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Evaluation of lake eutrophication under different hydrological connectivity conditions

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ABSTRACT

Lake eutrophication has become a significant water environmental issue worldwide. In order to further explore the mechanism of hydrologic connectivity on lake eutrophication and effectively control it, this study selected Poyang Lake, Junshan Lake, Chi Lake, Taibo Lake, and Yao Lake with varying degrees of hydrological connectivity in the Poyang Lake region as research subjects. The study utilized the comprehensive Trophic Level Index (TLI) method to assess the eutrophication of lakes. It also examined the impact of hydrological connectivity on eutrophication evaluation indices and the eutrophication state on a spatiotemporal scale. The results showed that the change in the hydrological period has little effect on the eutrophication of lakes, whether they are connected or obstructed. Except for Yao Lake, which was in a moderately eutrophic state (60, 70], the other four lakes were in a mildly eutrophic state (50, 60], consistent with the Trophic State Index (TSI) evaluation results. The eutrophication evaluation indices of obstructed lakes were significantly different from those of river-connected lakes. The change in eutrophication evaluation index of obstructed lakes was more likely to be influenced by human factors, whereas that of rivers-connected lakes was closely associated with hydrological connectivity. At present, there is a risk of a cyanobacteria bloom outbreak in Poyang Lake and its surrounding lakes. Therefore, this study suggests that strict control of point and non-point source pollution in the lake region, along with the scientific and reasonable formulation of a cultivation model, will effectively prevent lake eutrophication and cyanobacteria bloom outbreaks. This study provides theoretical support for investigating the mechanisms of lake eutrophication.

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Water connectivity; eutrophication evaluation; Poyang Lake region; cyanobacteria bloom; human activity

1. Introduction

As an important carrier of surface water, lakes have multiple functions such as regulating water, preventing floods, improving the environment, maintaining ecological balance, and

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purifying water (Zhang et al. 2023). However, with the input of nutrients, such as excessive nitrogen and phosphorus, lake eutrophication has posed a significant challenge for water environments worldwide. This not only causes serious harm to aquatic ecosystems but also has a notable impact on the biogeochemical cycle of carbon and other elements (Liu and Fang 2017; Ho et al. 2019). Studies have shown that 60% of the global lakes with an area of more than 25 km^2 are in a state of eutrophication. In China, over 85% of large lakes (with an area of more than 10 km^2) are in a eutrophic state (Wang et al. 2018). The middle and lower reaches of the Yangtze River feature a cluster of large shallow lakes, which are unparalleled globally (Guo et al. 2022). And there is no seasonal thermal stratification in these lakes (Zeng and Wu 2013). Eutrophication is more likely to occur in shallow lakes under human disturbance, and recovery is challenging once it sets in Qin et al. (2020). The lakes in the middle and lower reaches of the Yangtze River have become one of the regions with the highest levels of nutrients in China (Huang et al. 2020; Qin et al. 2023).

The harm of lake eutrophication mainly includes the following aspects: (1) The blooms of blue and green algae lead to turbid water and a significant decrease in transparency (Tarafdar et al. 2022). (2) Algae accumulation not only affects the landscape, but also releases a foul smell when it decays (Barna 2019). (3) Harmful algae (such as Microcystis, anabaena, etc.) can secrete or release toxins and harmful substances, posing a threat to the health of people and other organisms that consume the contaminated water (Watson et al. 2016; Veerman et al. 2022). (4) As a large quantity of algae die, it reduces the dissolved oxygen in the lake, leading to the death of aerobic aquatic animals due to oxygen depletion (Scavia et al. 2014; Watson et al. 2016). (5) Once the water reaches a eutrophic state, its natural ecological balance will be disrupted, leading to reduced stability and diversity of aquatic organisms, ultimately destroying the ecological equilibrium of the water body (Duan et al. 2022).

In order to improve the prevention and restoration of lake eutrophication, it is essential to conduct an accurate evaluation of the lake's eutrophication state. In this regard, numerous researchers have conducted extensive research and proposed a variety of methods and criteria based on environmental factors or aquatic organisms to assess the eutrophication status of lakes (Ding et al. 2021; Suresh et al. 2023). For example: (1) The characteristic method focuses on qualitative analysis but cannot accurately evaluate the true state of lake eutrophication. (2) The parameter method has poor applicability, and the evaluation criteria are formulated based on the lake situation in the study area. (3) The scoring method is often influenced by environmental factors beyond the evaluation criteria, leading to reduced accuracy in evaluation outcomes. (4) The phosphorus budget model has not been widely adopted due to its complex operation and analysis methods. (5) Biological assessment methods vary in their evaluation results depending on the aquatic biological groups selected in the same area (Yang et al. 2008; Sharifinia et al. 2016; Du et al. 2019; Zhang et al. 2021). Limited by the characteristics of these evaluation methods or their applicability, only a few methods have been widely used. Through extensive research, it has been determined that the comprehensive Trophic Level Index (TLI), which integrates five indices including total nitrogen, total phosphorus, chlorophyll-a, chemical oxygen demand, and transparency, is the most widely utilized method for evaluation and standardization (Zhang et al. 2021; Qian et al. 2023).

The lakes in the basin experience varying hydrological periods (wet season, normal season, and dry season) as a result of seasonal changes. During various hydrological periods, there are significant fluctuations in water level and lake area. Environmental factors like water temperature, chemical oxygen demand, dissolved oxygen, and pH directly or indirectly influence the concentration of nitrogen and phosphorus nutrients in the water, leading to fluctuations in lake eutrophication (Wang et al. 2015; Lan et al. 2023). In the same hydrological period, lakes with the same eutrophication state may exhibit varying eutrophication trends because of factors such as the duration of connection between lakes and rivers, water exchange capacity, and the quality of water entering the lakes (Wang et al. 2015; Yin et al. 2023). In order to effectively manage lake eutrophication, it is necessary to study the temporal and spatial evolution of this phenomenon. Therefore, based on the difference in hydrological connectivity between lakes and rivers, Poyang Lake, Junshan Lake, Chi Lake, Taibo Lake, and Yao Lake in the middle and lower reaches of the Yangtze River were chosen as the focus of the study. By monitoring and evaluating the eutrophication status of these five lakes in different hydrological periods, we explored the influence mechanism of hydrological connectivity on lake eutrophication. This study provides theoretical support for controlling lake eutrophication through hydrological regulation and a scientific basis for the protection and restoration of the lake water ecological environment in the middle and lower reaches of the Yangtze River.

2. Materials and methods

2.1. Study area

The study area is located in the northern part of Jiangxi Province, China, on the southern bank of the lower reaches of the Yangtze River. It experiences a subtropical humid monsoon climate with an average annual temperature of approximately 17 °C, abundant rainfall, and an average annual precipitation ranging from 1300 to 2150 mm (Jiangxi Water Resources Department 2009). Notably, Poyang Lake stands is China's largest freshwater lake and a significant shallow lake within the Yangtze River basin (Liu and Fang 2017; Li et al. 2019). A strong interaction exists between the Yangtze River and Poyang Lake. Annually, water from the Yangtze River replenishes Poyang Lake from April to June, while water from Poyang Lake recharges the Yangtze River between July and October (Xu et al. 2024). Junshan Lake lies on the southern bank of Poyang Lake as a sub-lake connected through a gate but not linked to the Yangtze River (Jiangxi Water Resources Department 2009). Chi Lake is located in the northwest of Poyang Lake and connects with the Yangtze River (Cao et al. 1999; Jin and Tu 1990). Taibo Lake is located in the northeast of Poyang Lake. It was formed by water accumulation in an abandoned ancient riverbed of the Yangtze River and is also connected to this river system (Cao et al. 1999; Zhang et al. 2021). Yao Lake is an urban lake situated in the southwest of Poyang Lake, with no connection to the Yangtze River (Cao et al. 1999; Jiangxi Water Resources Department 2009). Detailed information about Poyang Lake and its four surrounding lakes can be found in Table 1.

2.2. Data sources and data analysis

In the present study, samples were collected from the aforementioned five lakes during both the wet and dry seasons. The samples in the wet season were collected from August 11 to August 20, 2012, and the dry season samples were collected from April 24 to April 27, 2013. A total of 35 monitoring points were used in Poyang Lake during the wet season, while 23 monitoring points were used during the dry season. In addition, four monitoring points were used in Jushan Lake, three in Chi Lake, three in Taibo Lake, and four in Yao Lake. Figure 1 shows the locations of the monitoring points.

In order to ensure the representativeness and reliability of the samples, a 5 L upright Plexiglass sampler was used to collect 500 ml of water samples from 0.5 m below the lake surface and the same amount from 0.5 m above the lake bottom. Then, the surface and

Table 1. The characters of the lake form around Poyang Lake.

Lake	Longitude (N)	Latitude (E)	Length × Width (km × km)	Average depth (m)	Water level (m)	Water area (km^2)	Connectivity
Poyang Lake	28°22′–29°45′	115°47′–116°45′	173 × 18.6	7.38	22.67	3150	Rivers-connected lake
Junshan Lake	28°24′–28°38′	116°15′–116°28′	25 × 7.7	4.5	18	184	Obstructed lake
Chi Lake	29°44′–29°50′	115°37′–115°45′	12 × 6.7	2.8	16	47.1	Rivers-connected lake
Taibo Lake	29°58′–30°02′	116°43′–116°44′	13 × 1.6	5.0	15.5	20.7	Rivers-connected lake
Yao Lake	28°38′–28°44′	116°01′–116°04′	7 × 1.4	2.5	18.7	14.9	Obstructed lake

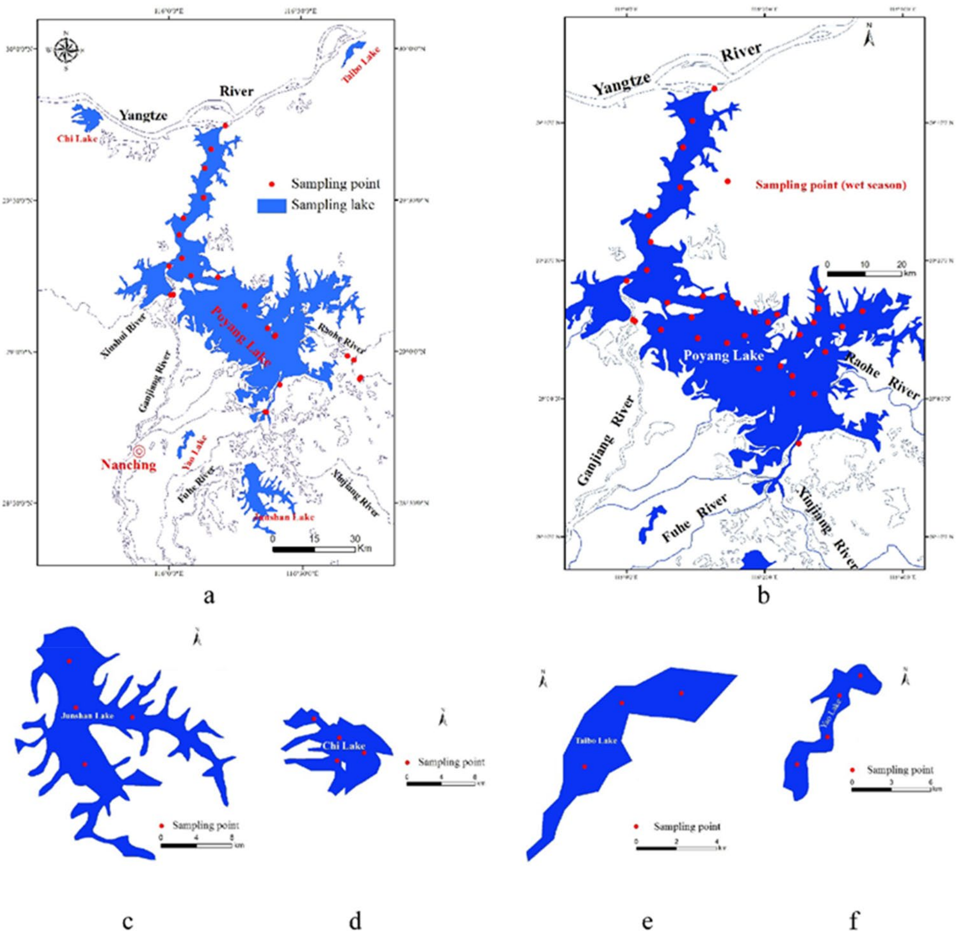

Figure 1. Sketch of the location and sampling points of the Lakes round Poyang Lake region. ((a) The location and sampling points during dry season in Poyang Lake. (b) The location and sampling points during wet season in Poyang Lake. (c) Sketch of the sampling points of Junshan Lake. (d) Sketch of the sampling points of Chi Lake. (e) Sketch of the sampling points of Taibo Lake. (f) Sketch of the sampling points of Yao Lake.).

bottom water samples are mixed and stored in a 1 L polyethylene bottle. Finally, the collected water samples were placed in a refrigerator with ice or dry ice and transported back to the laboratory. The index was determined within 24 h.

Except for transparency, which was measured directly in the field using the Secchi disk, other indices were measured in laboratory experiments. The water samples collected from the field were divided into unfiltered and filtered samples. Total phosphorus (TP), total nitrogen (TN) and chemical oxygen demand (COD_{Mn}) were measured in unfiltered samples. The concentration of total nitrogen in water was determined using alkaline potassium persulfate digestion ultraviolet spectrophotometry, while the concentration of total phosphorus in water was determined through ammonium molybdate spectrophotometry. The analysis of COD_{Mn} is based on the potassium dichromate ($K_2Cr_2O_7$) method, and the optimal operating temperature is approximately 160 °C. The detailed operations followed the detection and analysis method for water and wastewater (fourth edition) (State Environmental Protection Administration Water and Wastewater Monitoring and Analysis Methods Editorial Committee, 2002). The remaining water samples were filtered using a 0.45 μm mixed fiber filter membrane. The concentration of chlorophyll a was determined through spectrophotometry after extracting the filter membrane with 95% ethanol, following lake eutrophication survey specifications (second edition) (Jin and Tu 1990).

Comprehensive Trophic Level Index (TLI). The method of Jini (Gao et al. 2012) was utilized in this study. The TLI ranges from approximately 0–100, representing the trophic state of a lake. The trophic state values range from Oligotrophic (<30), Mesotrophic (≤50), Eutrophic (>50), Light eutrophic (≤60), Middle eutrophic (≤70), to Hyper eutrophic (>70). The TLI of the various trophic state variables was calculated using the following equations.

$$TLI(\Sigma) = \sum_{j=1}^{m} W_j \cdot TLI(j) \tag{1}$$

$$W_j = r_{ij}^2 \Big/ \sum_{j=1}^{m} r_{ij}^2 \tag{2}$$

$$TLI(Chla) = 10(2.5 + 1.086\ln(Chla)) \tag{3}$$

$$TLI(TP) = 10(9.436 + 1.624\ln(TP)) \tag{4}$$

$$TLI(TN) = 10(5.453 + 1.694\ln(TN)) \tag{5}$$

$$TLI(SD) = 10(5.118 + 1.94\ln(SD)) \tag{6}$$

$$TLI(COD_{Mn}) = 10(0.109 + 2.661\ln(COD_{Mn})) \tag{7}$$

where *TLI* is the Trophic Level Index; w_j is the related weight of the number *j* parameter, it is calculated by Equation (2); r_{ij} is the correlation coefficient between the number *j* parameter and Chl-a; *TLI* (*j*) is the euTrophic Level Index of the number j parameter; *m* is the number of the parameters; *Chl-a* is the chlaorophyll-a (mg/m^3); *TP* is the total phosphorus (mg/L); *TN* = total nitrogen (mg/L); *SD* is the Transparency (m); COD_{Mn} is the permanganate index (mg/L).

The five parameters and eutrophication index used for eutrophication evaluation were presented in the form of mean ± standard deviation. Before comparing data differences, Shapiro–Wilk and Bartlett tests were performed to assess the normal distribution and homogeneity of variance for each variable. When the assumptions of normal distribution and homogeneity of variance were met, a *t*-test was used to compare two variables, while Tukey's Honestly Significant Difference (HSD) method was employed for pairwise comparisons involving more than two variables (Ni and Li 2022). If the assumptions of normality and homogeneity of variance are not met, the Kruskal–Wallis non-parametric test and the Wilcoxon test were used for pairwise comparisons. The p-values were adjusted using the Bonferroni correction (Fouché et al. 2020). The above analyses and drawings were conducted using RStudio 1.4.1717 (R 4.1.0) software (http://www.r-project.org).

3. Results and analysis

3.1. Comparative analysis of eutrophication evaluation indices of Lakes in different hydrological periods

The lake eutrophication indicators in the wet and dry seasons were comparatively analyzed (Figure 2). During the wet season, SD values of each lake in descending order were as follows: Chi Lake, Junshan Lake, Poyang Lake, Taino Lake and Yao Lake. Among them, Junshan Lake had the largest SD, reaching 1.47 m, while Yao Lake had the lowest SD at only 0.29 m. Compared with the wet season, SD value decreased significantly during the dry season ($p < 0.05$), except forYao Lake (Figure 2a). The SD of Chi Lake was 0.77 m, decreasing by 47.6%, but it was still the largest among the lakes.

During the wet season, TN concentration in each lake ranged from 0.52 to 1.36 mg/L. The highest TN concentration was in Taibo Lake, followed by Yao Lake, Poyang Lake, Junshan Lake, and Chi Lake. During the dry season, there was an increase in TN concentration in each lake, ranging from 0.99 to 3.25 mg/L. Specifically, Taibo Lake increased by 58.2% and Junshan Lake increased by 24.1%. The sequence changed to Taibo Lake, Chi Lake, Yao Lake, Poyang Lake, and Junshan Lake (Figure 2b).

During the wet season, the TP concentration of each lake ranged from 0.03 mg/L to 0.16 mg/L. In descending order, the sequence was as follows: Yao Lake, Taibo Lake, Junshan Lake, Poyang Lake, and Chi Lake. During the dry season, the TP concentration exhibited an increasing trend, ranging from 0.06 to 0.19 mg/L. The sequence changed to Taibo Lake, Poyang Lake, Yao Lake, Chi Lake, and Junshan Lake (Figure 2c).

During the wet season, the COD_{MN} concentration in each lake ranged from 2.23 to 7.65 mg/L, with Yao Lake having the highest concentration and Poyang Lake the lowest among them. During the dry season, the COD_{MN} concentration ranged from 2.11 to 3.42 mg/L. Besides Chi Lake, the concentration of COD_{MN} in the other four lakes decreased compared to the wet season. Among them, Yao Lake and Junshan Lake showed the most significant decreases ($p < 0.05$), with reductions of 62.6% and 57.5%, respectively (Figure 2d).

Chl-a concentration in each lake ranged from 1.95 to19.56 mg/m^3 during the wet season. The lakes, from highest to lowest concentration, were Taibo Lake, Yao Lake, Poyang Lake, Chihu Lake, and Junshan Lake. During the dry season, the Chl-a concentration was in the range of 1.70–24.22 mg/m^3, from high to low, were as follows: Yao Lake, Chihu Lake, Taibo Lake, Poyang Lake, and Junshan Lake. The concentration of Chl-a in different lakes did not exhibit regular changes between various hydrological periods. Specifically, the concentration of Chl-a in Poyang Lake, Junshan Lake, and Taibo Lake decreased during the dry season, while that in Chihu Lake and Yao Lake increased (Figure 2e).

3.2. Comparative analysis of eutrophication evaluation indices among five lakes

In order to further explore the spatial differences in eutrophication evaluation indices among the five lakes, it was found that the eutrophication evaluation indices of the two

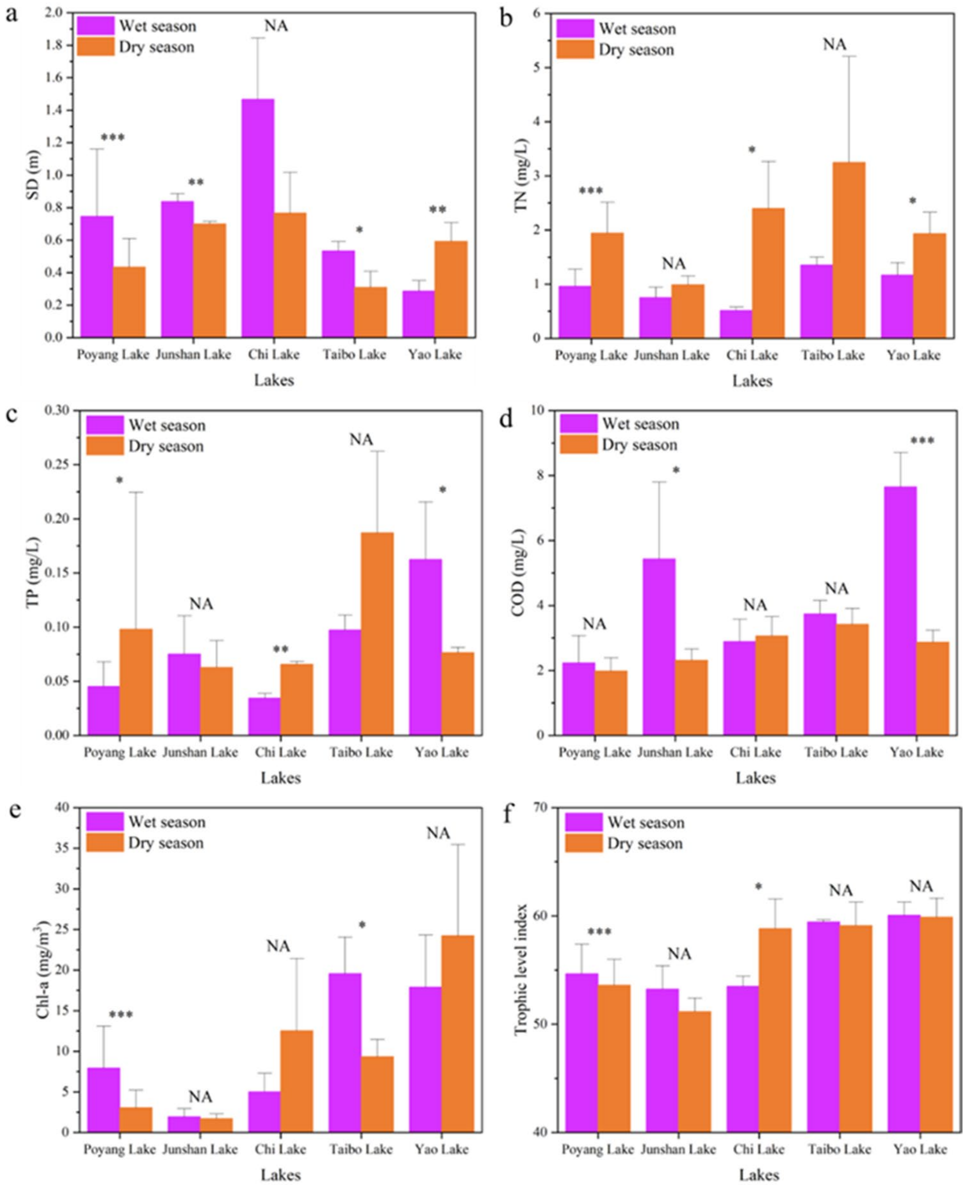

Figure 2. The eutrophication evaluation indicators of the lakes around Poyang Lake region in dry and wet season.

obstructed lakes, Junshan Lake and Yao Lake, had the largest differences compared to those of the other connected lakes (Table 2) through a comparative analysis between the lakes. Among them, the relatively high concentration of SD and relatively low concentrations of TN in Junshan Lake were the main reasons for the significant differences between Junshan Lake and the other four lakes ($p < 0.05$). The relatively high concentrations of CODMn and Chl-a in Yao Lake were the main reasons for the significant differences between Yao Lake and the other four lakes ($p < 0.05$). The eutrophication evaluation indices of Poyang Lake, Taibo Lake, and Chihu Lake, which were connected to the Yangtze River, show little difference.

Table 2. Analysis of significant difference of eutrophication evaluation indices among lakes around Poyang Lake.

Lake	Transparency (m)	Total nitrogen (mg/L)	Total phosphorus (mg/L)	Permanganate index (mg/L)	Chlorophyll-a (mg/m^3)
Poyang Lake	Junshan (0.005); Chi (<0.001)	Junshan (0.004); Taibo (0.001)	Taibo (0.019)	Junshan (<0.001); Chi (0.021); Taibo (<0.001); Yao (<0.001)	Taibo (0.001); Yao (<0.001)
Junshan Lake	Poyang (0.005); Chi (0.017); Taibo (0.017); Yao (0.015)	Poyang (0.004); Chi (0.032); Taibo (<0.001); Yao (0.009)	Taibo (0.045)	Poyang (<0.001); Chi (0.049); Yao (0.002)	Chi (0.033); Taibo (<0.001); Yao (<0.001)
Chi Lake	Poyang (<0.001); Junshan (0.017); Taibo (<0.001); Yao (<0.001)	Junshan (0.032); Taibo (0.006);	Taibo (0.019);	Poyang (0.021); Junshan (0.049); Yao (<0.001)	Junshan (0.033); Yao (0.001)
Taibo Lake	Junshan (0.017); Chi (<0.001)	Poyang (0.001); Junshan (<0.001); Chi (0.006); Yao (0.008)	Poyang (0.019); Junshan (0.045); Chi (0.019)	Poyang (<0.001); Yao (0.001)	Poyang (0.001); Junshan (<0.001); Yao (0.041)
Yao Lake	Junshan (0.015); Chi (<0.001)	Junshan (0.009); Taibo (0.008)		Poyang (<0.001); Junshan (0.002); Chi (<0.001); Taibo (0.001)	Poyang (<0.001); Junshan (<0.001); Chi (0.001); Taibo (0.041)

Table 3. Trophic level index values assessment of the lakes round Poyang Lake.

Lake	Trophic level index		
	Wet season	Dry season	Year
Poyang Lake	54.65 ± 2.74	53.61 ± 2.39	54.81 ± 2.66
Junshan Lake	53.26 ± 2.15	51.16 ± 1.26	52.41 ± 1.88
Chi Lake	53.50 ± 0.94	58.83 ± 2.75	57.11 ± 3.23
Taibo Lake	59.44 ± 0.22	59.10 ± 2.17	59.78 ± 1.44
Yao Lake	60.07 ± 1.21	59.89 ± 1.76	60.53 ± 1.40

Statistical significance was determined at $p < 0.05$. The index in the parentheses showed the significant factor.

3.3. Evaluation results of lake eutrophication in Poyang Lake region based on TLI

The eutrophication index method was used to evaluate the eutrophication of the five lakes (Table 3). The results showed that in the wet season, except for Yao Lake, which showed middle eutrophic ((60,70]), the other four lakes were characterized by light eutrophic ((50,60]). The eutrophication levels from high to low were Yao Lake, Taibo Lake, Poyang Lake, Chihu Lake, and Junshan Lake. During the dry season, the five lakes exhibited light eutrophication ((50,60]), ranked from highest to lowest as Yaohu Lake, Taibo Lake, Red Lake, Poyang Lake, and Junshan Lake. Comparing the eutrophication index of the five lakes during the dry season and wet season, it was found that, except for Chihu Lake, the eutrophication index of the other four lakes decreased during the dry season. Throughout the year, the eutrophication status of the lakes remained consistent with that of the wet season. However, only Yao Lake exhibited middle eutrophic state ((60,70]).

Through a comparative analysis of the eutrophication indices of the five lakes during various hydrological periods, it was observed that among the three lakes connected to the Yangtze River, Poyang Lake and Chihu Lake exhibited significantly different eutrophication indices during the two hydrological periods ($p < 0.05$). In contrast, Junshan

Lake and Yao Lake, which were isolated from the Yangtze River, did not show significant differences in eutrophication indices between the two hydrological periods (Figure 2f).

4. Discussion

It can be seen from Figure 2a–e that the eutrophication evaluation index changed with hydrological period. In the five lakes, SD and COD_{Mn} levels increased during the wet season compared to the dry season, while TN concentration decreased during the wet season compared to the dry season. The change of TP concentration may be related to the hydrological connectivity of the lakes, but no significant change was found in the Chl-a concentration. In the wet season, the water level of the lake rises, increasing the amount of water and improving the water transparency of the lake (Pin et al. 2019; Yang et al. 2021). The concentration of TN in the five lakes was higher in the dry season than in the wet season, a trend also observed in the studies of other lakes in the middle and lower reaches of the Yangtze River (Wang et al. 2012; Wang et al. 2014). The reason for this phenomenon may be that the increase in lake water volume during the wet season dilutes the nutrients in the water body (Yang et al. 2021). During the wet season, elevated water temperatures would enhance the growth and decomposition of plankton, submerged plants, and microorganisms in the water. This process led to an increase in organic matter in the lake, ultimately resulting in higher levels of COD_{Mn} (Zhang et al. 2009; Guo et al. 2021). In this study, it was found that the TP concentration in Poyang Lake, Taibo Lake and Chi Lake, which were connected to the Yangtze River, decreased during the wet season. In contrast, the TP concentration in Junshan Lake and Yao Lake, which were isolated from the Yangtze River, increased during the wet season. There may be two reasons for this phenomenon: (1) The nutrient concentration in connected lakes would be diluted by the water backflow of the Yangtze River (Wang et al. 2014); (2) Higher water temperature in the wet season contributed to the release of phosphorus from lake sediments (Liu et al. 2020), but obstructed lakes could not exchange water with rivers, resulting in increased TP concentration in lakes. Chl-a concentration was one of the crucial components of phytoplankton, and the growth of phytoplankton was influenced by water temperature, flow rate, and nutrient salts (Evangelia et al. 2018). However, the varying trends of different environmental factors during wet and dry seasons resulted in distinct variations in the concentration of Chl-a in the five lakes studied.

Due to regional geographical characteristics, natural climate conditions, aquatic ecosystems, and pollution characteristics, there would be different eutrophication statuses of water bodies (Xiong et al. 2016). Studies have shown that when the concentration of total phosphorus and total nitrogen in water reached 0.02 and 0.2 mg/L, respectively, cyanobacteria bloom phenomenon may occur in lakes (Håkanson and Lindgren 2008; Melendez et al. 2019). According to the results of this study, these five lakes already had the nutrient conditions necessary for a cyanobacteria bloom outbreak. Among the five lakes, only Yao Lake was in a moderately eutrophic state, which was considered the highest level. This was mainly due to the fact that Yao Lake was an urban lake with a significant aquaculture presence. The lake faces considerable pollution from surrounding point sources, and the release of aquaculture bait further elevates the concentration of nutrient salts in Yao Lake. Additionally, the limited exchange with other rivers contributed to its eutrophic state (Liu et al. 2010; Jiang et al. 2013; Li 2023). Poyang Lake, Taibo Lake, and Chi Lake were connected or semi-connected to the Yangtze River. The eutrophication evaluation index of Taibo Lake and Chi Lake was similar, and both were higher than that of Poyang Lake. This difference may be attributed to the aquaculture practices in Taibo Lake and Chi Lake. The input of food would inevitably increase the nutrient concentration of nitrogen and phosphorus, resulting in an increase in the eutrophication degree of the lake. In addition, Poyang Lake had higher connectivity with the Yangtze River and more frequent water exchange, which was not conducive to the accumulation of nutrients (Cao et al. 1999; Li et al. 2020; Liu et al. 2023). Junshan Lake had the lowest eutrophication evaluation index. Originally, it was a lake with grassy surroundings, and its water quality met the Class II standard. However, due to the expansion of aquaculture areas and the barriers created by the construction of dams, it has been transformed into a grass-type lake (Fan et al. 2012; Huang et al. 2022). Although Junshan Lake had become a eutrophic lake, its water quality was relatively better compared to other lakes (Liu et al. 2014). Based on the study content above, it can be inferred that obstructed lakes in a eutrophication state were more susceptible to human interference, whereas rivers-connected lakes' eutrophication state was closely linked to hydrological connectivity.

In general, the most significant differences in the eutrophication evaluation indices and eutrophication states were observed between Junshan Lake and Yao Lake, which were isolated from the Yangtze River and other interconnected lakes. Meanwhile, the eutrophication evaluation indices of the three lakes connected to the Yangtze River were similar to each other (Tables 2 and 3). These findings reflect the influence of hydrological connectivity on environmental factors and eutrophication in lakes (Mayora et al. 2013; Li et al. 2020; Pan et al. 2022). Similarly, in Poland, lakes connected to the Bug River were found to have significantly higher concentrations of nutrients and chlorophyll than lakes that were obstructed (Kufel and Leśniczuk 2014). Comparing lakes in Albania and Czechia, it has been found that the eutrophication state of lakes connected with rivers shows similarity (Šlachtová et al. 2023). In summary, lake eutrophication and hydrological connectivity are closely linked.

5. Conclusion

In this study, the eutrophication levels of Poyang Lake and four surrounding lakes were assessed using a comprehensive evaluation method based on eutrophication indices. The results showed that except for Yao Lake, which was in a state of moderate eutrophication, the other four lakes were in a moderate eutrophication state. The nutritional conditions of Poyang Lake and its surrounding lakes may contribute to the outbreak of cyanobacteria blooms. In addition, the eutrophication of obstructed lakes is more likely to be influenced by human factors, while the eutrophication of river-connected lakes is closely related to hydrological connectivity.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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