RESEARCH ARTICLE

Spatiotemporal heterogeneities and driving factors of water quality and trophic state of a typical urban shallow lake (Taihu, China)

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Abstract
Water quality deterioration and eutrophication of urban shallow lakes are global ecological problems with increasing concern and greater environmental efforts. In this study, spatiotemporal changes of water quality and eutrophication were assessed by trophic level index (TLI), cluster analysis, and spatial interpolation methods in Lake Taihu and its sub-lakes from 2015 to 2019. Results showed that the Taihu had poor water quality and maintained a light-eutropher state overall, mainly astricted by the total nitrogen (TN) and the total phosphorus (TP). All nutrient parameters reached relatively higher concentrations in the northwestern and northern areas. Meiliang Bay was the most polluted and nutrient-rich area. In terms of trend, the Mann–Kendall test highlighted that the TP and chlorophyll-a (Chl-a) concentrations increased significantly while the TN and five-day biochemical oxygen demand (BOD5) decreased. The massive nutrient loads caused by human activity from the northwestern Taihu and the geomorphological characteristic of the north closed bays were the main contributors to the spatial heterogeneity in water quality. The main driving force of the alleviative nitrogen pollution was the declining river inflow nitrogen loading, and phosphorus pollution was affected more by accumulated endogenous pollution and decline in aquatic plants area, as well as closely linked with algae biomass. Further water pollution and eutrophication restoration of Taihu should focus on the nutrient reductions and those heavily polluted closed bays.

Keywords Lake Taihu · Water quality · Eutrophication · Spatiotemporal heterogeneities · Driving factors · Urban shallow lakes

Introduction
With the speed-up of industrialization, urbanization, and agriculture, abundant industrial, domestic, and rural wastewater inflow into urban lakes, accelerating water quality deterioration and eutrophication ulteriorly. Shallow lakes have the characteristics of low water depth with strong hydrodynamic disturbance and intense lake-land, air–water, and water–sediment interactions, which make them more vulnerable to water pollution (Hatvani et al., 2020). Such phenomenon has been found in a lot of shallow lakes, such as Lake Erie (North America)(Steffen et al. 2014), Lake Kasimagaura (Japan) (Xu et al. 2010), Lake Victoria(African) (Olokotum et al. 2020), and Lake Chaohu and Taihu (China) (Qin 2020; Zhang and Kong 2015). As shallow lakes usually have crucial functions of drinking-water source, aquaculture, and irrigation, a series of protective programs have been launched to control the decline in freshwater quality (Qin 2007; Schindler 2006).
China has paid impressive environmental efforts to alleviate water pollution and gained specific positive effects in some lake basins (Ma et al. 2020; Qin et al. 2019). However, the water environment of many lakes still has not been fundamentally improved. The water pollution in different lakes varies with the basin natural environment (e.g., geomorphological characteristic of the lake, monsoon), anthropogenic activities (e.g., wastewater effluent, water diversion project, government treatment policy), and also change over time. Therefore, spatiotemporal heterogeneity analysis, which reflects the complexity of ecological variables (Guo et al. 2020), for water quality and eutrophication status of different lakes individually is helpful to identify the main parameters. Moreover, distinguishing the driving forces of water quality is essential to maintain water environment sustainability according to local conditions. Numerous studies have used different methods to analyze the spatiotemporal heterogeneities of water quality and their drive forces in large urban lakes (Wang et al. 2019a, b, c, d; Wu et al. 2015; Zha et al. 2019). However, developing a common method framework for water quality spatiotemporal heterogeneities and driving factors analysis for lakes is still needed.

Lake Taihu (referred to as “Taihu” below), a typical large urban shallow lake, has long been a popular research area in the world due to its frequent water environment deterioration events (Paerl et al. 2011; Qin et al. 2010, 2013). Taihu is the distribution center of mass point source and non-point source sewage with a complex river network of 228 rivers or channels (TBA 2018) and is greatly affected by human activities (Gao et al. 2002; Wang et al. 2019a, b, c, d). With intensive treatment after the occurrence of the Wuxi water pollution incident of Taihu in May 2007, water environment quality of Taihu improved apparently. However, the frequency and formation area of cyanobacterial blooms in Taihu seemed to have a rising trend since 2015 (Yang et al. 2016; Zhang et al. 2021). Limiting nutrient inputs (N or P) to the waterbody received a specific effect on eutrophication management in Taihu in the early stage (Dai et al. 2016; Xie et al. 2017). However, it is difficult to achieve satisfactory effects only by taking this treatment blindly under the new situation, especially since 2015. So, it is necessary to analyze the water quality and trophic state change features of Taihu and judge whether there are any abnormal phenomena after 2015.

But current research is still insufficient, parts of them are limited to focus on a particular area of urban lakes (Wang et al. 2019a, b, c, d; Wang et al. 2019a, b, c, d), and some were limited to analysis of TN and TP concentrations separately (Zhu et al. 2013, 2021). So, it is urgent to identify driving factors of water quality and take corresponding measures nowadays by analyzing more nutrient, physical, and ecological water quality parameters and exploring the pollution situation in different sub-lakes of the whole Taihu in more detail. As a result, analyzing longitudinal time series data and contrasting each Taihu sub-lake area horizontally of multiple water quality parameters with a typical technical framework is helpful to fill the lack of the previous research.

The primary objectives of this study are as follows: (1) Exploring the temporal and spatial variation characteristics of the water quality and trophic state of Taihu from 2015 to 2019; (2) Identifying the main factors affecting the water quality of Taihu and its changing trend; (3) Exploring the inflow rivers pollution load, the hydrometeorological conditions, shape of the lake, and other factors concerning water quality. These conclusions serve as a theoretical basis for the comprehensive treatment of Taihu in line with seasonal and local circumstances.

**Materials and methods**

**Study area and data sources**

Taihu (119° 52’~120° 36’ E and 30° 55’–31° 32’ N), the third-largest freshwater lake in China, is a typical subtropical shallow lake located in the southeastern of the Yangtze River Delta, with a maximum water depth of 2.6 m and an average water depth of 1.9 m (Zhang et al. 2014). The Taihu Basin, one of the most industrialized, urbanized and densely populated areas of China, plays a vital role in drinking water supply, flood controlling, tourism supporting, shipping, and aquaculture. The northwest sector of Taihu accounts for 83% of the total runoff into the lake, and the outflow rivers concentrate in the southeast sector.

Datasets from 17 sampling sites were divided into seven sub-lakes according to the Taihu Basin Authority of Ministry of Water Resources (TBA) to analyze the spatiotemporal heterogeneity of water quality of Taihu. These sub-lakes are the Zhushan Bay, Meiliang Bay, Wuli Bay, Gonghu Bay, Eastern Region, Western Region, and Central Region (Fig. 1), respectively. Datasets were collected from 2015 to 2019 on a monthly basis, with monitoring parameters permanganate index (CODMn), total nitrogen(TN), total phosphorus (TP), ammonia nitrogen (NH3-N), five-day biochemical oxygen demand (BOD5), Secchi disk (SD), and chlorophyll a (Chl-a). The unit of SD and Chl-a is the meter (m) and mg/m³ separately, and the units of the rest parameters are all mg/L. Water quality and hydrology data were obtained from Taihu Basin Ecology and Environmental Science Research Center.

**Methods for data analysis**

The technical framework for water quality spatiotemporal heterogeneities and driving factors analysis was shown in Fig. 2.
After data preprocessing, the concentration of each parameter was calculated by the mean values of all sampling sites in its spatial range. According to the climate characteristics in Taihu Basin, the seasons were divided into spring (March to May), summer (June to August), autumn (September to November), and winter (December to February). The seasonal and annual mean concentration was calculated from the monthly means.

The Single Factor Evaluation method was used to assess the water quality level of each sampling site. The main idea is to compare the monitoring concentration of each water quality parameter with the standard value of the target parameter according to the Environmental Quality Standard for Surface Water of China (GB) (MEP 2002) Level III. After comparing all of the evaluation parameters, the worst water quality parameter level is selected as the level for the entire water body.

The trophic condition of Taihu was assessed by Trophic Level Index (TLI) (Wang et al. 2002). TLI is a weighted sum based on the correlations between Chl-a and other four parameters (TP, TN, SD, and CODMn) for both qualitative and quantitative aspects. The calculation includes Eqs. (1)–(2):

\[
TLI(\sum_j) = \sum_{j=1}^{m} w_j \times TLI(j)
\] (1)

\[
TLI(\text{Chl-a}) = 10[WC2.5 + 1.0861n(\text{Chl-a})]
\] (2)

\[
TLI(\text{TP}) = 10[9.436 + 1.6241n(\text{TP})]
\] (3)

\[
TLI(\text{TN}) = 10[5.453 + 1.6241n(\text{TN})]
\] (4)

\[
TLI(\text{SD}) = 10[5.118 - 1.941n(\text{SD})]
\] (5)

\[
TLI(\text{CODMn}) = 10[0.109 + 2.6611n(\text{CODMn})]
\] (6)

where, \(j\) present Chl-a, TN, TP, SD or CODMn, TLI(\(j\)) is trophic level index of \(j\), \(W_j\) is correlative weight for each parameter (Chl-a, 0.266; TP, 0.188; TN, 0.179; SD, 0.183; CODMn, 0.183) (Wang et al. 2019a, b, c, d). The unit of each

Fig. 1 The locations of the sampling sites and the sub-lakes in the Taihu
The parameter is consistent with the description in the preceding text.

The TLI ranges from 0 to 100, with high values representing high eutrophication levels. Trophic status is classified into five grades based on the TLI scores: oligotropher (TLI < 30); mesotropher (30 ≤ TLI ≤ 50); light-eutropher (50 < TLI ≤ 60); middle-eutropher (60 < TLI ≤ 70); hyper-eutropher (TLI > 70). The trophic status of each sampling site was assessed from the corresponding TLI calculated value, and the TLI value of the whole Taihu is the mean value of all sampling sites.

The spatial distribution of the Taihu water environment was drawn by Inverse Distance Weighted (IDW) method using Arcgis software. Hierarchical cluster analysis (HCA) was carried out on the above-mentioned divided seven sub-lakes, and then the lakes with similar water quality were divided into a group.

The Mann–Kendall (MK) statistical test was selected to analyze the long-term trend of the water quality sequence. MK test, a rank-based non-parametric method, has been widely used for detecting trends in hydrometeorological time series (Ali et al. 2019; Kisi and Ay 2014; Wu and Qian 2017). Compared to parametric tests, it has no requirements of homoscedasticity or prior assumptions on the distribution of the data sample and is less sensitive to outliers. As the MK test statistic is determined by the ranks and sequences of time series rather than the original values, it is robust when dealing with non-normally distributed data, censored data, and time series with missing values, which are commonly encountered in hydrometeorological time series (Wang et al. 2020; Yue and Wang 2004). Pearson’s correlation coefficient was used to estimate the correlation among different water quality and hydrological parameters.

### Results and discussion

#### Water quality assessment and eutrophication state evaluation of Taihu

The mean concentration of BOD$_5$, COD$_{Mn}$, and NH$_3$-N for Taihu in 2015–2019 was 2.25, 3.94, and 0.15 mg/L (Table 1), meeting Level I, Level II, and Level III separately. The TP concentration of Taihu reached 0.076 mg/L, belonging to Level IV (0.05 ~ 0.1 mg/L), and the TN concentration was as high as 1.59 mg/L, belonging to Level V (1.5 ~ 2.0 mg/L). This showed that TN and TP were the main water quality indicators that below the standard in Taihu.

During the past five years, the overall proportion of water quality was mainly of Level IV (42.66%), followed by Level III and Level V, accounting for 31.25% and 20.73% (Fig. 3), respectively. The proportion reaching or superior to Level III increased from 24.48% in 2015 to 33.82% in 2019.
2019, while Level IV reduced by 14 percentage points approximately. This presented that the water quality of Taihu was generally poor with a slight improvement in the last five years. The proportion reaching or inferior to Level V increased, indicating that the water pollution treatment of Taihu still had a long way to go. Taihu had been in a state of slightly eutrophic overall for these years. The mean TLI of Taihu during 2015–2019 was 53.6, with a fluctuation of 53.1–54.6.

Water pollution in different sub-lakes varied greatly. Zhushan Bay had the worst water quality, whose total proportion of reaching or inferior to Level V was 90%. The water quality in the Western Region and Meiliang Bay also was poor, for them both accounted for less than 25% of the Level II-III. The Eastern Region had the best water quality. The TLI of each sub-lake was that Zhushan Bay (59.8) > Western Region (56.7) > Meiliang Bay (55.7) > Central Region (53.3) > Gonghu Bay (53.0) > Wulihu Bay (52.7) > 50 (lightly eutrophic) > Eastern Region (49.2). The TLI of Zhushan Bay was significantly higher than that of other sub-lakes, and it reached middle-eutropher in nearly half of the observation months, announcing that Zhushan Bay was the focus area affecting the water quality Taihu.

Spatial heterogeneity of water quality and trophic state in Taihu

Spatial variation of water quality and cluster analysis of sub-lakes

To represent the spatial variability of water quality parameters and TLI, the Inverse Distance Weighted (IDW) method was used to interpolate the five-year mean concentration of 17 sampling sites (Fig. 4). The water quality of Taihu showed apparent spatial heterogeneity: the concentrations of each parameter (except SD) and TLI were all lower from the northwest to the southeast.

SD is an integrated response parameter of lake plankton and both organic and inorganic solutions, reflecting the clarity and turbidity of the lake directly. Low values of SD appeared in the Western Region (0.32 m) and Central Region (0.34 m). Due to many rivers with a massive amount of sediment entering the Western Region, the SD value of this area was the lowest. In the Central Region, open lake surface with a higher monthly mean wind speed than that of the lakeshore (Zhang et al. 2003), sediments were easily suspended under the disturbance of wind and flow, resulting in a high concentration of suspended substances in water. High values of SD appeared in Wuli Bay (0.496 m) and Gonghu Bay (0.44 m).

Based on the monthly mean concentration of seven parameters, seven sub-lakes were divided into three groups by hierarchical clustering analysis (HCA) (Fig. 4i). Zhushan Bay, whose water quality was the worst, belongs to a single group. The second group contained Wuli Bay, Meiliang Bay, and Western Region with poor water quality; The last group was the Eastern Region, Central Region, and Gonghu Bay, representing better water quality. The clustering result was also consistent with the above conclusions of spatial heterogeneity—the water quality of Taihu improved from northwest sector to southeast.

Factors determining water quality spatial heterogeneity

The north and northwest of Taihu were the most polluted area, taking most pollutant loads of the inflow rivers. Cities along these rivers had developed industry and agriculture and high population density with numerous ports, so the pollution load of river inflow was tremendous. A statistic about pollution loads of the sub-lakes of northern and northwestern Taihu from 2007 to 2014 found that the
Western Region and Zhushan Bay were the main areas where most pollution remained (Xie et al. 2017). After the occurrence of the Wuxi water pollution incident of Taihu in May 2007 (Zhang et al. 2010), the sluices of Zhihugang and Wujingang, originally connected to Meiliang Bay, were closed, resulting in most of the pollutants being diverted to Zhushan Bay (Hu et al. 2010). It greatly affected the water environment of Zhushan Bay, making it the most polluted area with the most severe degradation of the ecosystem.

To analyze the impact of external pollution source input carried by the river inflow in the northern and northwestern Taihu, monitoring sites on the estuary were divided according to the location of sub-lakes. Correlation analysis was carried out between the quarterly mean concentration of water quality parameters (COD$_{Mn}$, NH$_3$-N, TN, and TP) in four sub-lakes (Zhushan Bay, Wuli Bay, Meiliang Bay, and Western Region) with the corresponding concentration of inflow river water (Fig. 5). The results showed that the water quality concentration of Zhushan Bay and
Wuli Bay was greatly related to the estuaries. The water quality improvement in inflow rivers was the main reason for water quality promotion in the north and northwest of Taihu. The NH\textsubscript{3}-N and TN concentrations of the estuary water were much higher than that of the lake water, reflecting that the external input N loads were the primary source of N in the Taihu lake.

There were many pocket-like small bays in the northern and northwestern Taihu, such as the Zhushan Bay, Meiliang Bay, and Wuli Bay. These areas received a large amount of nutrient-rich wastewater, far exceeding their assimilative capacity, from nearby cities (e.g., Wuxi and Changzhou). With slight flow movement and almost blocked water exchange, the self-purification ability of these bays was poor. Thus, pollutants in lake bays were not easy to transfer to the open lake area and then accumulated in situ. Those made these bays became heavily polluted areas of Taihu. As for the factors affecting the spatial characteristics of Chl-a, the monsoon must be mentioned. In summer, the southeast monsoon prevailed in Taihu and blew the algae to the northwest, resulting in a higher Chl-a concentration in the northwest, where the bays were located.

Specially, the Chl-a concentration and TLI of Gonghu Bay were relatively low. It might be related to Water Diversification from the Yangtze River Project (WDP). Benefiting from the WDP, Gonghu Bay received not only clean water from the Yangtze River (Zhu et al. 2020), but also discharges polluted water outboard. This had a positive effect on the Gonghu Bay’s water exchange and alleviated its trophic state (Yan et al. 2011).

**Temporal trends of water quality in Taihu**

**Annual dynamics of water quality**

The interannual variation of seven parameters and TLI for Taihu from 2015 to 2019 was shown in Fig. 6. The trophic state of Taihu and each sub-lake was relatively stable. Zhushan Bay reached middle-eutrophication and the Eastern Region was mesotrophic in most years, while the other sub-lakes were light-eutrophication. Mk test was applied to estimate the long-term variation trend of each parameter based on monthly mean concentration (Fig. 7). Results illustrated that the concentration of BOD\textsubscript{5} \((p < 0.05)\) and TN \((p < 0.01)\) of Taihu decreased significantly, but the value of TP \((p < 0.01)\), SD \((p < 0.01)\), and Chl-a \((p < 0.05)\) increased notably in the last five years.

The concentration of COD\textsubscript{Mn}, BOD\textsubscript{5}, and NH\textsubscript{3}-N had maintained a good state and decreased in most sub-lakes for these years, and all of them met GB Level III in 2019. TN was the most severe parameter that inferior to the standard, but TN concentration of the Taihu had marked downward trends. The TN concentration for Taihu declined from 1.69 mg/L in 2015 to 1.42 mg/L in 2019, and six sub-lakes had reductions close to or more than 25%. The water quality of Zhushan Bay had improved most obviously in the past five years, with concentration...
declining from 4.28 mg/L in 2015 to 3.1 mg/L (inferior to Level V) in 2019. While Zhushan Bay was still the most polluted area, whose TN concentration was much higher than the mean concentration of lake-level (1.31 mg/L).

At the lake level, the yearly concentration of TP, Chl-a, SD substantially increased by 33.41%, 23.72%, and 41.20% respectively, between 2015 and 2019 (Fig. 6b). The increase of the transparency in all sub-lakes showed that the turbidity of Taihu decreased and the underwater light environment improved. The TP concentration of Zhushan Bay was the highest among the seven sub-lakes, and it fluctuated between 0.127 and 0.176 mg/L, reaching Level IV for five years. It had the biggest increasing rate (162%) of Chl-a concentration in five years.

Fig. 6 a Annual changes of water quality parameters and TLI of each sub-lakes and the Taihu from 2015 to 2019; b The rate of change in concentration of parameters comparing 2015 with 2019.

Fig. 7 MK test results of long-term trend for water quality parameters of Taihu from 2015 to 2019.
Drivers of water quality long term trends in Taihu

(1) Decline of the pollutant concentration in rivers inflow leads the decrease of concentration of TN, CODMn, BOD5, and NH3-N

In recent years, CODMn, BOD5, NH3-N, and TN concentrations in Taihu reduced in varying degrees (Fig. 6; Fig. 7). A series of countermeasures aimed at decreasing wastewater effluent discharge and water quality improvement has been implemented, including the upgrading and reconstruction of sewage treatment plants in the basin, the shutdown of heavily polluting and substandard enterprises, the construction of high standard farmland, the installation of sewage pipeline network, and reduction in the usage of chemical fertilizer (Qin et al. 2019). All these measures made the water quality of the rivers around the lake better and further improved the water environment of Taihu.

Taihu remained light-eutropher stably in recent years. The main reason for TLI changing slightly in the long term was that the value of TN, CODMn, and SD reduced while the TP and Chl-a concentration increased. As a result, the value of TLI remained steady under the synchronous interaction for improvement and deterioration.

(2) The accumulated P load in the sediment and the higher algae biomass in Taihu make the TP and Chl-a concentration increase

The TP and Chl-a concentration rebounded around 2015, which was a remarkable phenomenon that also was identified in several latest studies (Wang et al. 2019a, b, c, d; Zhang et al. 2021; Zhu et al. 2018, 2021). The TP concentration in Taihu raised from 0.061 mg/l in 2015 to 0.081 mg/l in 2019 (Fig. 6), notwithstanding the decline of TP pollution load from the input rivers since 2016 (TBA, 2018). It is difficult to restore a eutrophic lake solely by nutrient reduction. The endogenous pollution plays an important role in the process of P pollution. Compared to N, P is more likely to combine with metal ions to form sediment deposited at the bottom of the lake. The proportion of TP flowing out of the lake is small, so the P concentration of sediment is always at a high level in the annual accumulation despite the decline of external input P loading (Mao et al. 2020).

There is a feedback between P nutrient and cyanobacteria. The rapid growth of cyanobacteria, pumping a large amount of P from the sediment, facilitates the release of P nutrients and increases the P concentration in the lake. The number of cyanobacteria in Taihu increased significantly since 2015 (Table 2). The average density of cyanobacteria rose from 39.2 million/L in 2015 to 86.2 million/L in 2018. Data assisted in explaining that the mounting algae of Taihu affected the increase of P concentration. Previous researches demonstrated that in the case of the inextricable problem of the high algae biomass in the lake, TP concentration would still maintain a high level (Lau and Lane 2002; Zhu et al. 2021).

(3) Sharp reduction of submerged vegetation area in 2015 reduced the absorption of nutrients

Aquatic plants, a main factor affecting the nutrients release of the sediment, serve to retard stormy waves, immobilize the bottom mud, increase water transparency, and suppress the growth and reproduction of algae (Wang et al. 2019a, b, c, d). However, the distribution area of aquatic plants of Taihu reduced sharply in 2015, being the smallest in the past decade (TBA, 2018). The submerged vegetation area in 2013 was 682 km², while the area in 2016 was only 184 km² (Fig. 6). Although the distribution area gradually increased after 2016, the scope had not recovered to half of the largest distribution area in 2013. This significant change was also found by remote-sensing image interpretation, announcing that the high-intensity, large-scale, and mechanized salvage of aquatic plants conducted by the local government are the main reason for the sharp decrease of submerged macrophyte (Wang et al. 2019a, b, c, d). The decrease of submerged vegetation not only reduced the absorption of P directly but also indirectly inhibit the growth of algae by competing with algae for nutrients (Wu et al. 2021a, b)(Wu et al. 2021a, b). The effects of these functions were weakened after the sharp reduction of submerged plant area, which led to the increase of Chl-a and TP concentration in the lake.

| Year | Submerged vegetation area(km²) | Cyanobacteria density (×10⁶ cell/L) |
|------|--------------------------------|-----------------------------------|
| 2013 | 682                            | 40.1                              |
| 2014 | /                               | 56.6                              |
| 2015 | /                               | 39.2                              |
| 2016 | 184                            | 82.8                              |
| 2017 | 268                            | 117.7                             |
| 2018 | 284                            | 86.2                              |

Data obtained from Taihu Basin Authority Ministry of Water Resources. The value of submerged vegetation area in 2014 and 2015 was lacking.
Seasonal variation of main water quality parameters in Taihu

The TN, TP, and Chl-a concentrations showed notable seasonal characteristics (Fig. 8a). The TN concentration was higher in spring and winter, while the TP and Chl-a concentrations were higher in summer and autumn reversely. These observations were consistent with the finding of previous studies (Wang et al. 2019a, b, c, d; Zha et al. 2018). To explore the factors influencing the seasonal change of these parameters, correlation analysis (Fig. 8b) was applied for the above three water quality parameters with two hydrological parameters, water temperature (WT) and water level (Z), based on the monthly monitoring data of each sampling site.

Seasonal variation of TN concentration is mainly due to the following two reasons. For one thing, the change characteristics of monthly mean TN concentration of Taihu were consistent with those of main rivers entering the lake (Fig. 5). The heavy use of fertilization during the spring cultivation period raises the external N load input carried by surface and underground runoff. For another, there was a significant negative correlation between TN concentration and water temperature, as well as a slight negative correlation with the water level (Fig. 8). The low precipitation and water level in cold winter condense the N concentration in the lake. Therefore, for seasonal pollution prevention of N of Taihu, attention should be paid to the adjustment of the water level in the dry season and the strict limitation of the input of non-point source N load.

Monthly Chl-a concentration in Taihu has a good positive response relationship with TP concentration and water temperature, especially in small bays such as Wuli Bay and Zhushan Bay (Fig. 8b, Fig. 9). Higher water temperature and P concentration in summer and autumn are beneficial to the growth of algae, and the algae inhabitation can promote the release of P in sediment and accelerate the P cycle in lake, indirectly increasing the TP concentration in turn (Wu et al. 2021a, b). The significant fluctuation of monthly concentration is a basic feature of Chl-a in Taihu. The algal biomass and Chl-a concentration in lake may be more affected by hydrometeorological conditions, such as intense rainfall and strong winds, than nutrients (Zhu et al. 2018). Therefore, it is necessary to prevent the great impact of hydrological and meteorological conditions on cyanobacteria blooms. In addition, seasonal cyanobacteria blooms and P pollution in small bays should be paid more attention.

Conclusion

Our study puts forward a technology framework to explore the spatiotemporal dynamics of water quality and trophic state and their driving factors in the urban lakes, which was used in Lake Taihu with data from 2015 to 2019. The results indicated that water quality in Taihu remained poor (GB Level IV) these years and Taihu was generally in a state of light-eutropher (TLI, 53.1 - 54.6). Benefited from the comprehensive control measures of limiting the external pollution loading, the concentration of COD$_{\text{Mn}}$, NH$_3$-N, BOD$_5$,...
TN, and SD in Taihu, especially in northwestern Taihu, meliorated in varying degrees. However, the concentration of TP and Chl-a got worse. In light of the above, we found out reasons and put forward the suggestions.

(1) P and Chl-a, the two most prominent indicators affecting eutrophication, have great natural fluctuations caused by sediment release, submerged plant area, algae blooms and seasonal factors (e.g., temperature, rainstorm), and other factors. These natural fluctuations of P and Chl-a in the water body should be fully considered when making nutrient concentration control targets for large shallow eutrophic lakes.

(2) Besides focusing on the sub-lakes that have always had poor water quality (e.g., Zhushan Bay), more attention should be paid to the sub-lakes with potential deterioration trends like Wuli Bay. It needs diversiform measures to mitigate water pollution and eutrophication in small and closed bays, such as limiting the coastal point and non-point source pollution into lake, implementing ecological engineering to enhance water self-purification capability, and constructing water diversion project to increase water flow and water exchange.

Author contribution The authors state that they participated in the design of the article prepared in the following way: Y., W: Conceptualization, Writing-Original Draft & Review & Editing, project administration. Y., G: Writing—Original Draft & Review & Editing, Visualization, Supervision. Y., Z: Resources, Supervision, Funding acquisition.

L., W: Writing- Review & Editing. Y., C: Investigation, Methodology. L., Y: Formal analysis.

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Data availability Not applicable.

Declarations

Ethics approval The authors express their ethical approval of the contents of the submitted work.

Consent to participate The authors express their consent to have participated in the submitted work.

Consent for publication The authors state that the data used is in the public domain and may be published.

Competing interests The authors declare no competing interests.

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