoring Site	Measured (mg/L)	Simulated (mg/L)	Relative Error (%)
COD_{Mn}	Longkan	3.73	3.53	5.36
	Tacun	3.76	3.54	5.85
	Xiaoguanyi	3.76	3.52	6.38
	Huxin	3.69	3.52	4.61
	Taoyuan	3.81	3.54	7.09
TP	Longkan	0.028	0.026	7.14
	Tacun	0.026	0.027	−3.85
	Xiaoguanyi	0.029	0.028	3.45
	Huxin	0.026	0.028	−7.69
	Taoyuan	0.029	0.031	−6.90
TN	Longkan	0.59	0.64	−8.47
	Tacun	0.59	0.61	−3.39
	Xiaoguanyi	0.62	0.60	3.23
	Huxin	0.61	0.60	1.64
	Taoyuan	0.67	0.73	−8.96

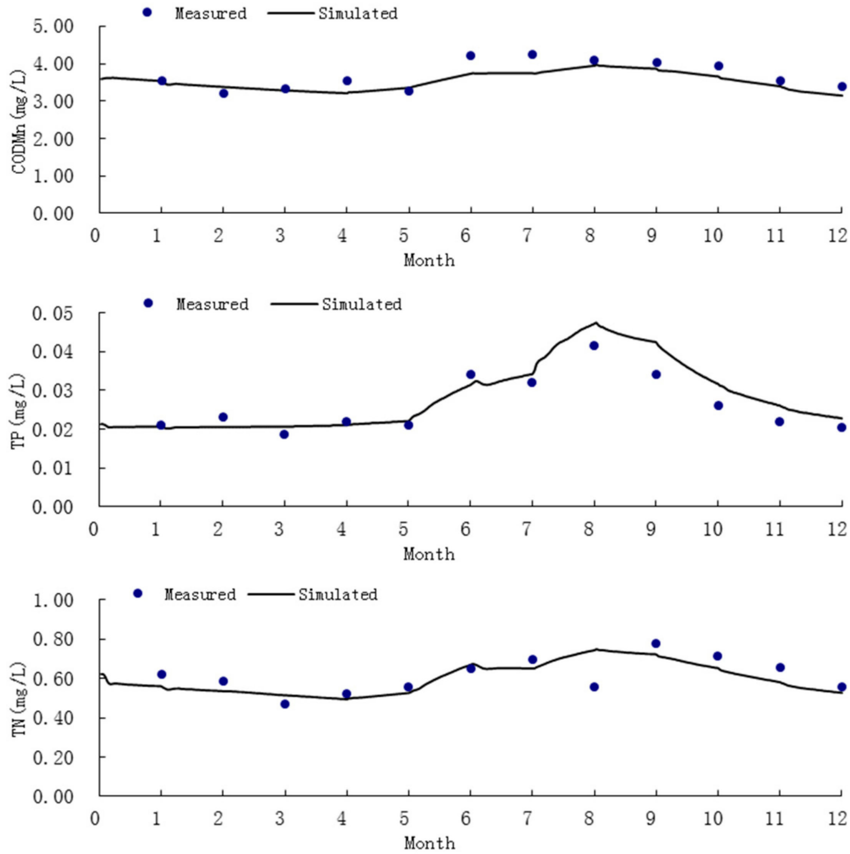

Figure 2. Comparison of simulated and measured water quality results at the Huxin site in 2018.

3. Results and Discussion

3.1. Annual Water Quality Changes

In China, COD_{Mn}, TP, and TN have different water quality standards. The current surface water standard in China divides water quality into five categories: Class I, Class II, Class III, Class IV, and Class V. According to the Functional Zoning of Surface Water and Water Environment in Yunnan Province (2010–2020), the water environment functions in Lake Erhai include water in the national nature reserve, drinking water, aquatic habitat water, and swimming water, thus the Class II water quality standard is implemented. The annual average concentrations of COD_{Mn}, TP, and TN from 2009 to 2019 in Lake Erhai are shown in Figure 3. The annual average concentrations of COD_{Mn} in the entire lake have increased year by year, but they are still not above the limit value of the Class II water quality standard. It is worth noting that the average concentration of COD_{Mn} in 2019 reached 4.0 mg/L (the limit value of the COD_{Mn} standard for Class II). The decrease in the TP concentration in Lake Erhai was not obvious, and the concentration of TP fluctuated around the limit value of the standard. The TP concentration met the standard from 2009 to 2012 and in 2014, 2015, and 2019, and exceeded the standard in the other years. From 2016 to 2019, the TP concentration decreased. The TN concentration in Lake Erhai decreased first and then increased. The TN concentration in 2014 was the lowest, after which it increased every year. The TN concentration from 2009 to 2019 in Lake Erhai exceeded the standard, except in 2014.

As shown in Figure 3, the concentration of TP decreased after 2016, but the concentrations of COD_{Mn} and TN increased. In general, the increased pollutant concentrations in the lake were directly related to the increase in the population and GDP in the basin. According to the annual changes of the population and GDP in Dali Bai Autonomous Prefecture (Figure 4), the economic and social development in the Erhai basin has led to an increase in pollutant sources, thus the COD_{Mn} and TN concentrations have increased.

Since the implementation of the "seven actions" and "eight key battles" for comprehensive water pollution control in the Erhai basin in 2016, these measures have had a great effect on TP interception, and the TP concentration shows a downward trend. However, these pollution control measures have not significantly improved the COD_{Mn} and TN in Lake Erhai, and the concentrations of COD_{Mn} and TN have continued to rise since 2016. In addition, the average annual concentrations of TP in 2014 and 2015 were lower than in other years. According to the annual average water level data from 2009 to 2019 in Lake Erhai (Figure 5), the average annual water levels in 2014 and 2015 were lower than in other years, which may have affected the concentrations of TP.

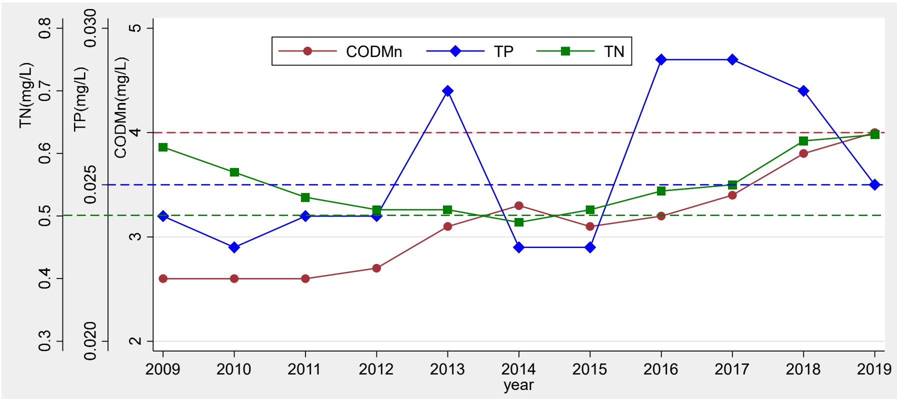

Figure 3. Annual average concentrations of COD_{Mn}, TP, and TN from 2009 to 2019 in Lake Erhai (the brown dashed line is the limit value of COD_{Mn}, the blue dashed line is the limit value of TP and the green dashed line is the limit value of TN).

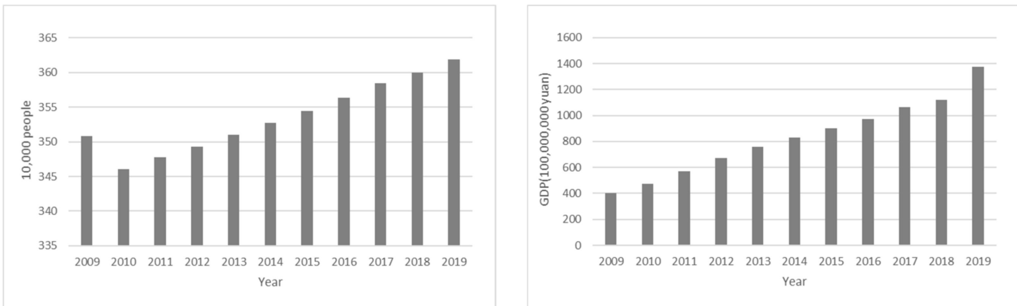

Figure 4. Annual average population and gross domestic product (GDP) in Dali Bai Autonomous Prefecture.

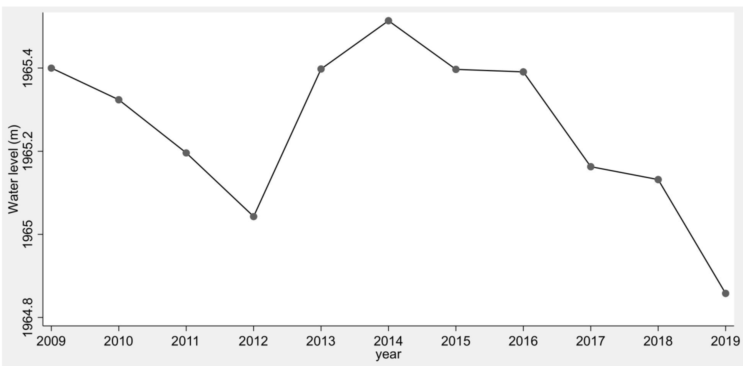

Figure 5. Annual average water levels from 2009 to 2019 in Lake Erhai.

3.2. Monthly Water Quality Changes

According to the monthly average of the concentrations of COD_{Mn}, TP, and TN (Figure 6), the water quality of Lake Erhai is better in winter and spring than in summer and autumn. The concentrations of COD_{Mn} and TN increased starting in May, reached the maximum in July, and remained high from July to October. Concentrations began to decline in November and remained low from December to April of the following year. The concentrations of TP increased starting in April, reached the maximum in July, and remained high from July to October. Concentrations began to decline in November and remained low from December to March of the following year. The seasonal variation of water quality in Lake Erhai is consistent with the research results of other scholars in plateau lakes [28–30].

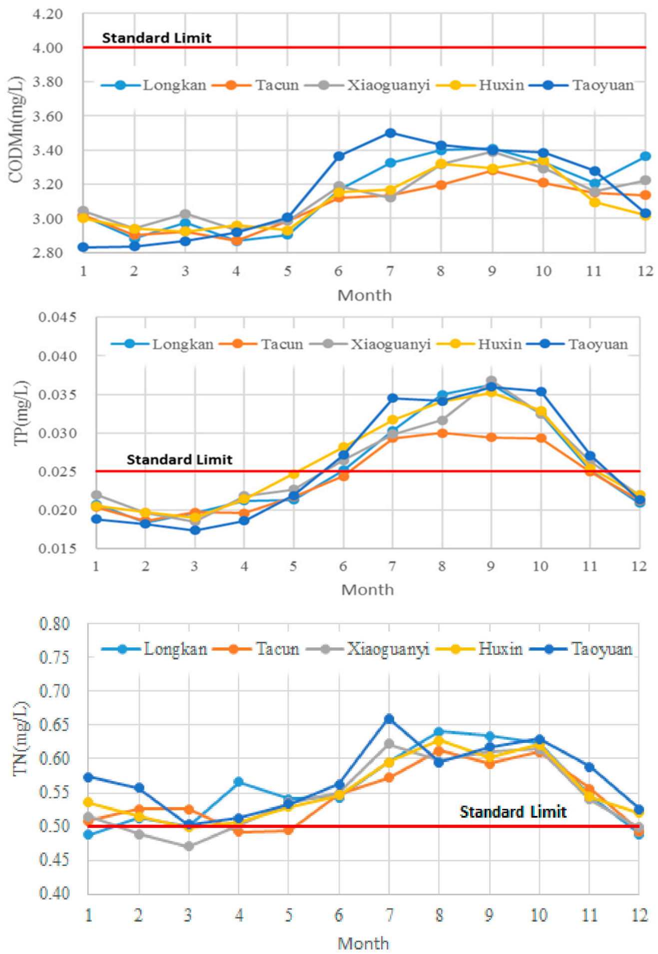

Figure 6. Monthly average concentrations of COD_{Mn}, TP, and TN from 2009 to 2019 in Lake Erhai (five monitoring sites: Longkan, Tacun, Xiaoguanyi, Huxin, and Taoyuan).

As shown in Figure 6, the concentration of COD_{Mn} at all monitoring sites met the standard in all months, while the concentrations of TP and TN at some monitoring sites exceeded the standard in some months. The concentration of TP at Longkan, Tacun, Xiaoguanyi, Huxin, and Taoyuan exceeded the standard from June to November, but met the standard in other months. The concentration of TP at Tacun exceeded the standard from May to November and met the standard in other months. The concentration of TN at Longkan exceeded the standard from February to November but met the standard in other months. The concentration of TN at Tacun exceeded the standard from January to March and from June to November but met the standard in other months. The concentration of TN at Xiaoguanyi exceeded the standard in January and from April to November but met the standard in other months. The concentration of TN at Taoyuan exceeded the standard in all months. The concentration of TN at Huxin met the standard only in March.

Analysis of the monthly average rainfall data (Figure 7) from 2009 to 2019 at the Dali Meteorological Station revealed that average monthly rainfall gradually increased from May to October and gradually decreased from November to April. Based on the annual report of Water Resources monitoring and evaluation in the Erhai Basin in 2016, we estimated the monthly flow of the rivers around Lake Erhai. By multiplying flow with pollutant concentration of the rivers, the temporal distribution of pollutants entering Lake Erhai in 2016 was obtained, as shown in Table 3. More pollutants entered the lake in the rainy season than in the dry season. The agriculture industry in the Erhai basin is developed, and agricultural non-point source pollution has always been the main factor responsible for the decline of the water quality of Lake Erhai because pollutants flow into the lake with rainfall. TN is the main index of water quality deterioration in Lake Erhai at present, and the reduction of TN entering Lake Erhai should be emphasized in the future.

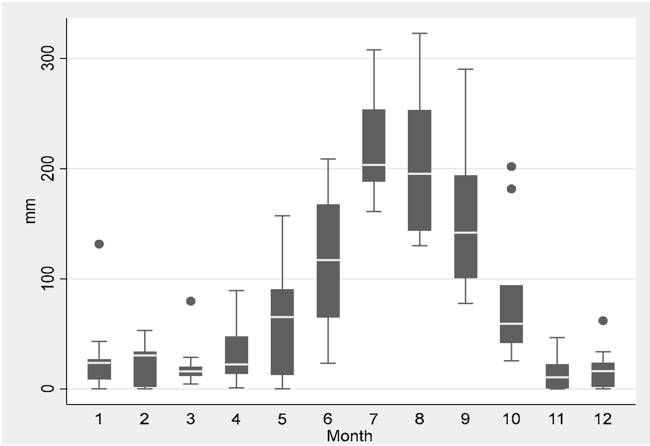

Figure 7. Boxplot of monthly average rainfall from 2009 to 2019 at Dali Meteorological Station.

Table 3. Temporal distribution of pollutants entering Lake Erhai in 2016 (Unit: t).

Types of Pollutants	Rainy Season (June to September)	Dry Season (October to May of the Following Year)
Chemical oxygen demand	6801	3923
TP	93	35
TN	1088	658

3.3. Spatial Variation of Water Quality

According to the average concentrations of COD_{Mn}, TP, and TN at different monitoring sites (Figure 6), there were different spatial variations of water quality in the dry season and the rainy season. During the dry season (November to April of the following year), the concentrations of COD_{Mn} and TP were higher in the southern area of Lake Erhai, and the highest concentrations of COD_{Mn} and TP were 3 mg/L and 0.022 mg/L, respectively; the concentrations of TN were higher in the northern area of Lake Erhai and the highest concentration of TN was 0.57 mg/L. During the rainy season (May to October), the concentrations of COD_{Mn}, TP, and TN were higher in the northern area of Lake Erhai, and the highest concentrations of COD_{Mn}, TP, and TN were 3.5 mg/L, 0.035 mg/L, and 0.66 mg/L, respectively.

With the developed planting industry in the Erhai Basin, the surface runoff from farmland flows directly into the adjacent ditches and nearby rivers, resulting in the decline of water quality of rivers that flow into the lake. By multiplying flow with the pollutant concentration of the rivers, the spatial distribution of pollutants entering Lake Erhai in 2016 was obtained, as shown in Table 4. Northern rivers contained the greatest amount of pollutants. These findings indicate that the spatial variation of water quality is mainly affected by agricultural non-point source pollution. The north of Lake Erhai has a strong degree of agricultural development; therefore, in the rainy season, more pollutants enter the northern area of Lake Erhai along with the rain, which eventually leads to a higher pollutant concentration in the northern area during this time.

Table 4. Spatial distribution of pollutants entering Lake Erhai in 2016 (Unit: t).

Pollutant	Northern Rivers	Western Rivers	Southern Rivers	Eastern River
Chemical oxygen demand	5610.7	4079.7	895.9	137.0
TP	43.6	67.7	14.0	2.5
TN	675.6	892.8	159.3	18.4

3.4. Water Quality Prediction of Lake Erhai

In the medium- and long-term plans for water ecological protection in the Erhai Basin of Yunnan Province (2020–2035), the water quality protection target of Lake Erhai by 2025 is as follows: the water quality of the entire lake should reach Class II, no large-scale algae blooms should occur in the lake, and the ecological function of the lake should recover. This study made predictions for a high-flow year (25% hydrological guarantee rate), a normal-flow year (50% hydrological guarantee rate), and a low-flow year (75% hydrological guarantee rate) in 2025.

The operation scheme of the water level of Lake Erhai in high-, normal-, and low-flow years (Figure 8) is as follows: Under the condition of satisfying the water resources balance of Lake Erhai and the ecological water requirements of Xier River, the water level of Lake Erhai should remain low from April to July, between 1964.60 m and 1965.70 m. Considering the current pollution control measures in the Erhai basin and the population and socioeconomic development of the basin, the pollutants entering Lake Erhai in 2025 will be as follows: 10,502.01-t chemical oxygen demand, 1483.19-t nitrogen, and 110.43-t phosphorus. The prediction was based on the hydrodynamic conditions and water quality of Lake Erhai at the end of 2018. In order to reflect the impact of rainfall change on water balance based on the long-term series of runoff results from 1952 to 2014 in Lake Erhai, the empirical frequency method was used to determine the water inflows into the lake in three typical hydrological years (high-, normal-, and low-flow years). The water inflows and pollutants into the lake in three typical hydrological years were used as boundary conditions for the prediction.

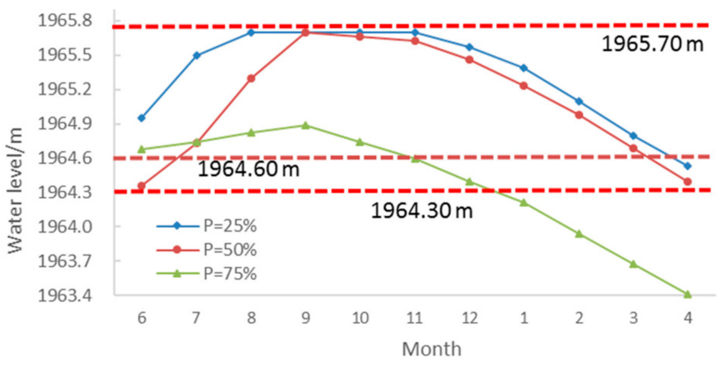

Figure 8. Monthly average water levels of Lake Erhai in 2025 under different hydrological flow levels.

For 2025, the prediction results of the two-dimensional hydrodynamic and water quality mathematical model are shown in Figure 9. The average annual concentrations of COD_{Mn}, TP, and TN in high-flow years were projected to be 3.79 mg/L, 0.026 mg/L, and 0.60 mg/L, respectively. The average annual concentrations of COD_{Mn}, TP, and TN in normal-flow years were 3.98 mg/L, 0.026 mg/L, and 0.59 mg/L, respectively. The average annual concentrations of COD_{Mn}, TP, and TN in low-flow years were 3.92 mg/L, 0.025 mg/L, and 0.57 mg/L, respectively. The overall water quality index of Lake Erhai was class III in high-, normal-, and low-flow years, and the most significant pollutant affecting the water quality class was TN. As shown in Figure 9, the concentrations of COD_{Mn} and TP from January to June and in December met the standard, and the concentration of TN from January to April met the standard.

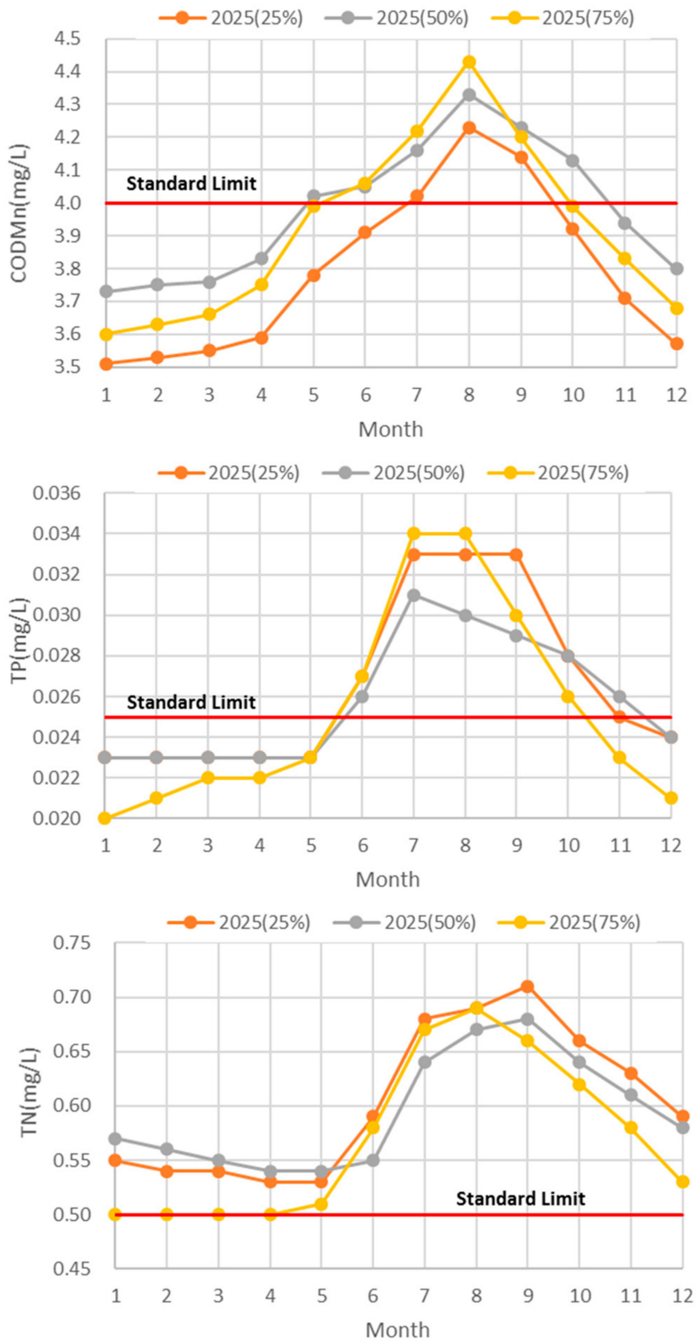

Figure 9. Monthly average concentrations of COD_{Mn}, TP, and TN in Lake Erhai in 2025 under different hydrological flow levels.

From the prediction results, if the "seven actions" and "eight key battles" measures for comprehensive water pollution control in the Erhai basin have been implemented and have begun to work, including pollution interception around the lake, the adjustment of planting structure, the replacement of chemical fertilizer with organic fertilizer, and the construction of ecological ponds, the concentrations of COD_{Mn}, TP, and TN will be considerably reduced by 2025. However, the prediction results also show that the pollutant concentrations of

Lake Erhai will exceed the standard by 2025, and these measures for comprehensive water pollution control in the Erhai basin cannot fundamentally improve the water quality of Lake Erhai. According to the research results of Lin et al. [31], the Erhai basin is influenced on a large scale by meteorological factors, causing the natural water resources of the Erhai basin to tend to decrease on the whole. Consequently, in this study we believe that the decrease in natural water resources is the main reason the pollutant concentrations of Lake Erhai will exceed the standard by 2025.

By 2025, the COD_{Mn}, TP, and TN concentration distribution in Lake Erhai from January to December in normal-flow years are shown in Figures 10–12, respectively. From the spatial distribution, the water quality in the southern lake was projected to be better than in the northern lake. From the time distribution, the water quality of Lake Erhai in winter and spring was projected to be better than in summer and autumn. These findings indicate that the introduction of a large quantity of agricultural non-point source pollutants into the lake is the main reason the water pollution concentrations exceed the standard in summer and autumn. Consequently, non-point source pollution still needs to receive greater attention in the near future.

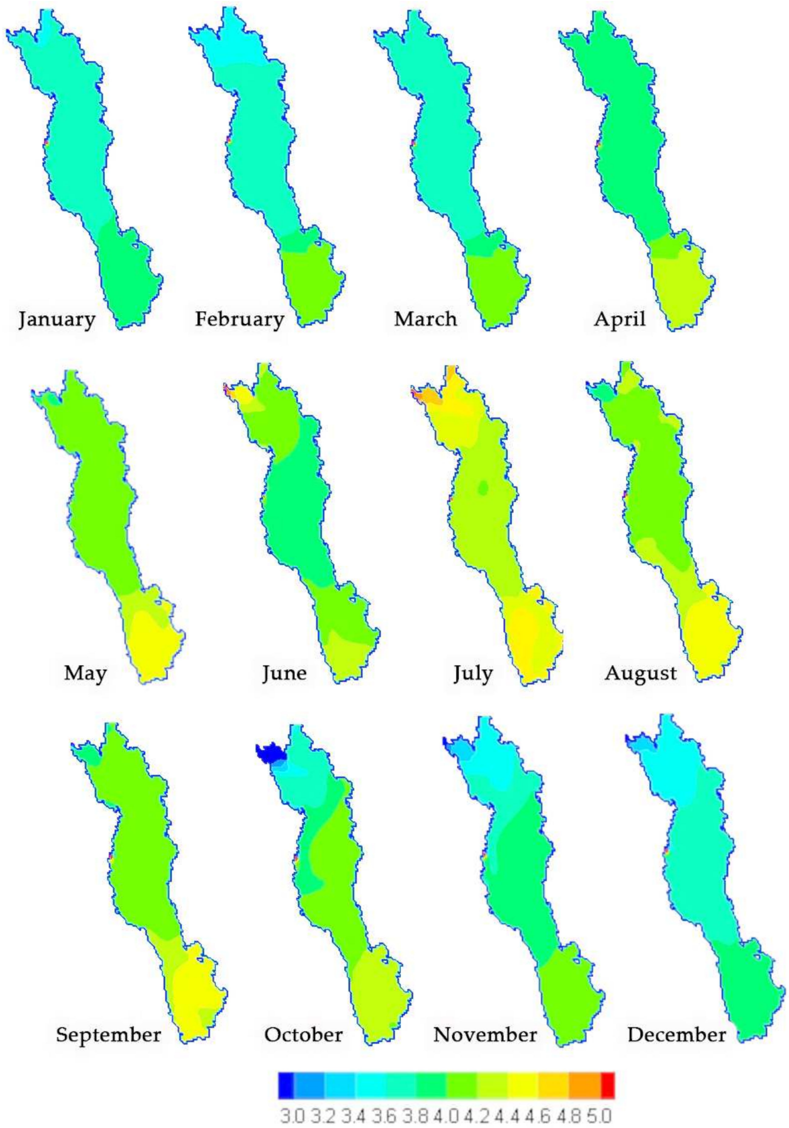

Figure 10. COD_{Mn} concentration distribution in Lake Erhai from January to December in normal-flow years by 2025.

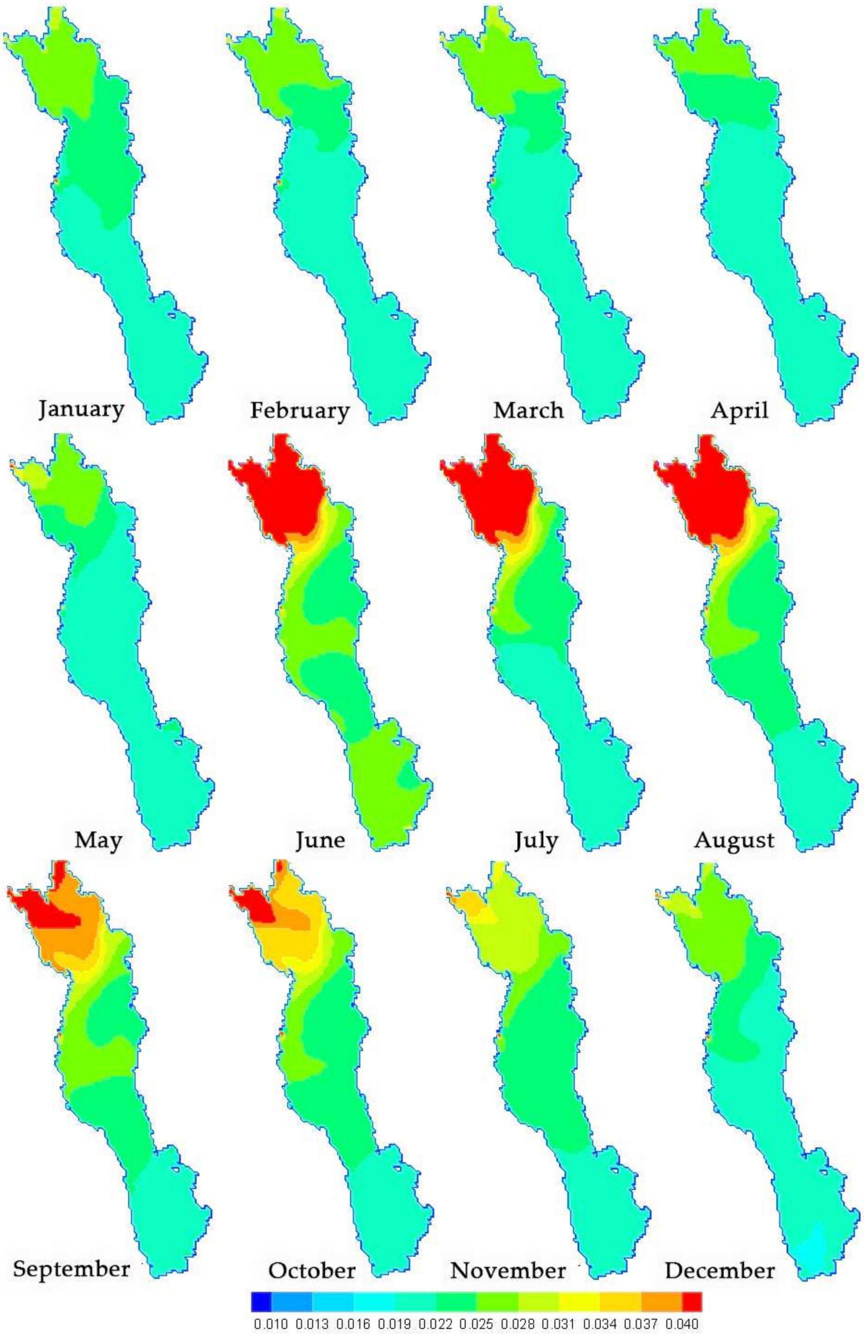

Figure 11. TP concentration distribution in Lake Erhai from January to December in normal-flow years by 2025.

In summary, Lake Erhai faces two problems: the reduction of natural water resources and the introduction of non-point source pollutants from agriculture. Based on the above research, this study suggests the following two water environmental protection measures for Lake Erhai: First, ecological ponds and wetlands [32,33] in lakeside zones should be constructed immediately and agricultural irrigation upgrades and renovations around the lake should be implemented as soon as possible in order to reduce non-point source pollutants entering Lake Erhai [34,35]. Second, the water quality of Lake Erhai can be continuously improved through the diversion of water from the outer basin, and the introduction of these pure water resources will be beneficial to the benign development of the aquatic ecosystem of Lake Erhai.

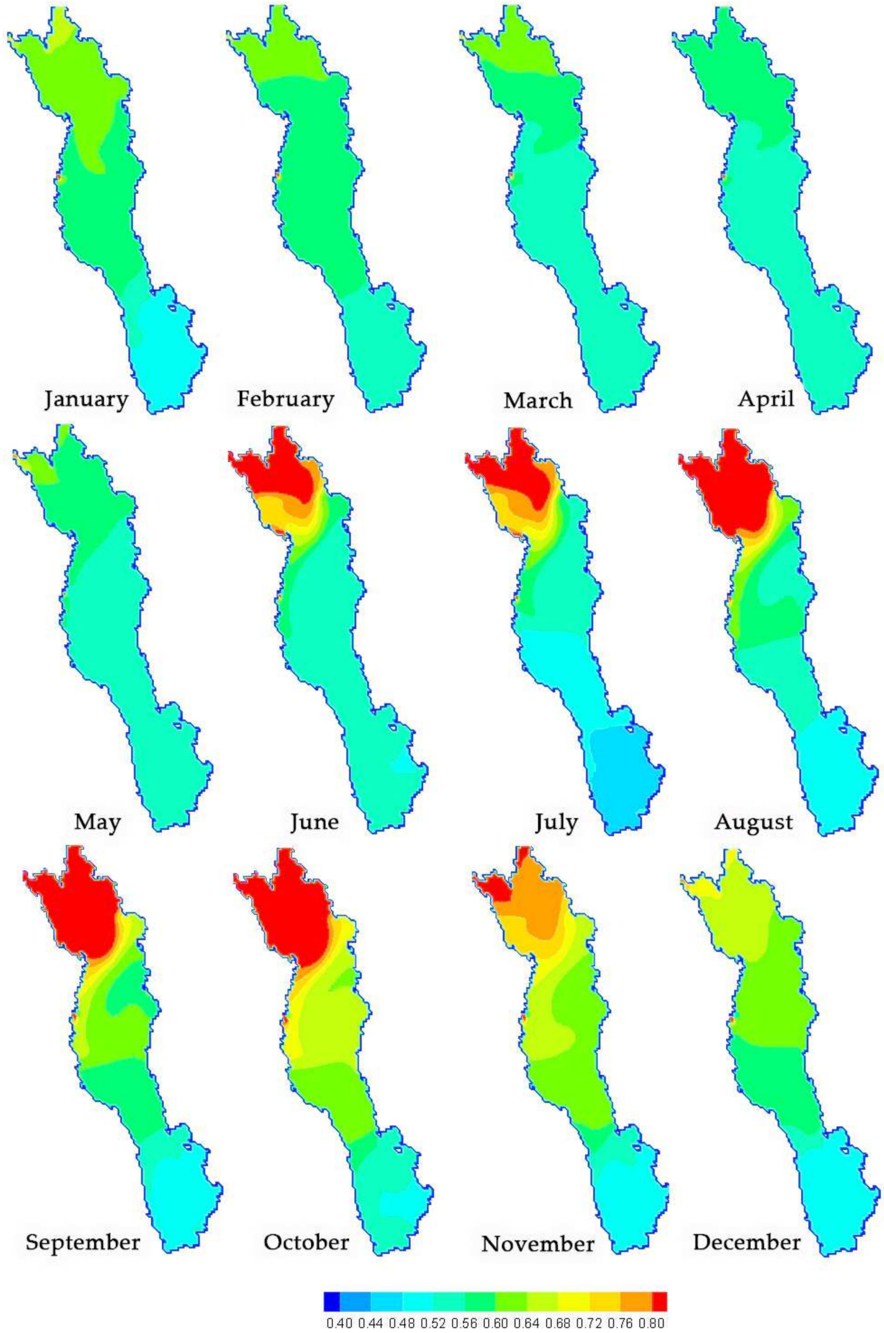

Figure 12. TN concentration distribution in Lake Erhai from January to December in normal-flow years by 2025.

4. Conclusions

Based on the water quality monitoring data from 2009 to 2019, a two-dimensional hydrodynamic and water quality mathematical model of Lake Erhai was constructed to predict the water quality of Lake Erhai in 2025 under different hydrological flow levels. The following three conclusions were drawn from this study.

1. According to the average annual concentrations of COD_{Mn}, TP, and TN in Lake Erhai, the concentration of TP decreased after 2016, but the concentrations of COD_{Mn} and TN showed an increasing trend. This was mainly because the protection measures implemented for Lake Erhai prevented TP from entering the lake. However, the pollution control measures did not have a noticeable effect on reducing COD_{Mn} and

TN concentrations due to the complex relationship between carbon and nitrogen inputs and water quality in Lake Erhai.
2. The water quality of Lake Erhai was better in winter and spring than in summer and autumn, and the southern lake water quality was better than the northern lake water quality. In summer and autumn, pollutants enter Lake Erhai with rainfall, which is the main reason why the water quality of Lake Erhai is better in winter and spring than in summer and autumn. The water quality of the southern lake is better than that of the northern lake because there are more agricultural enterprises and larger agricultural non-point sources adjacent to the northern lake. These findings indicate that non-point source pollution is still the main source of pollution in Lake Erhai, and rainfall is the main driving force of pollution exceeding the water quality standard.
3. Based on the prediction results, this study concluded that the water quality of Lake Erhai could not be fundamentally improved through the measures of the "seven actions" and "eight key battles" for comprehensive water pollution control in the Erhai basin. By 2025, the water quality of Lake Erhai will still fail to meet the Class II water quality standard due to the large quantity of non-point source pollutants entering the lake and the decrease in natural water resources in the basin. Finally, two recommendations were made, including supplementary non-point source pollution control measures and the diversion of water from external basins, which will promote the continuous improvement of water quality in Lake Erhai.

This study makes predictions based on the data already collected. To further analyze the effect of these measures on the protection of Lake Erhai, the collection of empirical data in the future will help improve our model.

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