Dynamics of TP Load in the Largest Freshwater Lake of China in the Past Decade

Hua Wang[1,2*], Fang Cui[1,2], Yi Wu[1,2], Jiale Li[1,2], and Yiran Zhu[1,2]

[1]Key Laboratory of Integrated Regulation and Resource Development on Shallow Lake of Ministry of Education, College of Environment, Hohai University, Nanjing 210098, China
[2]College of Environment, Hohai University, Nanjing 210098, China
Email: wanghua543543@163.com (H.W.); cuifang1678@163.com (F.C.); 2091484186@qq.com (Y.W.); ljl2990696337@icloud.com (J.L.); zyr20001123@icloud.com (Y.Z.)
*Corresponding author
Manuscript received July 14, 2023; revised August 23, 2023; accepted September 29, 2023; published April 17, 2024

Abstract—**In order to reveal the evolution of TP pollution in Poyang Lake and the driving mechanism, this paper analyses the TP concentration in Poyang Lake during the period of 2012–2022 based on Mann-Kendall test and Pearson coefficient method combined with exogenous influencing factors. Results revealed that (1) Trends of interracial TP concentration in Poyang Lake varied significantly, with peaks of 0.115, 0.293 to 0.05 mg/L in 2014 and troughs of 0.032, 0.003 to 0.002 mg/L in 2019 at each lake area. However, TP in The South Lake was the opposite. The spatial distribution pattern of TP concentration in Poyang Lake showed that The Middle Lake (0.083 mg/L) > North Lake (0.069 mg/L) > South Lake (0.053 mg/L), and there were correlations among the Middle Lake, North Lake to South Lake. TP concentration in Middle Lake was significantly and positively correlated with the TP concentration of Gan Jiang (*r*1=0.322), and TP concentration in Middle Lake and North Lake was also significantly correlated with the TP concentration of Rao River (*r*2=0.446, *r*3=0.537). Whereas, TP concentration in North Lake and South Lake were less affected by the rivers. This study thoroughly analyzed the changes in TP concentration in Poyang Lake during the last decade to view its space-time distribution pattern and the driving mechanism of multiple factors. Research results would facilitate to better understating the variation of TP concentration and supply the scientific bases for water resources management and protection in Poyang Lake.**

Keywords—**Poyang Lake, Mann-Kendall method, total phosphorus, trend, space-time distribution**

I. Introduction

Water eutrophication has been a globally highlighted environmental issue, especially in shallow lakes [1]. Excessive phosphorus loads in lake water have been closely interlinked with eutrophication [2]. Consequently, Phosphorus serves as the key limiting nutritional compound for lake-based primary productivity control [3]. Algal blooms exist in about 43% of lakes worldwide according to survey data [4], with the highest number of algal bloom lakes in North America and Asia [5]. Among 204 lakes (reservoirs) with monitored trophic status in China, moderate eutrophication represented 5.9% and slight eutrophication 24%, as noted in the State of the Environment in China (2022). Furthermore, previous studies have illustrated that TP concentrations in Chinese lakes (35.83 μg/L) are much higher than those in European lakes (19.38 μg/L) [6]. Thus, discussing the evolution trend of total phosphorus concentration has great significance for lake ecological improvement and warning of eutrophication hazards in aquatic bodies.

Artificial factors (industrial activities, agricultural fertilizers, etc.) along with watershed factors (land use, geomorphic features, etc.) might have direct impacts on water quality in lakes, streams, and wetlands [7]. Shiferaw *et al*. [8] identified agriculture and urban pollution as major pollution sources by the PMF method, identifying TP as limiting nutrients for algal blooms in Geum River. Different types of land use have a greater impact on phosphorus pollution from waters [9]. Mid- to high-latitude lake eutrophication has been linked with low overall rainfall and intensified human activities [10]. Currently, scholars focus on uncovering the sources of TP exceeding standards in rivers and lakes, together with proposals for corresponding protection and remediation measures for aquatic pollution. Further, at the present stage, for the analysis of water quality status trend, most of the water quality assessment studies are based on limited years, for example, some scholars invert the water quality of Ebenezer Lake basin based on Sentinel-2 MSI data in 2016 [11]; use the single factor pollution index method and Nemerow pollution index method to evaluate the water quality during 2019–2021 [12]; and comprehensive evaluation of water quality in the Sha ying River from 2013–2014 by harmony degree equation (WQA-HDE) method, but there are few studies related to the changes in the sequence of water quality factors over a long period. Regarding the study of TP pollution in Poyang Lake, the current study mainly focuses on the phosphorus content and distribution characteristics of surface sediments [13–15], the phosphorus release characteristics of the dominant plant litter in the watershed [16, 17] and the TP contribution weights of upstream rivers entering the lake [18], there are fewer analyses of TP evolution in the lake area of Poyang Lake, and the time series of the study is relatively short [19], which is insufficient to explain the long-term TP changes in the lake. In addition, there is no relevant study to investigate the driving mechanism of the upstream river on the TP changes in Poyang Lake, and this study fills the gap between the study of the long-term TP trend of the lake and the driving mechanism.

As the typical through-river lake in the mid-and lower reaches of the Yangtze River basin [20], and also the largest freshwater lake in China, the freshwater resources and wetland ecosystem of Poyang Lake serve as important functions for maintaining eco-balance and sustainable development of Poyang Lake and the surrounding areas. In the 1970s–1980s, water quality monitoring was advanced in China, aiming to investigate, utilize, and protect priority water resources, as well as long-term water qualitative

doi: 10.18178/ijesd.2024.15.2.1473

evolution. Poyang Lake was among the initial water quality monitored areas [21]. Nevertheless, following the rapid economic development in the lake area, the TP pollution problem of Poyang Lake has gradually become prominent. Since phosphorus is the most critical nutrient limiting the productivity of lakes [22], excessive phosphorus loading can cause a series of problems threatening the health of the aquatic ecosystems such as algal outbreaks and water quality deterioration, leading to the TP pollution becoming an important factor restricting the economic and social development of the watershed [23, 24], so the TP pollution in Poyang Lake has become an urgent water environment problem [25]. In the meanwhile, the water quality of Poyang Lake is related to the water quality of the rivers entering the lake, and the nutrient input from the rivers upstream of the lake is the main source of the nutrient load of Poyang Lake, which accounts for about 80% [26]. Therefore, based on the monthly water quality data and specific monitoring sites from 2012 to 2022, the following work was carried out: (1) Mann-Kendall series analysis was used to explore the temporal trend of TP concentration in different lake areas within Poyang Lake, and to reveal the details of the evolution of TP concentration in the whole lake in the past 10 years; (2) correlation analysis was used to calculate the correlation coefficients of TP concentration between different lake areas, and to analyse the correlation of TP concentration between lake areas and explain the reasons for the correlation; (3) The runoff volume into the lake, TP concentration and TP load of the river upstream of the lake were selected as the driving factors for the change of TP concentration in the lake, and the driving mechanism of the change of TP concentration in the lake was discussed. The results of this study reveal the development and influence mechanism of TP in Poyang Lake from various aspects, which can provide scientific references for the subsequent management of TP pollution in this lake.

II. Materials and Methods

A. Study Area

Poyang Lake (28°24′–29°26′N, 115°49′–116°46′E) is the largest freshwater lake in China, located in the middle and lower reaches of the Yangtze River (Fig. 1). The lake joins the southern bank of the Yangtze River at its northern Hukou, and the western, southern, and eastern parts of the lake receive water from five rivers: Xiu Shui Rivers, Gan Jiang, Fu He, Xin Jiang, and Rao He [27]. The basin area of Poyang Lake is approximately 1.622×10^5 km^2, approximately 9% of the Yangtze River basin, and the discharge is approximately 1.427×10^{11} m^3 per year, accounting for 15.5% of the average runoff of the Yangtze River [28]. The hydrological situation of the lake is characterized by obvious cyclical changes, with lake levels varying regularly from year to year in response to seasonal cycles of rise and fall [29]. Meanwhile, Poyang Lake is included in the "List of Wetlands of World Importance" as a wetland of international importance, with a large area of lakeshore grassland and rich wetland biological resources, that have worldwide ecological value [30]. There are 11 protected areas in the lake, including Poyang Lake National Nature Reserve and Poyang Lake Nanji Wetland National Nature Reserve, which support the wintering of many endangered birds such as white cranes, cygnets, and wild geese, and almost the entire global population of white cranes (over 99%) winters in Poyang Lake [31]. In addition, the lake is also an important habitat for the endangered Yangtze finless porpoise, which accounts for about 1/4 to 1/3 of its entire population in the lake [32].

Poyang Lake plays an important role in the regulation of water resources and the maintenance of ecological balance in water [33]. However, in recent decades, the water quality of Poyang Lake has been declining significantly, and many water quality monitoring indicators have seriously exceeded the standard, especially the nutrient concentration, and the lake has gradually changed from a mesotrophic state to an eutrophic state [34]. Eutrophication of lakes is considered to be one of the causes of algal outbreaks, which often lead to deterioration of water quality, health threats to aquatic organisms, and socio-economic losses, such as in the aquaculture industry [35].

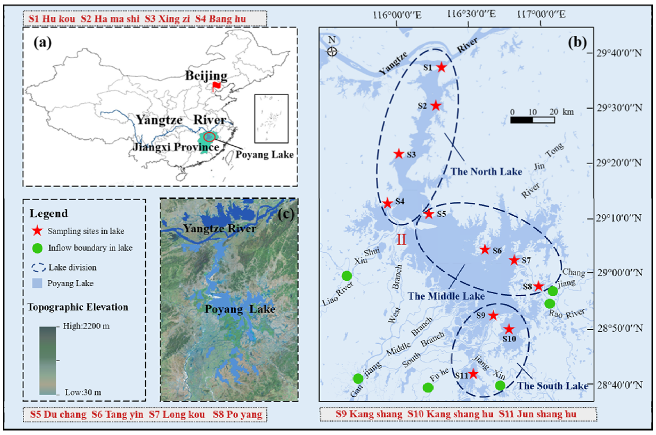

Fig. 1. Distribution of study area: (a) Location of Poyang Lake; (b) point map of Poyang Lake; (c) point map of Poyang elevation map of Poyang Lake.

Poyang Lake plays an important role in the regulation of water resources and the maintenance of ecological balance in water [33]. However, in recent decades, the water quality of Poyang Lake has been declining significantly, and many water quality monitoring indicators have seriously exceeded the standard, especially the nutrient concentration, and the lake has gradually changed from a mesotrophic state to an eutrophic state [34]. Eutrophication of lakes is considered to be one of the causes of algal outbreaks, which often lead to deterioration of water quality, health threats to aquatic organisms, and socio-economic losses, such as in the aquaculture industry [35].

B. Data Source

In this study, Poyang Lake was divided into three lake areas according to the topography: The North Lake, The Middle Lake, and The South Lake, and water quality monitoring stations were selected in each of the three lake areas for water sampling and monitoring from 1988 to 2022. Water samples were sampled in the first 10 days of each month and were tested by the Jiangxi Ecological and Environmental Monitoring Centre by the requirements of the "Technical Specification for Surface Water and Wastewater Monitoring in China (HJ/T 91-2002). The river runoff data and river TP concentration data of this study were provided by the Jiangxi Ecological and Environmental Monitoring Centre. Details of the 11 water quality monitoring sites that were selected for this study are shown in the following Table 1.

Table 1. Lake water quality testing site information

Lake District	Monitoring site	Longitude E	Latitude N
The North Lake	S1 (Hu Kou)	116°12′	29°44′
	S2 (Ha ma shi)	116°08′	29°37′
	S3 (Xing zi)	116°04′	29°28′
	S4 (Bang hu)	116°23′	39°54′
The Middle Lake	S5 (Du chang)	116°12′	29°16′
	S6 (Tang yin)	116°21′	29°05′
	S7 (Long kou)	116°29′	29°01′
	S8 (Po yang)	116°39′	28°59′
The South Lake	S9 (Kang shang)	116°25′	28°53′
	S10 (Kang shang hu)	116°30′	28°53′
	S11 (Jun shang hu)	116°23′	28°39′

C. Data processing Method

In this study, the Mann-Kendall test (M-K method) was chosen to extract the trend of TP concentration series in Poyang Lake in the last 10 years. The M-K test has been widely used in the analysis of climate parameters and hydrological series. Its specific calculation method and parameters are as follows.

For a time series X with n sample sizes and each sample is independent of the other and has the same continuous distribution, construct an order column:

$$s_k = \sum_{i=1}^{k} r_i, r_i = \begin{cases} 1, x_i > x_j, j = 1, 2, \dots i \\ 0, else \end{cases} \quad (1)$$

Under the assumption of random independence of the time series, define the statistic:

$$UF_k = \frac{s_k - E(s_k)}{\sqrt{Var(s_k)}}, K = 1, 2, \dots, n \quad (2)$$

$$E(s_k) = \frac{n(n-1)}{4}, Var(s_k) = \frac{n(n-1)(2n+5)}{72} \quad (3)$$

UF is a standard normal distribution, and the above calculation process is repeated by time series x inverse series to construct the inverse series UB. If UF>0, the series has an upward trend, and if UF<0, the series has a downward trend. When UF exceeds the critical confidence level straight line (the confidence level line is ±1.96 when the test confidence level α=0.05), it indicates a significant upward or downward trend, and the range above the critical line is determined as the time region where the mutation occurs. If the intersection of UF and UB occurs between the critical line, the time corresponding to this intersection is the time when the mutation starts.

Pearson coefficient between the TP time series of each monitoring point in Poyang Lake was calculated and tested for correlation, two significance levels of 0.01 and 0.05 were set, $p<0.05$ indicates statistically significant correlation, and $p<0.01$ indicates significant correlation. The specific formula of Pearson coefficient calculation is as follows:

$$\begin{cases} r = \frac{l_{xy}}{\sqrt{l_{xx} l_{xy}}}, l_{xx} = \sum_{i=1}^{n} x_i^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}; \\ l_{xx} = \sum_{i=1}^{n} y_i^2 - \frac{(\sum_{i=1}^{n} y_i)^2}{n}; \\ l_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n}; \end{cases} \quad (4)$$

Where r is the correlation coefficient of two points, and are the TP concentration time series of the study points, respectively, and n is the sample size. The larger the absolute value of the correlation coefficient, the stronger the correlation, the closer the correlation coefficient is to 1 or −1, the stronger the correlation, and the closer the correlation coefficient is to 0, the weaker the correlation. The correlation degree can be empirically classified into the following cases: when $0.8\leq|r|<1$, it is regarded as a very strong correlation; when $0.6\leq|r|<0.8$, it is regarded as a strong correlation; when $0.4\leq|r|<0.6$, it is regarded as a moderate correlation; when $|r|<0.4$, it means that the correlation between the variables is extremely weak, or it is regarded as no correlation.

III. Result and Discussion

A. Properties of the Temporal Evolution of TP Concentration

Based on the measured data from 2012 to 2022, the TP fluctuation curve of each lake area of Poyang Lake is shown in Fig. 2a. From 2012 to 2022, the overall fluctuation of TP concentration in The North Lake area was large (0.032–0.128 mg/L), and the interannual mean value of total phosphorus concentration was about 0.064±0.014 mg/L. Two extreme points of the annual average TP concentration were observed, with an overall high level during 2012–2017 and peaking in 2014 with an average concentration of 0.093 mg/L. During 2018–2019, the average annual value of total phosphorus concentration decreased abruptly, with a trough value of 0.044 mg/L. It showed a small increasing trend during 2020–2022 with an average value of about 0.056 mg/L.

From 2012 to 2017, the overall fluctuation of TP concentration in The Middle Lakes region during this period was significant, gradually decreasing and leveling off during 2018–2022, with an average interannual total phosphorus concentration of about 0.088±0.032 mg/L. There were two peaks in the average annual TP concentration, with the average TP concentration above 0.10 mg/L during 2012–2015. The TP concentration reached a maximum value in 2014 with a peak value of 0.157 mg/L; during 2016-2019, the concentration showed an overall decreasing trend with a trough value of 0.048 mg/L; the second peak occurred in 2020 with a TP concentration of 0.097 mg/L; after 2020 the TP concentration decreased slightly with a mean value of 0.058 mg/L. There was a clear downward trend overall, a trend that was similarly concluded in Ma and Li's study [11, 36].

During the period 2012–2022, the overall fluctuation of total phosphorus concentration in The South Lake area was more significant compared to The North and Middle Lake areas, but the overall concentration was low, with an interannual average value of 0.023±0.009 mg/L. The annual average concentration of TP showed three peaks. Between 2012 and 2016, the TP trend changed first up and then down, with the first peak in 2014, with a TP concentration of the second peak occurring in 2017 with a mean value of 0.026 mg/L, the lowest value being reached in 2019 with 0.010 mg/L, and the third extreme value occurred in 2020 with 0.049 mg/L. After that, it gradually stabilized with a mean value interval of 0.018–0.025 mg/L.

The study showed that the trend of TP concentration in each lake showed a clear cyclical annual variation. Every two-year interval, the total phosphorus concentration increased and tended to level off or decrease in odd years [36, 37], and this trend may be related to seasonal human activities such as agricultural activities and tourism in the watershed [38]. In addition, considering the possible seasonal flow and mixing of water bodies in Poyang Lake [39] may affect the distribution and variation of total phosphorus concentration.

To further reveal the trend of the TP series, the Mann-Kendall method was introduced to test the time trend of the TP series. The confidence level of $\alpha = 0.05$ was taken, and the critical value of 1.96 was checked in the normal score table, the results are shown in Fig. 2(b). UFk was less than 0 from January to June 2012, and from August 2016 to 2022 in the Northern Lakes, indicating a continuous decline in the Northern Lakes TP series during this period; |UFk| was >1.96 from July 2018 to October 2022, indicating a strong downward trend in the TP series during this period; and UFk was consistently greater than 0, indicating a continuous increase in TP sequences in the Northern Lakes during this period. In the Central Lakes region, UFk < 0 in 2012, April 2016 to October 2022, indicating a continuous decreasing trend in the TP series in the Central Lakes region during this period; for the rest of the period, TP showed an increase. Between April 2018 and October 2022, |UFk|>1.96, indicating that the TP series exhibited a significant upward trend. In the South Lake District, UFk was less than 0 from 2012 to 2020, indicating a persistently decreasing TP series during this period; among them, |UFk|>1.96 occurred from September 2013 to March 2019. UFk was greater than 0 from June 2020 and continued until 2022, indicating a persistent increasing TP series from 2020 onward. In general, total phosphorus in the North Lake region showed a small increase followed by a gentle decrease; the TP evolution in the Central Lake region was similar to that in the North Lake region, with a continuous increase followed by a slow decrease; the South Lake region showed a continuous decrease followed by a large increase, and eventually leveled off [40]. The trend was similar to that of the northern lakes.the author.

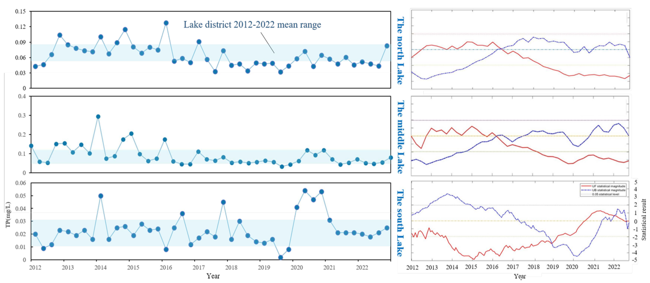

Fig. 2. The trend of TP concentration evolution in Poyang Lake from 2012 to 2022. (a) Evolution trend of annual average TP concentration in each lake area; (b) Mann-Kendall analysis of TP in each lake area.

B. *Analysis of Spatial Variability of TP Concentration*

The trend of TP concentration at the 11 monitoring points in Poyang Lake (Fig. 3(a)) showed a “ ∽ “ pattern. The concave point was at S4, with a TP concentration of 0.061 mg/L. The convex point was at S8, which was also the peak point with a TP concentration of 0.1 mg/L. It is possible that S4 and S8 are at the junction of the two lakes, and the TP concentration fluctuates more, and then the inflection point appears. The lowest value in the lake was at S11, with a TP concentration of 0.036 mg/L. This may be since S11 is in the upstream area, where there are no large-scale agricultural or industrial activities and the input of exogenous pollutants is low. There was a clear trend of increasing TP in the Central Lake area. The South Lake area showed a substantial decreasing trend compared to the North Lake area. In addition, TP concentrations, in general, showed that The Middle Lake (0.083 mg/L) > The North Lake (0.069 mg/L) > The South Lake area (0.053 mg/L), a finding similar to the findings of Liu and Jiang [41]. Overall, the higher TP concentrations in Poyang Lake were concentrated in the northwestern and central parts of the lake [42]. This trend may be due to a combination of factors, including the larger area and slower flow velocity in the central part of the lake, which is influenced by upstream water and sand, leading to sediment deposition and the gradual release of phosphorus from the sediment to the overlying water column [43, 44] On the other hand, considering the relatively dense agricultural and industrial areas around the central and northern lakes, agricultural surface pollution may lead to agricultural nutrients (including phosphorus) entering the water bodies [34, 45].

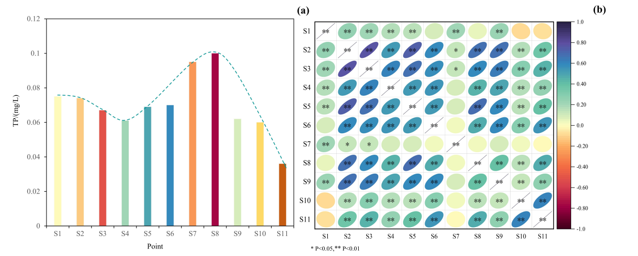

Fig. 3. Analytical graph of total phosphorus at monitoring points in the Poyang Lake basin. (a) Trend of total phosphorus concentration in each point; (b) Relevance of total phosphorus concentration in each point.

As in Fig. 3(b), S2, S3, and S4 had good positive correlations with most of the points in the Central and South Lakes and had a greater influence on the Central Lakes. S7 showed weak positive correlations with S1 and S2 ($r1$=0.20, $r2$=0.12, $r3$=0.13), but not with other points. Considering that S7 is located in the Yangtze finless porpoise nature reserve [46] The difference in phosphorus input to the other areas led to a low correlation between S7 and the other areas, as the area is less influenced by anthropogenic inputs and other areas have inputs of pollutants such as agriculture and industry. The weak correlation with S1 and S2 may be a spurious correlation due to random errors in data collection. S8 and S9 were both significantly correlated with points in the S2-S6 region. It is assumed that the reason was that S8 and S9 are located in the more active water flow area and the water bodies are exchanged frequently, contributing to TP’s good transferability between different sites. S10 and S11 showed a negative correlation with S1 ($r4$=−0.092, $r5$=−0.067) and a weak correlation with other sites. During the flow of water bodies from south to north in Poyang Lake [47], TP was subsequently transported to the middle and north lakes, and in turn, there was some correlation between the middle and north lakes and the south lakes.

C. *Analysis of the Mechanism Driving the Evolution of TP Concentration*

The TP concentration of a body of water is susceptible to a variety of factors, among which agricultural non-point source pollution is the leading factor of excessive TP concentration

[48]. Complex surface runoff due to water circulation, nutrient loading, land cover type, and non-point source pollution in the watershed also contributes to the variability of TP concentrations [49]. In this section, the influences of runoff volume, TP concentration, and inlet load of five rivers upstream of Poyang Lake on TP concentration within the lake area are selected as the driving factors.

The runoff volume of rivers in the upper reaches of Poyang Lake shows an obvious seasonal change pattern, gradually increases with the arrival of the flood season (July-August) and gradually decreases after the end of the flood season, and the change cycle (1 year) of five rivers keeps synchronized (Fig 4(a)). Except for Gan Jiang, where the average annual runoff has been at its highest at 2344 m^3/s, the average annual runoff of the remaining rivers is within the range of 397–647 m^3/s. Although Gan Jiang has the highest average annual contribution to the lake TP load (46.77%), the TP concentration in Gan Jiang has been maintained at a low and stable level (Fig 4(b)-(c)). The TP concentration in the Rao was consistently high until 2018 when the annual average TP concentration reached 0.259 mg/L and decreased significantly to an average value of 0.045 mg/L. Thus, it can be seen that changes in runoff and TP concentrations in the rivers entering the lake have an impact on the TP concentration in the lake.

Under the condition of $p<0.05$, the TP concentration in the middle lake of Poyang Lake showed a significant positive correlation ($r1=0.322$) with the TP concentration in Gan Jiang (Fig. 4(d)). Both the runoff volume and TP load contribution of Gan Jiang into the lake account for about 50% of the total volume of five rivers into the lake, and the middle branch of Gan Jiang enters the lake in the west of the middle lake, so the TP concentration in the middle lake area will be significantly influenced by Gan Jiang. Meanwhile, the TP concentration in Rao showed a significant positive correlation with that in the middle and south lakes ($r2=0.446$ and $r3=0.537$). The explanation is that Rao enters the lake on the east side of the middle lake area of Poyang Lake, and the high TP input from Rao affects the TP concentration in the middle lake area, and this effect extends to the north lake area spatially. In addition, the TP loading of Rao also showed a significant positive correlation with the TP concentration in the middle lake area, indicating that the TP concentration in the middle lake area is vulnerable to the influence of the water quality in Rao He. Phosphorus is considered to be the limiting factor for algal blooms [50]. In the middle lake area of Poyang Lake, the high input of TP from Rao has led to the algal bloom in the area. This phenomenon was particularly evident until 2018 when TP concentrations in Rao He were consistently high. And this is supported by relevant studies: Wu *et al*. [51] found cyanobacterial outbreaks in Middle Lake in the summer; found that the concentrations of Microcystis aeruginosa and cyanobacteria were high in middle lake, respectively [52], [53].

The runoff, TP concentration, and TP load of the remaining rivers did not show significant correlations with the TP concentration in each lake. The TP concentration in the north lake is less directly influenced by the inlet rivers because of its proximity to the Yangtze River and its distance from the rivers entering the lake. The south lake receives the confluence of water flow from the south branches of Gan Jiang, Fu He, and Xiu Shui; the topography of this area is complex, and the driving mechanism of TP concentration in this area needs to be further studied and explored.

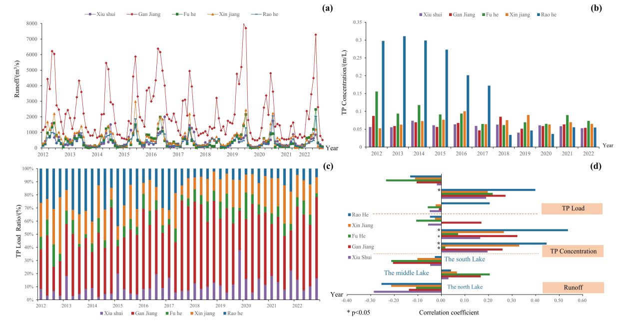

Fig. 4. Driving mechanism analysis of TP concentration in Poyang Lake. (a) Entry flow of the five rivers in Poyang Lake; (b) Entry total phosphorus concentration of the five rivers in Poyang Lake; (c) Ratio of total phosphorus loading to the five rivers in Poyang Lake; (d) Correlations between TP concentration and driving mechanism in each lake of Poyang Lake. The driving mechanism refers to the runoff flow of the five rivers, total phosphorus concentration into the lake, and total phosphorus load into the lake.

IV. Conclusions

This study analyzed the spatial and temporal discrepancies of TP concentrations in three lake areas of Poyang Lake, North, Middle, and South, by the Mann-Kendall method and related examination according to the long-term series of water quality in Poyang Lake from 2012 to 2022, and explored the driving mechanisms of river runoff, TP concentration, and influent load on the TP concentration of each lake area. The main conclusions are as follows:

- The overall fluctuation of TP concentration was more obvious in South Lake compared with North Lake and Middle Lake, and its trend showed periodic annual fluctuation. Total phosphorus in North and Middle Lakes showed a rise and then a steady decline, whereas in South Lake, it showed a steady decline and then a large increase, finally leveling off.
- The change curve of total phosphorus in 11 points monitored within the lake showed a "∽ " shape, with extreme values in S4 and S8, and the TP concentrations were 0.061 mg/L and 0.1 mg/L. The higher TP concentrations in Poyang Lake were concentrated in the northwest and middle. Besides, there was also a certain correlation of TP concentration between The Middle Lake, The North Lake, and The South Lake.
- The runoff of rivers entering Poyang Lake had no significant effect on the TP concentration in the lake area, and only the TP load of Rao River showed a positive correlation with the TP concentration in the middle lake area. The middle lake area was most affected by the TP concentration of rivers entering the lake (middle branch of Gan Jiang River and Rao River). The North and South Lakes were relatively less affected by the direct influence of the incoming rivers on the TP concentration. The North Lake area was mainly affected by the Yangtze River system, while The South Lake was exposed to the combined influence of multiple factors on TP concentrations due to its location and complicated fluvial inputs.
- By comparing the variable trends and influencing factors in different lake areas of Poyang Lake, the present study elaborates on the spatial and temporal

variability of TP concentrations in different lakes and the complex driving mechanisms. The subsequent research would be carried out on pollution source localization, climate change, and pollutant migration transformation to deepen insight into the driving mechanism of TP concentration evolution in Poyang Lake and formulate more appropriate management and conservative strategies.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Hua Wang conducted the research and proposed the methodology and wrote the manuscript; Fang Cui collected the data and wrote the manuscript; Yi Wu collected the data and wrote the manuscript; Jiale Li calculated the data and revised the manuscript; Yiran Zhu calculated the data and revised the manuscript; all authors had approved the final version.

Funding

This work was supported by the National Natural Science Foundation of China (No. 52179064), A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions, and National Nature Science Foundation of China (Grant No. 51479064), Water conservancy science and technology project of Jiangxi Province (202023ZDKT12).

Acknowledgment

The authors wish to thank Jiangxi Hydrological Bureau for providing the water quality data of Poyang Lake.

References

[1] Y. Ding, J. Zhao, W. Peng, J. Zhang, Q. Chen, and Q. Fu, "Stochastic trophic level index model: A new method for evaluating eutrophication state," *Journal of Environmental Management*, vol. 280, 111826, Feb. 2021.

[2] J. Yao, G. Wang, B. Xue, P. Wang, F. Hao, G. Xie, and Y. Peng, "Assessment of lake eutrophication using a novel multidimensional similarity cloud model," *Journal of Environmental Management*, vol. 248, 109259, Oct. 2019.

[3] A. Iho, H. Valve, P. Ekholm, R. Uusitalo, J. Lehtoranta, H. Soinne, and J. Salminen, "Efficient protection of the Baltic Sea needs a revision of phosphorus metric," *Ambio*, vol. 52, no. 8, pp. 1389–1399, Aug. 2023.

[4] J. C. Ho, A. M. Michalak, and N. Pahlevan, "Widespread global increase in intense lake phytoplankton blooms since the 1980s," *Nature*, vol. 574, no. 7780, pp. 667–670, Oct. 2019.

[5] M. Xiao, M. A. Burford, S. A. Wood, L. Aubriot, B. Belings, M. Prentice, E. Galvanese, T. D. Harris, and D. P. Hamilton, "Schindler's legacy: from eutrophic lakes to the phosphorus utilization strategies of cyanobacteria," *Fems Microbiology Reviews*, vol. 46, no. 6, Nov. 2022.

[6] Y. D. Tong, Z. Huang, A. B. G. Janssen, M. Wishart, W. He, X. J. Wang, and Y. X. Zhao, "Influence of social and environmental drivers on nutrient concentrations and ratios in lakes: A comparison between China and Europe," *Water Research*, vol. 227119347, Dec. 2022.

[7] F. Wu, Y. Fang, M. F. Feng, Z. C. Xie, L. Zhu, and J. F. Feng, "Developing Ecological Thresholds for Nitrogen and Phosphorus in the Haihe River Basin in China," *International Journal of Environmental Research and Public Health*, vol. 19, no. 24, Dec. 2022,

[8] N. Shiferaw, J. Kim, and D. Seo, "Identification of pollutant sources and evaluation of water quality improvement alternatives of a large river," *Environmental Science and Pollution Research*, vol. 30, no. 11, pp. 31546–31560, Mar. 2023.

[9] H. T. Chen, L. J. Zheng, W. C. Wang, and R. Shi, "Study on the effect of land-use change on phosphorus pollution in water China, Jianjiang River, Huazhou station control basin," *Polish Journal of Environmental Studies*, vol. 31, no. 3, pp. 2537–2547, 2022.

[10] J. Chen, L. J. Zheng, W. C. Wang, and R. Shi, "Common fate of sister lakes in Hulunbuir Grassland: Long-term harmful algal bloom crisis from multi-source remote sensing insights," *Journal of Hydrology*, vol. 594, 125970, Mar. 2021.

[11] B. Li, G. Yang, and R. Wan, "Multidecadal water quality deterioration in the largest freshwater lake in China (Poyang Lake): Implications on eutrophication management," *Environmental Pollution*, vol. 260, 114033, May 2020.

[12] K. Su, Q. Wang, L. Li, R. Cao, Y. Xi, and G. Li, "Water quality assessment based on Nemerow pollution index method: A case study of Heilongtan reservoir in central Sichuan province, China," *Plos One*, vol. 17, no. 8, e0273305, 2022.

[13] W. Liu, Y. F. Chu, Q. Y. Tan, J. M. Chen, L. L. Yang, Q, H. Zhou, Z. B. Wu, and F. He, "Distributional characteristics and evaluation of nitrogen,phosphorus and organic matter in the surface sediments of rural ponds around the western part of Lake Poyang in summer," *Journal of Lake Sciences*, vol. 35, no. 1, pp. 192–202, 2023.

[14] S. Xiang and W. Zhou, "Phosphorus existing forms and distribution characteristic in Lake Poyang sediments," *Scientia Limnologica Sinica*, vol. 22, no. 5, pp. 649–654, 2010.

[15] J. Xu, L. Xu, R. Gong, and K. Ding, "Adsorption and release characteristic of phosphorus and influential factors in Poyang Lake sediment," *Ecology and Environmental Sciences*, vol. 23, no. 4, pp. 630–635, 2014.

[16] J. Xu and X. Wang, "Changes of contents of nitrogen and phosphorus in the water during decomposition process of shoot and leaf residues of three kinds of typical plants in Poyang Lake under two kinds of temperatures," *Wetland Science*, vol. 16, no. 2, pp. 266–272, 2018.

[17] Q. Zhang, G. S. Zhang, S, X. Wan, Y. Liu, S. X. Xia, Y. Li, C. Xu, and X. B. Yu, "Effects of herbivorous overwintering migratory birds' droppings on the decomposition of Carex cinerascens Kukenth and C,N,P release in Lake Poyang wetland," *Journal of Lake Sciences*, vol. 31, no. 3, pp. 814–824, 2019.

[18] D. Luo, X. Wu, S. Li, C. Hu, and W. Zhou, "Investigate Study on TP Pollution Load of Poyang Lake by Water and Salt Balance," *Acta Scientiarum Naturalium Universitatis Pekinensis*, vol. 47, no. 2, pp. 337–343, 2011.

[19] X. Chen, Y. Zhang, L. Zhang, L. Chen, and J. Lu, "Distribution characteristic of nitrogen and phosphorus in Lake Poyang during high water period," *Journal of Lake Sciences*, vol. 25, no. 5, pp. 643–648, 2013.

[20] L. Y. Qi, J. C. Huang, Q. Huang, J. F. Gao, S. G. Wang, and Y. Y. Guo, "Assessing aquatic ecological health for Lake Poyang, China: Part II index application," *Water*, vol. 10, no. 7, Jul. 2018.

[21] H. Wang, M. A. Wu, Y. Q. Deng, C. Y. Tang, and R. Yang, "Surface water quality monitoring site optimization for Poyang Lake, the largest freshwater lake in China," *International Journal of Environmental Research and Public Health*, vol. 11, no. 11, pp. 11833–11845, Nov. 2014.

[22] J. Cui, Y. Du, C. C. Ding, J. F. Li, F. S. Gao, Y. J. Chang, J. B. Zhang, X.J. Liu, and D. R. Yao, "Phosphorus fraction and abatement of lakes in China: A review," *Ecology and Environmental Sciences*, vol. 31, no. 3, pp. 621–633, 2022.

[23] M. Gao, X. Jiang, and Y. Chu, "Study on phosphorus forms in typical rivers of Chaohu Lake basin under different hydrological conditions," *Journal of China Hydrology*, vol. 43, no. 1, pp. 90–95, 2023.

[24] L. W. Ngatia, Y. P. Hsieh, D. Nemours, R. Fu, and R. W. Taylor, "Potential phosphorus eutrophication mitigation strategy: Biochar carbon composition, thermal stability and pH influence phosphorus sorption," *Chemosphere*, vol. 180, pp. 201–211, Aug. 2017.

[25] Z. Yang, M. Zhang, C. Hao, X. Hou, L. Wang, R. Xia, J. Yin, C. Ma, Q. Wang, and Y. Zhang, "Source apportionment of total phosphorus pollution in poyang lake basin based on source-sink process modeling," *Research of Environmental Sciences*, vol. 33, no. 11, pp. 2493–2506, 2020.

[26] S.-Y. Wang, Y. Gao, Y. Lu, J. J. Jia, Z. X. Li, M. Z. Ma, and X. F. Wen, "Transport characteristics of phosphorus sources at the multi-scale watershed and the associated ecological effects on Poyang Lake," *Environmental Science*, vol. 41, no. 7, pp. 3186–3193, Jul. 2020.

[27] A. Huang, X. Liu, W. Peng, F. Dong, B. Ma, J. Li, and W. Wang, "Spatiotemporal characteristics, influencing factors and evolution laws of water exchange capacity of Poyang Lake," *Journal of Hydrology*, vol. 609, p. 127717, Jun. 2022.

[28] C. Xu, G. Yang, R. Wan, W. Ou, and P. Wang, "Toward ecological function zoning and comparison to the ecological redline policy: A case study in the Poyang Lake Region, China," *Environmental Science and Pollution Research*, vol. 28, no. 30, pp. 40178–40191, Aug. 2021.

[29] F. Y. Jiang, R. Y. Kuang, A. X. Xia, Q. Y. Feng, and M. Zhou, "Variation characteristics of Poyang Lake water area and its response to meteorological factors in recent 35 years," *Journal of Water and Climate Change*, Jun. 2023.

[30] L. I. Xiuying, Chen Zhihe, Kong Meng, and L. V. Chaoyin, "Study of interfacial interaction properties of sediment particles with the change in water environments," *Acta Scientiarum Naturalium Universitatis Sunyatseni*, vol. 50, no. 4, pp. 139–143, 2011.

[31] Z. Wei, Y. Z. Xu, Y. Y. Zhao, Y. Y. Zhao, L. L. Bai, H. L. Jiang, and C. H. Wang, "The settling of resuspended lake sediment related to physicochemical properties of particles of different sizes: Implication for environmental remediation," *International Journal of Sediment Research*, vol. 36, no. 4, pp. 542–554, Aug. 2021.

[32] X. Liu, Z. G. Mei, J. X. Zhang, J. J. Sun, N. N. Zhang, Y. Y. Guo, K. X. Wang, Y. J. Hao, and D. Wang, "Seasonal Yangtze finless porpoise (Neophocaena asiaeorientalis asiaeorientalis) movements in the Poyang Lake, China: Implications on flexible management for aquatic animals in fluctuating freshwater ecosystems," *Science of the Total Environment*, vol. 807, 150782, Feb. 2022.

[33] S. X. Xia, Y. Liu, Y. Y. Wang, B. Chen, Y. F. Jia, G. H. Liu, X. B. Yu, and L. Wen, "Wintering waterbirds in a large river floodplain: Hydrological connectivity is the key for reconciling development and conservation," *Science of the Total Environment*, vol. 573, pp. 645–660, Dec. 2016.

[34] H. Wang, Y. Wu, Y. Q. Deng, D. F. Liang, Y. C. Zeng, X. Y. Zhang and Y. P. Li, "Examination of changes in selected nutrient concentrations from 1988 to 2018 in the Largest Freshwater Lake in China," *Journal of Hydrologic Engineering*, vol. 27, no. 11, Nov. 2022.

[35] Y. Li, Q. Zhang, H. Tao, and J. Yao, "Integrated model projections of climate change impacts on water-level dynamics in the large Poyang Lake (China)," *Hydrology Research*, vol. 52, no. 1, pp. 43–60, 2019.

[36] C. Fu and W. Kang, "Research on spatial characteristics of TN &TP of agricultural non-point source pollution in the surrounding area of the Poyang Lake," *Resources and Environment in the Yangtze Basin*, vol. 21, no. 7, pp. 864–868, 2012.

[37] Z. Wang, J. N. Lin, Y. Zhang, H. Wang, C. Qian, Y. Chen, R. Xia, Q. Wang, and X. J. Zhang, "Water quality limits of nitrogen and phosphorus in the inflow rivers of Poyang Lake," *Research of Environmental Sciences*, vol. 33, no. 5, pp. 1163–1169, 2020.

[38] W. 3Wang, P. Yang, J. Xia, S. Zhang, and S. Hu, "Changes in the water environment and its major driving factors in Poyang Lake from 2016 to 2019, China," *Environmental Science and Pollution Research*, vol. 30, no. 2, pp. 3182–3196, 2023.

[39] R. Kuang, W. Luo, and M. Zhang, "Optical Classification of Poyang Lake waters Based on in situ measurements and remote sensing images," *Resources and Environment in the Yangtze Basin*, vol. 24, no. 5, pp. 773–780, 2015.

[40] B. Li, G. Yang, and R. Wan, "Multidecadal water quality deterioration in the largest freshwater lake in China (Poyang Lake): Implications on eutrophication management," *Environmental Pollution*, vol. 260, 114033, 2020.

[41] L. Yao and J. Hui, "Retrieval of total phosphorus concentration in the surface waters of Poyang Lake based on remote sensing and analysis of its spatial-temporal characteristics," *Journal of Natural Resources*, vol. 28, no. 12, pp. 2169–2177, 2013.

[42] Z. Lu, H. Huang, L. Xu, and H. Fan, "Application of WQI method for water quality evaluation of Poyang Lake based on entropy weight," *The Administration and Technique of Environmental Monitoring*, vol. 33, no. 4, pp. 30–34, 2021.

[43] Z. Wang, D. Yu, W. Wang, F. Luo, J. Tang, and J. Yang, "End-member analysis of sedimentary dynamics indicated by the grain-size of surface sediments in the Quanzhou Bay," *Tropical Geography*, vol. 41, no. 5, pp. 975–986, 2021.

[44] W. Gao, S. H. Liu, J. Liu, Y. Q. Xu, and P. Li, "The sedimentary facies and dynamic environment of the Diaokou lobe in the modern Huanghe River Delta of China," *Acta Oceanologica Sinica*, vol. 37, no. 11, pp. 40–52, Nov. 2018,

[45] J. H. Gao, J. J. Jia, A. J. Kettner, F. Xing, Y. P. Wang, X. N. Xu, Y. Yang, X. Q. Zou, S. Gao, S. H. Qi, and F. Q. Liao, "Changes in water and sediment exchange between the Changjiang River and Poyang Lake under natural and anthropogenic conditions, China," *Science of the Total Environment*, vol. 481, pp. 542–553, May 2014.

[46] Z. Mei, Y. Hao, J. Zheng, Z. Wang, K. Wang, and D. Wang, "Population status and conservation outlooks of Yangtze finless porpoise in the Lake Poyang," *Journal of Lake Sciences*, vol. 33, no. 5, pp. 1289–1298, 2021.

[47] Y. L. Li, Q. Zhang, and J. Yao, "Investigation of residence and travel times in a Large Floodplain Lake with complex Lake-River interactions: Poyang Lake (China)," *Water*, vol. 7, no. 5, pp. 1991–2012, May 2015.

[48] X. Yuan, S. R. Wang, F. Q. Fan, Y. Dong, Y. Li, W. Lin, and C. Y. Zhou, "Spatiotemporal dynamics and anthropologically dominated drivers of chlorophyll-a, TN and TP concentrations in the Pearl River Estuary based on retrieval algorithm and random forest regression," *Environmental Research*, vol. 215, 114380, Dec. 2022.

[49] C. Jinyue, S. S. Chen, R. Fu, X L. Yin, C. Y. Wang, D. Li, and Y. S. Peng, "Analysis of water quality status and driving factors in Guangdong Province," *Acta Ecologica Sinica*, vol. 42, no. 19, pp. 7921–7931, 2022.

[50] L. Chen, P. Zhang, G. P. Lv, and Z. Y. Shen, "Spatial–temporal distribution and limiting factor variation of algal growth: three-dimensional simulation to enhance drinking water reservoir management," *Int. J. Environ. Sci. Technol.*, vol. 16, no. 11, pp. 7417–7432, Nov. 2019.

[51] Z. Wu, H. He, Y. Cai, L. Zhang, and Y. Chen, "Spatial distribution of chlorophyll a and its relationship with the environment during summer in Lake Poyang: a Yangtze-connected lake," *Hydrobiologia*, vol. 732, no. 1, pp. 61–70, Jul. 2014.

[52] X. Liu, Y.-L. Li, B.-G. Liu, K.-M. Qian, Y.-W. Chen, and J.-F. Gao, "Cyanobacteria in the complex river-connected Poyang Lake: horizontal distribution and transport," *Hydrobiologia*, vol. 768, no. 1, pp. 95–110, Mar. 2016.

[53] J. Zhang, "Investigation on the invasive plants in Nanjishan Nature Reserve of Poyang Lake," *Journal of Tropical and Subtropical Botany*, vol. 23, no. 4, pp. 419–427, 2015.