Pol. J. Environ. Stud. Vol. 31, No. 5 (2022), 4383-4397
DOI: *10.15244/pjoes/149350* ONLINE PUBLICATION DATE: 2022-07-14

Original Research

Long Term Comprehensive Evaluation of Temporal and Spatial Variation of Water Quality in Chaohu Lake, China

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Received: 2 March 2022
Accepted: 21 April 2022

Abstract

To clarify trends in water quality in Chaohu Lake, 480 surface water samples were collected monthly from 8 sampling sites in the eastern and western Chaohu Lake regions from 2016 to 2020. The content of dissolved oxygen (DO), permanganate index (COD_{Mn}), ammonia nitrogen (NH_3-N), total phosphorus (TP), total nitrogen (TN), and Chlorophyll a (Chl-a) were analyzed, and the water quality of Chaohu Lake was comprehensively evaluated by a comprehensive nutrient status index method and a fuzzy clustering method. The average contents of TP and TN in Chaohu Lake decreased over time. The mean values of TP and TN ranged from 0.049 to 0.16 mg/L and 0.98 to 2.2 mg/L, respectively. The mean value of NH_3-N decreased from 0.27 mg/L in 2016 to 0.098 mg/L in 2020. The mean value of COD_{Mn} decreased by 22.96% compared with 2016. Based on the fuzzy clustering method and a comprehensive trophic state index, the water quality of the lake was increased from 2018 to 2020, and the comprehensive trophic state value decreased significantly, also indicating that the overall water quality of Chaohu Lake has improved since 2018. The results of this study could provide a reference for the prevention and control of water pollution in the Chaohu Lake Basin.

Keywords: nutrient content, trophic level index, fuzzy clustering, water quality assessment, Chaohu Lake

Introduction

As one of the five major fresh water lakes in China, Chaohu Lake has a high population density and vigorous economic activity [1-3]. In recent years, with the further acceleration of urbanization, the total amount of pollutant emissions has increased, resulting in serious eutrophication and frequent outbreaks of cyanobacteria blooms, which affect the sustainable development of the regional social economy [4-6]. Scientific evaluation of water quality indicators in Chaohu Lake is conducive to an in-depth understanding of the mechanisms of eutrophication in Chaohu Lake, and can provide a basis for the scientific formulation of water pollution prevention and conservation planning [7, 8]. How to objectively and accurately reflect the current situation of water pollution in Chaohu Lake is the focus of scientific evaluation.

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At present, the commonly used water quality evaluation methods include the single factor evaluation, water quality index, comprehensive nutritional status index, and fuzzy clustering methods [9]. The single factor evaluation method is the main method of water quality evaluation in China at present. It is simple and feasible to determine the overall pollution degree of a water body by using the pollution level of the worst factor, and it is the water quality evaluation method stipulated in The Surface Water Environmental Quality Standard [10]. This can directly reflect the individual components of pollution, but it does not fully reflect overall water quality [11, 12]. The comprehensive trophic state index method is used to identify the trophic level of lakes by evaluating the eutrophication status [13]. However, the evaluation result is only a relative value, and it can not be used to assess the functional category of water quality, resulting in a similar trend of eutrophication levels in different areas of the lake [14]. The fuzzy clustering evaluation method is based on fuzzy mathematics [15]. According to the principle of membership degree in fuzzy mathematics, qualitative assessments are transformed into a quantitative evaluation, rendering a more comprehensive evaluation of an object as affected by multiple factors [16, 17]. For lakes, it fully considers the transition of water quality grading boundaries, and can objectively and comprehensively reflect the water quality under the influence of multiple factors [18, 19]. The fuzzy clustering evaluation and comprehensive nutrient index methods have different emphases in water quality evaluation. Fuzzy clustering evaluation evaluates lake quality from the water pollution level, whereas the comprehensive nutrient index method evaluates lake status from the overall environmental quality level of the ecosystem. The combination of these two evaluation methods can provide a robust evaluation of the water quality for Chaohu Lake.

This study examined the water quality of surface water in Chaohu Lake from 2016 to 2020, including dissolved oxygen, permanganate index, ammonia nitrogen, total phosphorus and chlorophyll a. The comprehensive nutritional status index and fuzzy clustering methods were utilized. The evaluation results provide data to support the comprehensive management of Chaohu Lake and provide insights into the environmental status of other similar lake systems.

Material and Methods

Field Sampling

Chaohu Lake water samples were collected from 2016 to 2020, once a month in the middle of the month. Chaohu Lake is divided into East Lake District and West Lake District. Eight sampling sites were set up (East Lake District: S1-S4, West Lake District: S5-S8).

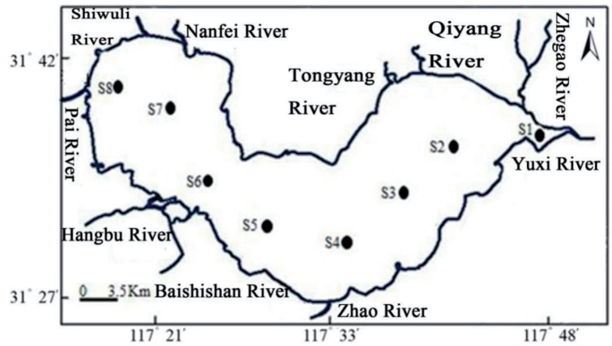

Fig. 1. Sampling sites in Chaohu Lake, China.
(S1-S8 are the locations of sampling points)

Specific sampling points are shown in Fig. 1. One litter of surface water sample was taken for testing.

Determination of Water Quality

The dissolved oxygen (DO) was measured by an oxygen dissolving instrument at the sampling site. In the laboratory, the permanganate index (COD_{Mn}) was measured by digital thermostatic water bath (HH-4) and 50 mL acid burette; and ammonia nitrogen (NH_3-N), total phosphorus (TP), total nitrogen (TN), Chlorophyll a (Chl-a) were measured by ultraviolet spectrophotometer (UV-5500PC).

The concentration of COD_{Mn} was determined by the acid volumetric method, and the specific steps were as follows: Take 100 mL water sample into 250 mL conical flask, add 10 mL (0.01 mol/L) $KMnO_4$ and 5 mL (1 + 3) H_2SO_4, heat in boiling water bath for 30 min, add 10 mL (0.01 mol/L) $Na_2C_2O_4$ sodium oxalate. The solution was then titrated with 0.01 mol/L $KMnO_4$, the volume used was recorded as V. And calculated by

$$COD_{Mn} = \frac{(10 \times K + V \times K - 10) \times M \times 8 \times 1000}{100}$$

The concentration of NH_3-N was determined by spectrophotometry with Nessler's reagent, and the specific steps were as follows: Take 50 mL water sample into 50 mL colorimetric tube, add 1 mL $KNaC_4H_4O_6$ (500 g/L), add 1.5 mL NaOH reagent (4 mol/L NaOH + 10 g/L KI + 100 g/L HgI_2), and let stand for 10 min. The absorbance was measured at 420 nm wavelength by ultraviolet spectrophotometer, and then the concentration of NH_3-N was calculated.

TP was determined by molybdenum-antimony resistance spectrophotometry, and the specific steps were as follows: take 25 mL water sample into 50 mL colorimetric tube, add 4 mL (50 g/L) $K_2S_2O_8$, dissolve in autoclerotic pot (120ºC, 30 min), cools it to room temperature, add water to 50 mL, then add 1 mL (100 g/L) $C_6H_8O_6$ and 2 mL molybdenate solution. The absorbance was measured at 700 nm on ultraviolet spectrophotometer, and then the concentration of TP was calculated.

The concentration of TN was determined by ultraviolet spectrophotometry with alkaline potassium persulfate digestion, and the specific steps were as follows: 10 mL water sample was put into 25 mL colorimetric tube, 5 mL alkaline potassium persulfate solution (40 g/L $K_2S_2O_8$ + 15 g/L NaOH) was added, digested in autoclave (120ºC, 30 min), cooled to room temperature, 1 mL (1 + 9) HCl was added, and then water was added to 25 mL. The absorbance was measured at 220 nm and 275 nm on ultraviolet spectrophotometer, and the concentration of TN was calculated by A = A220 - A275.

The concentration of Chl-a was determined by acetone extraction, and the specific steps were as follows: take 100 mL water sample for filtration, use tweezers to clip the filter membrane into 10 mL colorimetric tube, add 10 mL (90%) acetone, under dark and cold storage treatment (4ºC, 12 h), centrifugation (3000 r/min, 10 min). The absorbance was measured at 750 nm, 664 nm, 647 nm and 630 nm on ultraviolet spectrophotometer, and then the concentration of Chl-a was calculated by ρ = 11.85 × (A664 - A750) - 1.54 × (A647 - A750) - 0.08 × (A630 - A750).

For detailed analysis steps, refer to Water and Wastewater Monitoring and Analysis Method [20].

Data Processing and Evaluation Methods

Comprehensive Nutritional Status Index Method

The construction idea of the state index (*TLI*) is to divide the eutrophication level into a continuous score of 0-100. The higher the score is, the higher the eutrophication level is. It is assumed that the corresponding *TLI* (Chl-a) is 100 when the concentration of Chl-a reaches 10 mg/L, and the corresponding *TLI* (Chl-a) is 0 when the concentration of Chl-a reaches 0.0001 mg/L. The equation to calculate Chl-a was *TLI* (Chl-a) = 10 × (2.5 + 1.086 lnChl-a), and other water quality formulas were derived by combining the relationship between water quality indexes (TN, TP, SD, COD_{Mn}) and Chl-a [21].

The comprehensive nutritional state index (*TLI* (Σ)) was based on the *TLI* of Chl-a, and 2-3 state indexes close to the benchmark state index *TLI* (Chl-a) were selected from the other water quality indexes (TN, TP, SD and COD_{Mn}) to conduct weighted synthesis with *TLI* (Chl-a) [22]. The formula is:

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

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

where, W_j is the relative weight of the nutritional status index of the j[th] species parameter. *TLI* (j) represents the trophic state index of the j[th] species, and the parameter r_{ij} represents the correlation coefficient between the j[th] species parameter and the reference parameter Chl-a.

Lake nutrient status was divided into five grades: low (*TLI*<30), moderate (30≤*TLI*≤50), mild (50<*TLI*≤60), moderate (60<*TLI*≤70) and severe (*TLI*>70).

Fuzzy Clustering Method

The fuzzy clustering method was used to select DO, COD_{Mn}, NH_3-N, TP and TN as evaluation factors, and the annual average value of evaluation factors at each sampling point was taken as the annual monitoring value. The water quality of Chaohu Lake was analyzed by establishing the membership degree and weight of the factors along with the compound operation of the fuzzy matrix [16, 17].

Calculating the Membership Degree of the Factors

We established water quality category and grade representative value (e(n)) based on GB3838-2002 Environmental Quality Standard for Surface Water [23]. The representative values of water quality categories

Table 1. The quality of surface water.

On behalf of the value	I	II	III	IV	V
Water quality classification	National nature reserve, water quality is not polluted	Cleaner, can be used as drinking water after filtration	After filtration and cleaning, it can be used as common industrial water	Water for general agriculture, irrigation	Common landscape water

Table 2. The graded representative value of each evaluation factor.

The evaluation factors	e(I)	e(II)	e(III)	e(IV)	e(V)
DO	≥ 7.5	≥ 6.75	≥ 5.5	≥ 4	≥ 2.5
COD_{Mn}	≤ 2	≤ 3	≤ 5	≤ 8	≤ 12.5
NH_3-N	≤ 0.15	≤ 0.325	≤ 0.75	≤ 1.25	≤ 1.75
TP	≤ 0.01	≤ 0.0175	≤ 0.0375	≤ 0.075	≤ 0.15
TN	≤ 0.2	≤ 0.35	≤ 0.75	≤ 1.25	≤ 1.75

and selected factors are shown in Table 1 and Table 2 respectively.

The membership function of evaluation factors is a segmented function and the fuzzy distribution is a half trapezoidal distribution.

The membership function of the first-grade water quality is:

$$\mu_1(x)=\begin{cases}1 & x \le e(\mathit{I}) \\ \frac{[e(\mathit{II})-x]}{[e(\mathit{II})-e(\mathit{I})]} & e(\mathit{I}) \le x \le e(\mathit{II}) \\ 0 & x \ge e(\mathit{II})\end{cases} \quad (3)$$

The subordinate function of secondary water quality is:

$$\mu_2(x)=\begin{cases}1-\mu 1(x) & e(\mathit{I}) \le x \le e(\mathit{II}) \\ \frac{[e(\mathit{III})-x]}{[e(\mathit{III})-e(\mathit{II})]} & e(\mathit{II}) \le x \le e(\mathit{III}) \\ 0 & x \ge e(\mathit{III})\end{cases} \quad (4)$$

The membership function of the last grade water quality is:

$$\mu_{n+1}(x)=\begin{cases}0 & x \le e(n) \\ 1-\mu n(x) & e(n) \le x \le e(n+1) \\ 1 & x \ge e(n+1)\end{cases} \quad (5)$$

Calculate the Weights

The weight values of individual factors were calculated according to the following formula:

$$W_i = C_i / S_i \quad (6)$$

where, W_i is the weight of factor i; C_i is the measured concentration of factor i, and S_i is the environmental quality base point value of factor i (the cut-off point between "clean" and "polluted").

To carry out fuzzy operation, the weight value of each factor is normalized to get the weight of the factor

$$V_i = W_i / \sum W_i \quad (7)$$

Where V_i is the weight of factor i.

Compound Operation of the Fuzzy Matrix

The weight set of each factor at the same sampling point is multiplied by the membership matrix of the evaluation factor calculated above to obtain the comprehensive evaluation water quality level matrix. The water quality category corresponding to the maximum membership value in the matrix is regarded as the fuzzy comprehensive evaluation level of water quality.

Results and Discussion

Temporal and Spatial Variation of Water Quality Factor Content in Chaohu Lake

The quarterly monitoring mean and statistical comparison of each sampling point 2016-2020 are shown in the Attached Table part (Table 1 and Table 2). The seasonal contents of DO, COD_{Mn}, NH_3-N, TN, TP and Chl-a ranged from 6.76-13 mg/L, 1.97-9 mg/L, 0.03-2.43 mg/L, 0.63-4.55 mg/L, 0.03-0.24 mg/L and 1-111 mg/m^3, respectively. The p-values of the six data sets (DO, COD_{Mn}, NH_3-N, TN, TP and Chl-a) were all less than the given α-level (0.05), and the data presented non-normal distribution.

Time Distribution Characteristics of Each Water Quality Index

The temporal distribution of DO, COD_{Mn}, NH_3-N, TP, TN and Chl-a concentration in Chaohu Lake 2016-2020 is shown in Fig. 2. In addition, the Shapiro-Wilk test was used to analyze the normality of the above data sets, and non-parametric sign test was applied to judge the significant difference of data. According to the statistical results of non-parametric comparison methods, DO (2a), TN (2e) and Chl-a (2f) in water body did not change significantly year to year. The mean value of DO varied from 8.17 to 12.7 mg/L (P = 0.878). The average value of TN was 0.98-2.2 mg/L (P = 0.311). As can be seen from Fig. 2, TN generally decreasing from 1.7 mg/L in 2016 to 1.36 mg/L in 2020. The average value of Chl-a (2f) varied from 1.50 mg/m^3 to 35.25 mg/m^3 (P = 0.078) and showed an overall increasing trend, from 6.4 mg/m^3 to 9.8 mg/m^3. Non-parametric statistical results confirmed that COD_{Mn} (2b), NH_3-N (2c) and TP (2d) showed a decreasing trend. The mean value of COD_{Mn} was 2.98-6.31 mg/L (P = 0.005), which decreased from 4.53 mg/L in 2016 to 3.49 mg/L in 2020, 22.96% lower than that in 2016. The mean value of NH_3-N ranged 0.04-0.59 mg/L (P = 0.013), which decreased from 0.27 mg/L in 2016 to 0.098 mg/L in 2020, decreasing by 63.70% compared with 2016. The mean value of TP was 0.049-0.16 mg/L (P = 0.018), which increased from 2016 to 2017, and decreased from 2017 to 2020, with an overall decrease of 33.33%.

The overall concentrations of NH_3-N, TN and TP in Chaohu Lake decreased from 2016 to 2020. NH_3-N mainly comes from point source pollution discharge of urban living and industrial wastewater [24]. Zhang [25] showed that with the improvement of the take-over rate of the sewage pipe network in the Chaohu Lake basin and the improvement of urban domestic sewage treatment facilities, the direct discharge of wastewater was effectively controlled, which may have reduced the total amount of NH_3-N entering the lake. The sources of TN and TP in the lake body are not only related to point source pollution such as wastewater discharge, but also to non-point source pollution such as farmland water withdrawal, animal husbandry, and sediment disturbance and re-suspension in the lake body [24]. Wang [26] showed that in most cases in nature, N and P cycles are one-way flow processes, but N and P precipitate into the sediment. Under certain conditions, N and P in the sediment will be released into the water body again. With the improvement of urban sewage treatment efficiency and the implementation of watershed protection measures, the input of exogenous N and P pollution in the water body gradually decreases, but the release of endogenous N and P remains an important factor in maintaining the eutrophication status of a water body. Due to the lack of control on the internal release of Chaohu Lake, TN and TP in Chaohu Lake water decreased significantly.

The overall concentration of Chl-a increased from 2016 to 2020. Chl-a is an important indicator of phytoplankton standing stock, and the level of its content can reflect the nutritional status of a water body [27]. The content of Chl-a in a freshwater lake is controlled by many factors. In general, N and P nutrients have an important effect on the growth of algae in a lake. Water temperature also is an important variable for algae growth and photosynthesis, thus affecting the concentration of Chl-a [28]. In the summer of 2018, under the combined action of high phosphorus and high temperature. Microcystis multiplied rapidly and formed visible cyanobacteria blooms, which spread to the whole lake as driven by wind, resulting in an abnormal increase of Chl-a content, a finding consistent with the study of Zhang [25].

The content of COD_{Mn} increased significantly from 2018 to 2019. COD_{Mn} is a comprehensive index to assess organic pollution in water [29]. Wu [30] showed that the level of COD_{Mn} in a water body has a certain correlation

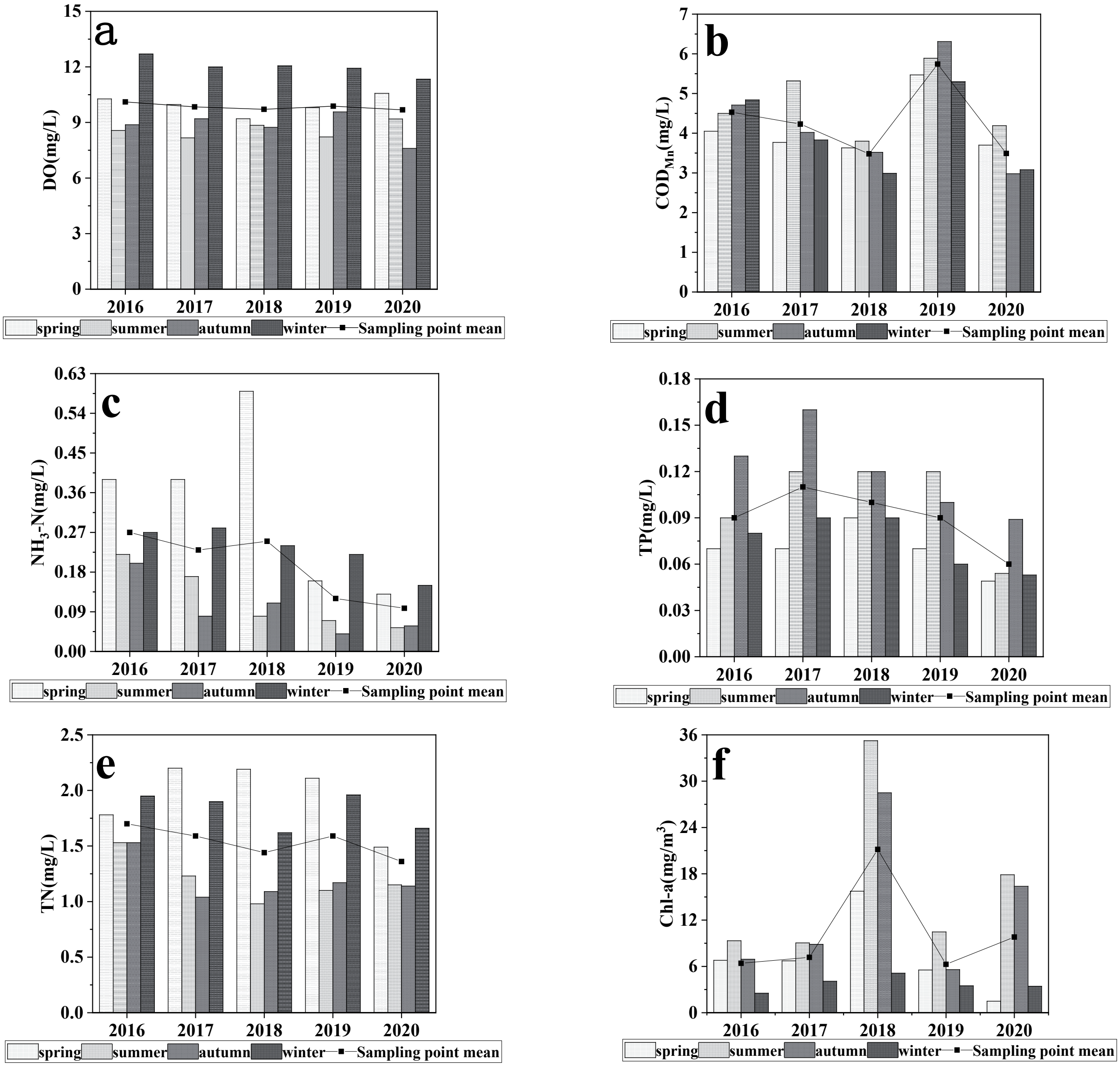

Fig. 2. Temporal distribution of DO a), COD_{Mn} b), NH_3-N c), TP d), TN e), Chl-a f) mean concentration in Chaohu Lake during 2016-2020.

with hydrological characteristics, as well as social and economic activities of adjacent regions. The significant increase of COD_{Mn} concentration 2018-2019 was because of the lack of ecological water turn over and poor water movement in Chaohu Lake. On the other hand, the content of Chl-a increased significantly after 2018, and the area of cyanobacteria bloom increased significantly [25]. The concentration of Chl-a reflects the type and quantity of phytoplankton (algae). Algae photosynthesis produces a large amount of organic matter, and COD_{Mn} increases when the abundance of algae in the water is high [31].

Spatial Distribution Characteristics of Each Water Quality Index

Fig. 3 shows the spatial distribution of DO (3a), COD_{Mn} (3b), NH_3-N (3c), TP (3d), TN (3e) and Chl-a (3f) concentrations in Chaohu Lake. According to the statistical results of non-parametric comparison methods. The concentrations of COD_{Mn}, NH_3-N, TP, TN and Chl-a in water tended to increase from east to west. The spatial distribution change of DO concentration was not obvious. Seasonal differences in water quality indexes also are obvious. The concentrations of DO, NH_3-N, and TN in the water body were relatively higher in spring and winter, but lower in summer and autumn; COD_{Mn}, TP and Chl-a are relatively high in summer and autumn, but low in spring and winter.

COD_{Mn}, NH_3-N, TN, TP and Chl-a concentrations in Chaohu Lake increased gradually from east to west [25]. Data show that a large number of industrial wastewater and domestic sewage flow into the west half of the lake through Tangxi River, Shiwuli River, Nanfei River, Pai River. As a result, about 80% of the incoming pollution load of Chaohu Lake enters the western half of the lake [4]. There is also, excess salt content in the western half of the lake [32], further contribution to worse water quality. Due to the inflow of the Yuxi river and Zhegao River, the concentrations of nutrients, organic matter and phycyanin in the eastern lake area showed a significant trend of increase [25]. Therefore, the concentrations of COD_{Mn} and Chl-a in the eastern lake are higher than those in the central lake.

Zhang [33] showed that water quality changes in different seasons were mainly affected by temperature, precipitation and hydrological conditions. The concentration of DO in water is strongly affected by temperature, the higher the temperature of the water, the lower the concentration of DO [34, 35]. In summer and autumn, with the increase of rainfall and run-off, organic pollution from agricultural non-point sources increased, leading to the increase of COD_{Mn} [23]. A large amount of water in summer and autumn has a strong dilution effect on N concentrations. At the same time, with the increase in water temperature, the effect of microorganisms in the basin is enhanced, which leads to decreased nutrient concentrations in the water. By contrast, low rainfall in winter and spring resulted in lower water levels, less dilution and purification capacity, and weaker microbial activity, and thus increased NH_3-N and TN contents in the water [33].

TP content is relatively high in summer and autumn. DO can control the adsorption and release of phosphorus in sediments by controlling the redox potential of water bodies. The low concentration of DO in summer and autumn leads to a low redox potential near the sediments, and the reduction reaction of Fe^{3+} occurs. During the reduction of Fe^{3+} to Fe^{2+}, a large amount of iron-bound phosphorus is released into the overlying water [36]. Conversely, because of the high water temperatures in summer and autumn, cyanobacteria will absorb N from the water, which promotes the release of phosphorus and leads to an increase in TP [37]. The concentration of Chl-a in water is mainly related to water temperature and N and P [28]. The average water temperature in Chaohu Lake reaches its lowest point from December to March. Even if abundant nutrients flow into the water at this time, the low water temperature will inhibit the growth of phytoplankton, resulting in a low concentration of Chl-a in spring and winter [27]. However, in summer and autumn, the water temperature can meet the needs of algae growth. At this time, the main influencing factor of Chl-a concentration change is the concentration of N and P nutrient, and the higher P concentration leads to the higher concentration of Chl-a [28].

In conclusion, from 2016 to 2020, although the evaluation factors showed an overall trend of improvement, the main pollution indicators TN, TP, and COD_{Mn} still showed a nonsignificant trend, and the pollution of Chl-a was deteriorated. The content of TN in the lake area was mainly related to exogenous pollution, whereas COD_{Mn}, TP and Chl-a were not only related to exogenous pollution but also affected by endogenous processes via cyanobacteria growth. Based on the variation of each index in different seasons, it can be concluded that in summer and autumn, focused attention should be paid to COD_{Mn}, TP and Chl-a. The influence of TN on water quality should be considered in spring and winter.

Chaohu Lake Water Quality Evaluation

Comprehensive Nutritional Status Index Method

Fig. 4a) shows the temporal changes of the nutrient status index of Chaohu Lake from 2016 to 2020. The comprehensive nutrient status index (*TLI* (Σ)) increased in 2016-2018, and decreased year by year from 2018 to 2020. *TLI* (Σ) showed an overall downward trend, and the nutrient status of the lake improved from light eutrophication in 2016 to mesotrophication in 2020. *TLI* (Σ) has obvious seasonal differences, with relatively high values in summer and autumn.

As can be seen from Fig. 4b), the *TLI* (Σ) of each sampling point shows increased from east to west. The mean cross sections of S1-S4 at each point in the East

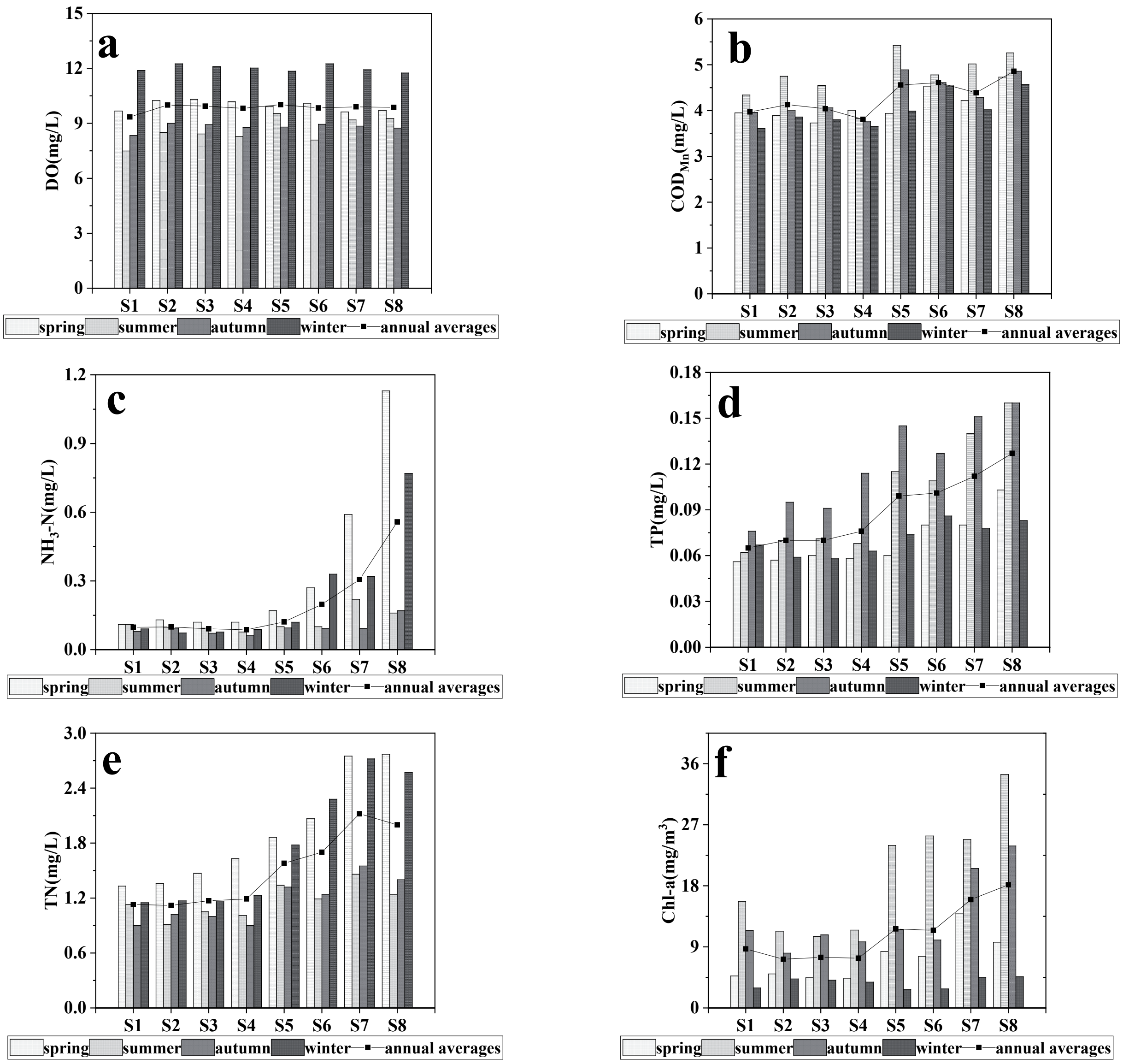

Fig. 3. Spatial distribution of DO a), COD_{Mn} b), NH_3-N c), TP d), TN e), Chl-a f) mean concentration during 2016-2020 in Chaohu Lake.

Lake Area were mesotrophic (47.89-48.09). The average cross sections of S4-S8 in The West Lake area reached a state of light eutrophication level (52.83-56.54), indicating that the main pollution of Chaohu Lake is still in the western half of the lake. There are significant seasonal differences in *TLI* (Σ) at each sampling point. Generally, *TLI* (Σ) was higher in summer and autumn, and *TLI* (Σ) was also higher in spring in the heavily polluted West Lake area.

The Fuzzy Evaluation Method

According to the calculation formula of Fuzzy clustering method, membership values of evaluation grades of each sampling point in Chaohu Lake during 2016-2020 were obtained as shown in fig. 5. In 2016, the water quality of S1-S4 sampling sites in the eastern half of the lake belonged to Class IV, and the water quality of S5-S8 sampling sites in the western half of the lake belonged to Class V. In 2020, the water quality of four sampling sites in the eastern half of the lake increased to Class III, and the water quality of the western half of the lake increased to Class IV except sampling site S8, which was still in Class V. The evaluation results showed that with time, the overall water quality of the sampling sites was improved. At the site, the overall water quality of each sampling site gradually deteriorated from east to west.

Since the comprehensive evaluation of the water quality of each sampling point cannot completely reflect the overall changes in water quality, a comprehensive evaluation result of water quality of Chaohu Lake can be obtained by weighted average of the evaluation sets of each sampling point. Based on the weighted average of the comprehensive evaluation sets of 8 sampling points in Chaohu Lake, the comprehensive evaluation

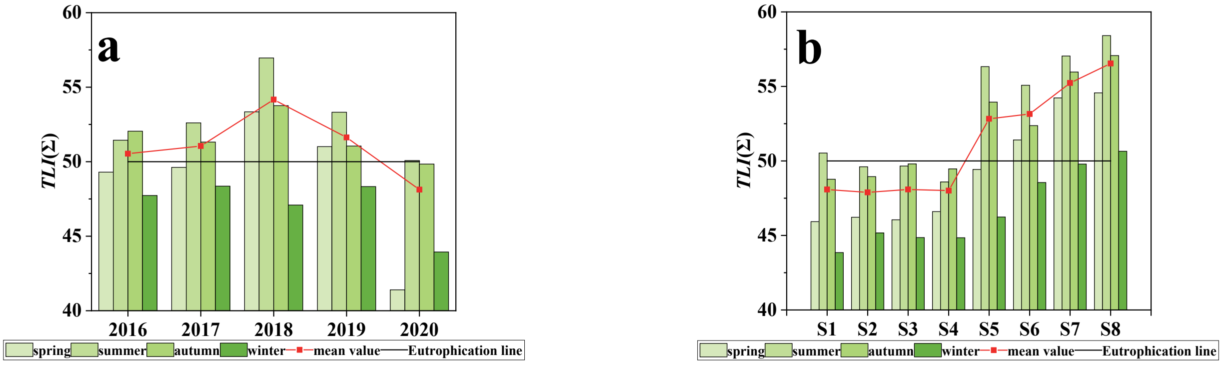

Fig. 4. Temporal changes a) and spatial changes b) of trophic level index of Chaohu Lake from 2016 to 2020.

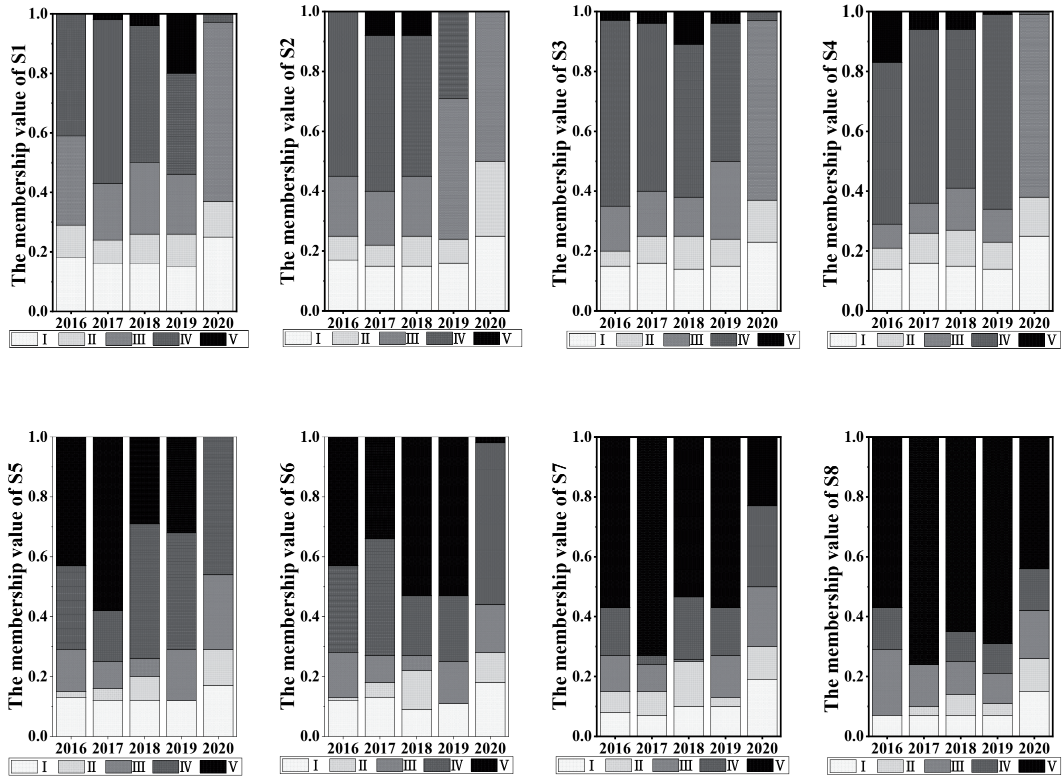

Fig. 5. Membership value of evaluation grade of each sampling point from 2016 to 2020.

results of Chaohu Lake in 2016-2020 were obtained. The comprehensive evaluation results of the whole lake area are shown in Table 3.

It can be seen that from 2016 to 2017, the water quality decreased from Grade IV to Grade V. From 2018 to 2020, the comprehensive evaluation water quality level increased from Grade IV to Grade III.

Comprehensive Analysis of Water Quality Results of Chaohu Lake

According to the evaluation results of comprehensive nutritional status, the eastern areas of Chaohu Lake had a mesotrophic status and the western area a mild eutrophic status. The evaluation of lake nutritional status can indicate the environmental quality level of the lake ecosystem, which indicates that the environmental quality of west Chaohu Lake is still poor, and the prevention and control efforts should be strengthened [24]. From 2016 to 2020, the nutritional status of each sampling site showed obvious seasonal differences, with a relatively high nutritional status in summer and autumn.

According to the evaluation results of the fuzzy clustering method, the overall water quality of Chaohu Lake improved during 2016-2020, which is consistent

Table 3. Comprehensive evaluation of the water quality in Chaohu lake from 2016 to 2020.

Year	I	II	III	IV	V	The evaluation results
2016	0.12	0.07	0.11	0.36	0.34	IV
2017	0.12	0.07	0.09	0.30	0.42	V
2018	0.13	0.12	0.03	0.47	0.25	IV
2019	0.14	0.02	0.15	0.41	0.28	IV
2020	0.21	0.11	0.36	0.32	0	III

with the analysis of the water quality change trend of Chaohu Lake by Zhang [25]. The water quality of some sampling sites in East Chaohu Lake (S1) and West Chaohu Lake (S8) was slightly decreased, and the water quality of other sampling sites (S2, S3, S4, S5, S7) was significantly improved. This indicates that the water quality in the middle part of Chaohu Lake is improving, and the water quality in the eastern and western parts of Chaohu Lake is deteriorating year by year [24]. The government should strengthen the prevention and control of the polluted rivers in the east (Yuxi River, Zhegao River) and the polluted rivers in the west (Hangbu River, Pai River, Shiwuli River, Nanfei River). The water quality of each sampling site gradually deteriorated from east to west, indicating that the release of endogenous nutrients is also an important source of maintaining eutrophication in Chaohu Lake [38]. Therefore, while treating exogenous pollution, we should strengthen the treatment of endogenous pollution.

Summary

The main summary of this study are as follows:

1) Analysis of water quality factors (DO, COD_{Mn}, NH_3-N, TP, TN, Chl-a) in Chaohu Lake from 2016 to 2020 showed that NH_3-N content decreased significantly, whereas the mean values of TP, TN, and COD_{Mn} decreased slightly. The content of Chl-a increased significantly. The contents of NH_3-N and TN in the whole lake area are relatively higher in spring and winter, concentrations of COD_{Mn}, TP, and Chl-a were relatively high in summer and autumn.

2) *TLI* (Σ) results show that the overall state of Chaohu Lake changed from light eutrophic to mesotrophic state from 2016 to 2020. The results of the fuzzy evaluation of water quality of each sampling point showed that the water quality of the eastern half of Chaohu Lake (S2, S3, S4) improved year by year, whereas the water quality of the western half of Chaohu Lake (S8) was generally poor and deteriorated. The water quality of the whole lake area decreased from Grade IV to Grade V from 2016 to 2017, and increased to Grade III in 2020.

3) The fuzzy clustering method was objective and comprehensive in evaluating the water quality, because the weight and membership degree of water quality factors are integrated to determine the water quality category, and the comprehensive impact of multiple factors on a water body is fully considered. The fuzzy clustering evaluation and comprehensive nutrition index methods were integrated to evaluate Chaohu Lake from two aspects: water pollution grade and environmental quality level of the lake ecosystem.

Acknowledgments

The study was financially supported by National Science Foundation of China (21777001). Key Research and Development Projects of Anhui Province (202004i07020006). Key Projects of Anhui Provincial Department of Education (KJ2018A0507). Thanks to the teachers and students of Anhui Jianzhu University for their help in writing this paper. The author appreciates all the participants and anonymous reviewers for their valuable comments and criticisms.

Conflict of Interest

The authors declare no conflict of interest.

Attached Tables

Table 1. Chaohu Lake 2016-2020 water quality index content value

Sampling-point	Year	DO (mg/L)				COD_{Mn} (mg/L)				NH_3-N (mg/L)				TP (mg/L)				Chl-a (mg/m^3)				(TN mg/L)			
		Spring	Sum.	Aut.	Wint.	Spring	Sum.	Aut.	Wint.	Spring	Sum.	Aut.	Wint.	Spring	Sum.	Aut.	Wint.	Spring	Sum.	Aut.	Wint.	Spring	Sum.	Aut.	Wint.
S1	2016	10.0	7.43	8.55	12.2	3.61	3.77	3.75	4.30	0.14	0.22	0.15	0.2	0.05	0.04	0.07	0.06	3.75	3.64	2.1	2.3	1.3	1.13	0.83	1.32
	2017	9.86	7.75	8.75	12.2	3.43	4.60	4.47	3.80	0.17	0.15	0.07	0.11	0.06	0.07	0.12	0.07	3.76	4.93	4	2.1	1.34	1.14	0.67	1.12
	2018	8.89	6.89	8.51	12.1	4.20	4.43	4.23	2.73	0.13	0.08	0.09	0.05	0.06	0.09	0.10	0.08	12	42	34	6	1.15	0.93	0.88	0.69
	2019	9.72	6.76	8.51	12.3	3.74	4.31	3.80	2.99	0.03	0.06	0.04	0.03	0.06	0.07	0.06	0.05	3.11	11.02	2.9	2.97	1.79	1.43	1.14	1.54
	2020	9.9	8.6	7.4	10.65	3.77	3.57	2.57	3.25	0.08	0.03	0.05	0.065	0.05	0.04	0.031	0.076	1	17	14	1.4	1.08	1.03	0.97	1.07
S2	2016	10.3	8.59	9.14	12.7	3.47	4.58	3.80	4.46	0.20	0.10	0.15	0.12	0.09	0.05	0.09	0.06	4.58	7.2	2.9	2.87	1.31	0.98	1.85	1.98
	2017	10.2	8.33	9.83	12.2	3.53	5.00	4.27	3.77	0.17	0.17	0.09	0.1	0.05	0.11	0.13	0.08	3.55	5.6	6.68	3	1.57	0.99	0.80	1.06
	2018	9.54	7.90	9.15	12.3	2.90	4.23	4.30	3.15	0.12	0.06	0.1	0.03	0.07	0.09	0.12	0.08	12	21	18	7	1.34	0.73	1.00	0.78
	2019	10.3	8.40	9.33	12.1	5.04	4.22	3.85	3.99	0.04	0.07	0.03	0.03	0.04	0.07	0.05	0.04	3.99	9.8	4.89	3.54	1.72	0.71	0.63	1.17
	2020	10.9	9.3	7.57	11.95	3.53	4.7	2.8	2.95	0.11	0.09	0.1	0.085	0.033	0.032	0.083	0.035	1	13	8	5	0.84	1.13	0.81	0.87
S3	2016	10.6	8.25	8.54	12.9	3.96	4.23	4.40	4.95	0.12	0.12	0.13	0.14	0.07	0.08	0.11	0.07	3.52	7.3	5.03	2.29	1.18	1.38	1.21	1.01
	2017	10.1	8.48	9.36	11.7	3.23	5.33	3.70	3.23	0.14	0.14	0.05	0.10	0.06	0.05	0.09	0.06	3.78	7.15	17	4.49	1.98	1.04	0.71	1.51
	2018	9.68	8.30	9.38	12.4	2.65	4.07	4.07	2.97	0.20	0.08	0.08	0.04	0.07	0.10	0.12	0.08	8	18	9	5	1.20	0.98	1.05	1.01
	2019	10.3	8.55	9.46	11.8	4.17	4.20	4.11	4.70	0.04	0.04	0.05	0.03	0.05	0.07	0.06	0.04	4.96	6.08	4.88	3.74	2.01	0.82	1.09	1.28
	2020	10.87	8.5	7.9	11.7	3.63	3.93	3.03	3.15	0.083	0.083	0.05	0.075	0.05	0.053	0.077	0.04	2	14	18	5	0.99	1.04	0.95	0.97
S4	2016	10.4	8.78	8.56	12.7	3.81	3.57	4.40	4.38	0.19	0.10	0.12	0.12	0.09	0.07	0.17	0.08	4.56	9.61	8.6	2.55	1.55	1.36	1.08	1.21
	2017	10.2	8.51	9.30	11.7	3.33	4.70	3.50	3.40	0.16	0.14	0.05	0.12	0.05	0.06	0.11	0.06	5.03	9.64	15	5.09	1.96	1.00	0.99	1.43
	2018	9.62	8.13	8.66	12.2	3.93	2.80	1.97	3.45	0.12	0.06	0.05	0.05	0.04	0.10	0.13	0.07	6	19	6	3	1.75	0.77	0.68	0.94
	2019	9.90	8.15	9.38	11.9	4.02	3.74	4.84	3.15	0.05	0.06	0.03	0.07	0.07	0.08	0.08	0.06	3.96	5.13	5.15	3.39	1.77	0.87	0.87	1.58
	2020	10.77	7.9	7.93	11.6	3.9	3.33	3.13	2.85	0.087	0.027	0.067	0.08	0.04	0.031	0.08	0.045	2	14	14	5	1.14	1.04	0.87	0.99
S5	2016	10.4	8.48	8.43	12.8	3.91	5.04	5.02	4.99	0.17	0.21	0.19	0.13	0.06	0.11	0.13	0.06	9.23	9.6	7.9	1.76	1.40	2.01	1.85	1.98
	2017	10.0	7.93	9.16	11.9	3.70	5.17	4.93	3.97	0.22	0.13	0.06	0.18	0.06	0.15	0.20	0.12	12.7	12.1	10.21	4	2.12	1.30	0.99	2.13
	2018	9.20	10.5	8.70	11.8	3.05	5.13	4.43	2.80	0.18	0.09	0.12	0.03	0.08	0.13	0.14	0.08	15	60	17	4	1.98	1.07	1.36	1.17
	2019	9.74	8.89	10.0	11.7	4.55	5.48	6.09	4.31	0.11	0.04	0.03	0.15	0.06	0.13	0.11	0.06	3.76	9.08	4.52	2.05	2.23	1.11	1.09	2.04
	2020	10.2	11.87	7.73	11.05	3.47	5.3	2.97	2.9	0.19	0.033	0.077	0.115	0.04	0.056	0.147	0.05	1	29	18	2	1.56	1.22	1.33	1.58

Table 1. Continued.

	2016	10.5	8.33	9.82	13.0	4.16	5.27	6.06	5.94	0.18	0.16	0.17	0.31	0.07	0.09	0.14	0.07	9.78	16.1	9.61	1.75	1.59	1.56	1.84	2.61
	2017	10.0	8.25	9.14	11.6	4.33	5.0	3.67	4.03	0.18	0.13	0.11	0.21	0.07	0.12	0.14	0.12	12.8	8.76	6	3.36	1.82	1.09	1.14	1.53
S6	2018	9.06	8.88	8.92	11.6	4.57	3.27	3.13	3.23	0.84	0.09	0.12	0.77	0.09	0.13	0.10	0.12	7	70	12	3	3.26	0.88	0.72	2.77
	2019	10.1	7.92	9.49	12.5	4.90	5.28	5.94	5.47	0.09	0.08	0.03	0.22	0.10	0.13	0.14	0.07	6.25	11.87	4.51	3.98	1.90	1.32	1.35	2.4
	2020	10.67	7.07	7.4	12.55	3.63	4.07	3.27	3.05	0.063	0.043	0.033	0.15	0.07	0.077	0.113	0.05	2	20	18	2	1.78	1.09	1.16	2.1
	2016	10.0	9.33	9.07	12.9	4.45	4.75	5.11	4.82	0.66	0.50	0.18	0.22	0.07	0.12	0.19	0.09	7.45	10	11.3	2.99	2.77	1.96	1.70	2.17
	2017	9.60	8.06	9.23	12.4	4.07	6.33	3.53	3.87	0.93	0.39	0.08	0.44	0.10	0.19	0.21	0.07	7.08	12.14	7	5.38	3.33	1.77	1.5	3.19
S7	2018	8.96	10.9	8.35	11.8	3.50	3.40	2.93	2.67	0.67	0.07	0.12	0.33	0.10	0.15	0.12	0.08	48	73	57	7	2.29	1.21	1.45	2.04
	2019	9.06	8.36	10.0	11.4	4.15	5.44	5.83	4.62	0.42	0.08	0.04	0.39	0.08	0.18	0.14	0.07	6.32	16.95	13.51	5.22	2.75	1.17	1.50	2.77
	2020	10.47	9.3	7.6	11.15	3.93	4.17	3.07	3.1	0.28	0.08	0.04	0.23	0.052	0.062	0.095	0.06	1	12	14	2	2.27	1.27	1.38	2.25
	2016	9.99	9.35	8.95	12.4	5.02	4.83	5.12	4.87	1.42	0.35	0.47	0.94	0.09	0.14	0.16	0.11	11.43	11.2	8	3.77	3.11	1.87	1.92	3.34
	2017	9.80	8.05	8.83	12.3	4.53	6.40	4.07	4.57	1.11	0.14	0.11	1.01	0.10	0.21	0.24	0.13	5.02	12.1	5	5.22	3.50	1.50	1.50	3.19
S8	2018	8.67	9.26	8.21	12.3	4.20	3.10	3.10	2.88	2.43	0.12	0.19	0.63	0.17	0.16	0.12	0.09	18	111	75	6	4.55	1.29	1.55	2.62
	2019	9.31	8.69	10.4	11.7	5.21	6.48	8.00	6.19	0.53	0.14	0.04	0.85	0.10	0.21	0.17	0.09	11.98	13.79	4.38	3.03	2.71	1.37	1.70	2.91
	2020	10.8	10.97	7.3	10.05	3.7	4.47	3.03	3.35	0.14	0.043	0.047	0.43	0.057	0.078	0.085	0.07	2	24	27	5	2.25	1.34	1.61	3.43

Table 2. The overall normality test results of each water quality index.

Parameter	Count	Kolmogorov-Smirnov test		
		W	P	Normality
DO	160	0.095	0.001	Non-normal
COD_{Mn}	160	0.071	0.045	Non-normal
NH_3-N	160	0.309	0.000	Non-normal
TP	160	0.154	0.000	Non-normal
TN	160	0.142	0.000	Non-normal
Chl-a	160	0.251	0.000	Non-normal

A normality test is a fundamental step in water quality statistics. It includes Shapiro-Wilk test and Kolmogorov-Smirnov test. The Shapiro-Wilk test is often used for a sample size of less than 50 and Kolmogorov-Smirnov test is often used for a sample size of more than 50.

Six data sets were analyzed in the Kolmogorov-Smirnov test. Each data set included 160 samples from eight sampling sites over four quarters from 2016-2020. Each data set was tested at a 95% confidence level (a-level 0.05). The null hypothesis is that the data is normally distributed. If the p-value was smaller than a given a-level (0.05), the null hypothesis was rejected. In this case, the data would show non-normal distribution. Results of the normality tests are presented in Table 2.

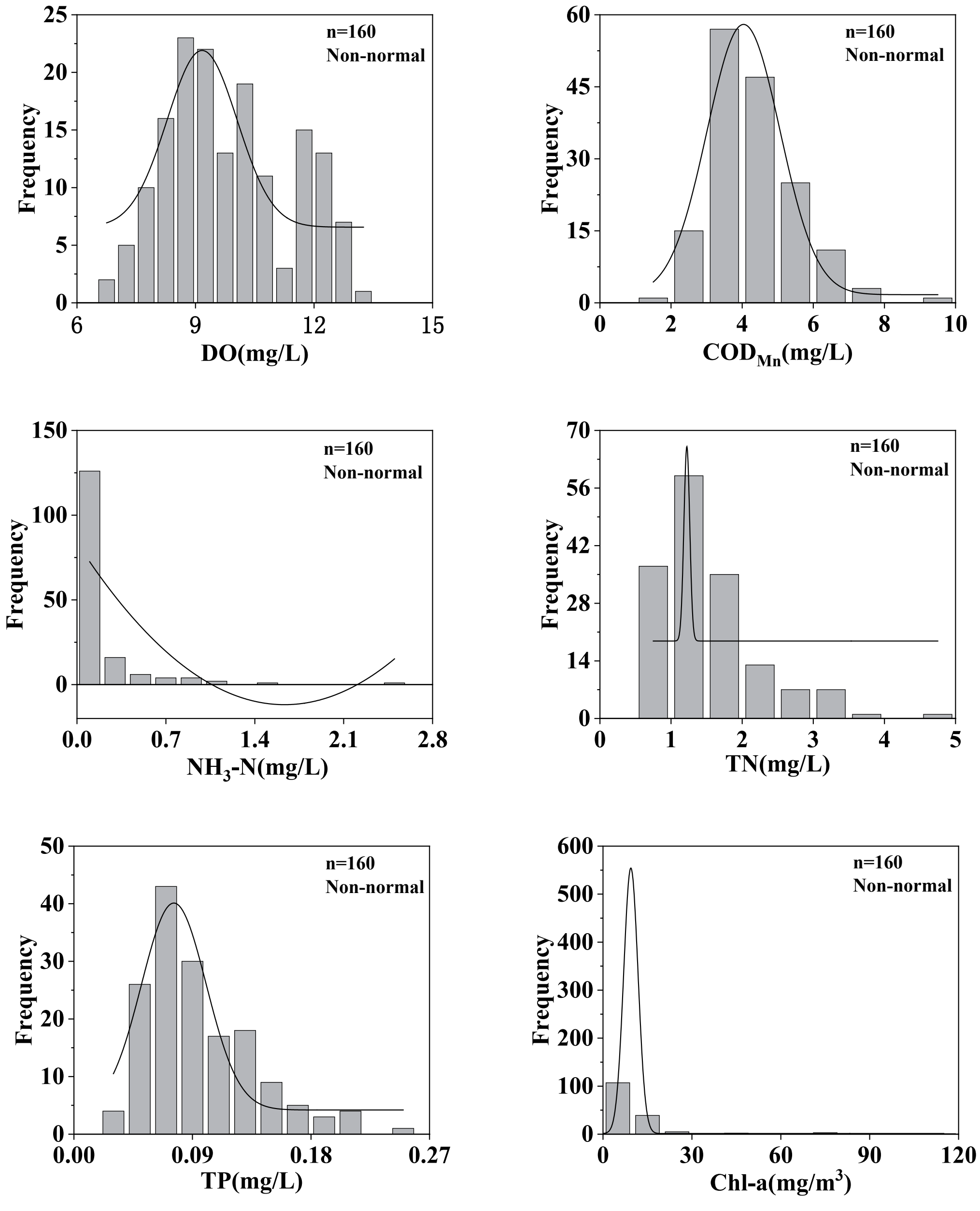

Fig. 1 Frequency histogram of overall water qualities with respect to data normality.

Table 3. The temporal and spatial normality test results of each water quality index.

Parameter	Temporal				Spatial			
	Count	W	P	Normality	Count	W	P	Normality
DO	20	0.932	0.171	Normal	32	0.899	0.006	Non-normal
COD_{Mn}	20	0.943	0.270	Normal	32	0.933	0.048	Non-normal
NH_3-N	20	0.883	0.020	Non-normal	32	0.559	0.000	Non-normal
TP	20	0.944	0.282	Normal	32	0.858	0.001	Non-normal
TN	20	0.915	0.078	Normal	32	0.831	0.000	Non-normal
Chl-a	20	0.797	0.001	Non-normal	32	0.846	0.000	Non-normal

The p-values of these six data sets were less than the given a-level (0.05), so the null hypothesis was rejected.

To identify the reason for the non-normal distribution, the frequency histogram of each data set was drawn and is shown in Fig. 1. From these figures, it can be recognized that most graphs have tails extending to the right with several outliers; these graphs are called right-skewed graphs. These right-skewed graphs are well known as very typical distribution of water quality data.

According to literature review, water quality data in natural rivers often present non-normal distribution with large temporal and spatial variations. Therefore, non-parametric comparison of water quality between different years and sampling points is required in statistics.

Results of the normality tests are presented in Table 3. Twelve data sets were analyzed in the Shapiro-Wilk test. For temporal, it included 20 samples from four quarters of 2016-2020. In this test, DO, COD_{Mn}, TP and TN was accepted, while NH_3-N and Chl-a was rejected. For spatial, it included 32 samples from eight sampling sites over four quarters. The p-values of spatial data sets were less than the given a-level (0.05), so the null hypothesis was rejected.

From the normality test, it was determined that most of the data sets should be shown as having non-normal distribution. Therefore, the nonparametric sign-test can provide a scientific judgment. The sign-test can only determine whether or not the water quality was improved. The degree of water quality change cannot be calculated from the sign-test. To compensate this weakness of the sign-test, the paired T-test was also applied.

Table 4 shows the results of the water quality comparison between temporal and spatial. As shown in the sign-test results, some of the water quality parameters (COD_{Mn}, NH_3-N and TP) were improved from 2016 to 2020. The DO, TN and Chl-a were not changed. From the paired T-test, some of the parameters (NH_3-N, TP, TN and Chl-a) should have improved. In the sign-test results, the DO were not changed from S1 to S8, but the (COD_{Mn}, NH_3-N, TP, TN, Chl-a) had declined.

Degrees of improvement were estimated from the paired T-test and are presented in Table 5. Since most of the data sets were proven to have non-normal distribution, these estimated degrees are only useful if there are significant differences in sign-test results.

Table 4. Results of Water Quality Comparison.

Category	Temporal						Spatial					
	Sign-test			Paired T-test			Sign-test			Paired T-test		
	Z	p	Result	t	p	Result	Z	p	Result	t	p	Result
DO	1.200	0.878	No change	0.830	0.468	No change	12.099	0.097	No change	-1.197	0.317	No change
COD_{Mn}	14.800	0.005	Improved	2.539	0.085	No change	20.417	0.005	Declined	-22.980	0.000	declined
NH_3-N	12.709	0.013	Improved	5.584	0.011	Improved	20.246	0.005	Declined	-1.951	0.146	No change
TP	11.887	0.018	Improved	6.977	0.006	Improved	23.431	0.001	Declined	-3.306	0.046	declined
TN	4.600	0.311	No change	12.273	0.001	Improved	24.051	0.001	Declined	-2.594	0.081	No change
Chl-a	8.400	0.078	No change	-0.978	0.400	No change	16.833	0.019	Declined	-2.470	0.090	No change

Table 5. Degree of Water Quality Improvement.

Category	Temporal			Spatial		
	Mean (2016)	Mean (2020)	Degree of Improvement (%)	Mean (S1	Mean (S8)	Degree of improvement (%)
DO	10.11	9.68	No change	9.35	9.87	No change
COD_{Mn}	4.53	3.49	+22.96	3.97	4.86	-22.42
NH_3-N	0.27	0.098	+63.70	0.10	0.56	-460
TP	0.09	0.06	+33.33	0.07	0.13	-85.71
TN	1.70	1.36	No change	1.13	2.00	-76.99
Chl-a	6.40	9.80	No change	8.70	18.15	-108.62

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