# Daily water quality evaluation of reservoir and cyanobacteria pollution index calculation

Wen Zhang and Zhiwei Liu


## ABSTRACT

Water quality evaluation is the most direct and quantitative description of a reservoir water environment. Due to the lack of biological factor evaluation in water quality evaluation at present, the conventional pollution index evaluation system was used to evaluate water quality and the correlation between the evaluation indexes and the concentration of cyanobacteria was studied. After determining the correlation, a novel calculation method using the cyanobacteria pollution index was determined by principal component analysis (PCA). The results showed that the eutrophication index and nitrogen phosphorus index of the water body were high. Biological pollution in reservoirs cannot be ignored. The correlation between eutrophication index and cyanobacteria concentration was weak (Pearson correlation = 0.242). For the reservoir, it was necessary to establish a special cyanobacteria pollution index. Five variables were used for the cyanobacteria pollution index calculation by the PCA method. The total variance of the two main components was 77.107%, which reflected most of the data information. In the reservoirs of other areas, similar parameters can also be selected to calculate the cyanobacteria pollution index. This research provides a reference for the biological factor evaluation of similar reservoirs in the world.


**Key words** | cyanobacteria concentration, principal component analysis, water eutrophication, water quality evaluation

**Wen Zhang** (corresponding author)
College of Biology and Environmental Engineering,
Zhejiang Shuren University,
Hangzhou 310015,
China
E-mail: *gillianjay@126.com*

**Zhiwei Liu**
College of environment and chemical engineering,
Yanshan University,
Qinhuangdao 066004,
China

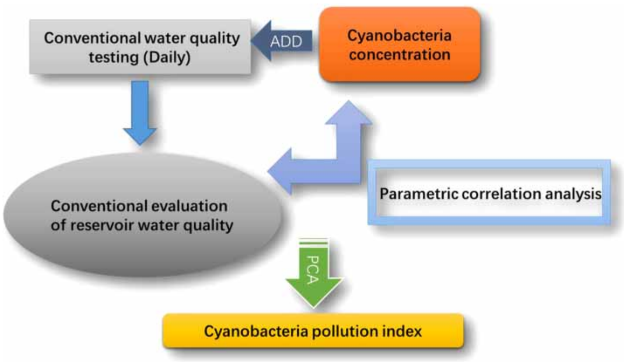
## HIGHLIGHTS

- A special daily water quality test was used in order to make an accurate judgment on water quality.
- PCA was selected to establish the calculation method of the cyanobacteria pollution index by considering the relationship between cyanobacteria concentration and other water quality factors.
- This research provides a reference for similar areas of the world on water quality evaluation of reservoirs.



doi: 10.2166/ws.2020.350

## GRAPHICAL ABSTRACT




## INTRODUCTION

Reservoir impoundment is the main way to alleviate the pressure of water supply in many countries. With the increasingly serious problems of the water environment, water quality of reservoirs has become an important issue related to the social development and the improvement of people's living standards (Xing *et al.* 2005). The water quality of reservoirs has attracted serious attention from the public and the government (Chen *et al.* 2016; Qu *et al.* 2016). Water quality evaluation is the most direct and quantitative description of reservoir water environment, and its accuracy directly affects the safety of drinking water supply (Štambuk-Giljanović 1999).

Water quality evaluation can provide support for water environmental protection and utilization of water resources based on evaluation criteria (Olsen *et al.* 2012; Carbajal-Hernandez *et al.* 2017). Because there are many different water quality factors such as total nitrogen (TN), total phosphorus (TP) and dissolved oxygen, to quantify the state of water quality accurately, many mathematical methods have been applied to water quality evaluation. The water quality index (WQI) model is one of these methods, and can transform large quantities of water quality data into a single number that represents the water quality (Lumb *et al.* 2011). The WQI method has been widely applied to assess water quality across the world (Bordalo *et al.* 2006; Liu *et al.* 2012). Two main methods including a single factor evaluation method and multifactor evaluation are always used for WQI modeling.

The single factor evaluation method compares the actual value and limit value (national environmental standard) of each water quality parameter to calculate the individual water quality category of each parameter. Xin *et al.* (2015) evaluated the water quality of Danjiangkou Reservoir using a single factor evaluation method and TP, permanganate index, dissolved oxygen and biochemical oxygen demand were selected as evaluation indexes. The multi/comprehensive factor evaluation method considers the relationship between water quality parameters and their effects. For example, the Carlson nutritional status index (CTSI), calculated from three water quality variables chlorophyll *a* (Chl*a*) concentration, TP concentration and Secchi depth, is widely used across the world. Many studies use CTSI as a WQI to show the eutrophication of water (Wang *et al.* 2002; Taheri Tizro *et al.* 2016; Chou *et al.* 2018). In addition, Zhang *et al.* (2014) used the improved comprehensive pollution evaluation method to evaluate water environmental quality, and determined that TP, followed by ammonia nitrogen ($NH_3$-N) and TN took the largest proportion of the water quality evaluation. Several studies have developed multiple linear regression methods using different environment parameters for spatial variations water quality analysis (Slaughter *et al.* 2017; Tomas *et al.* 2017). The multi/comprehensive factor evaluation method is more applicable than the single factor evaluation (Hou *et al.* 2016).

Conversely, with the gradual enhancement of people's awareness of ecological and environmental protection, the problems of water eutrophication and cyanobacterial blooms have also been of wide concern. Several major water supply reservoirs, such as Miyun Reservoir in Beijing, Qiaodun Reservoir in Wenzhou City, Nanwan Reservoir in Xinyang City and Hedi Reservoir in Guangdong Province, have experienced serious cyanobacterial blooms (Luo *et al.* 2018). Cyanobacteria can produce a large number of bioactive molecules, such as cyanobacterial toxins, which threaten human health and animal survival (Pomati *et al.* 2000). The production of cyanobacterial toxins in drinking water has attracted worldwide attention. The toxins produced by different cyanobacteria include hepatotoxins, cytotoxins, neurotoxins and skin toxins (Chorus *et al.* 1999). These toxins have serious consequences for human health, aquatic organisms and domestic animals (Buratti *et al.* 2017). In China, it is very difficult to remove the toxins produced by cyanobacteria from water treatment processes at the water treatment facilities. Therefore, if cyanobacteria multiply in large quantities in reservoirs, not only will water quality decline and destroy the ecological environment, but also the export of drinking water will threaten human health. However, there has been a lack of research on the relationship between the conventional water quality evaluation index and cyanobacteria concentration. The answer to whether the conventional water quality evaluation indexes are closely related to the concentration of cyanobacteria is still unclear. The Chl*a* index is commonly used to reflect the growth concentration of phytoplankton in water. Phytoplankton includes not only cyanobacteria, but also other algae such as Chlorophyta, therefore the Chl*a* index and cyanobacteria index cannot replace each other. Moreover, there is a lack of an established cyanobacteria pollution index method to measure the influence of cyanobacteria concentration on water quality.

A reasonable and scientific evaluation method should describe the water quality scientifically and accurately in order to ensure the safety of water supply (Xu *et al.* 2016; Tripathi & Singal 2019). At this time, the water quality detection of reservoirs in China generally stays at the level of monthly inspection. The frequency of detection is low, and the detection of cyanobacteria is lagging behind. In this study, taking Shihe Reservoir in Qinhuangdao City, Hebei Province, a typical reservoir in northern China, as an example, the traditional comprehensive factor evaluation was used to evaluate the water quality. In order to make the evaluation results more accurate to show the evolution characteristics of water quality, daily water quality detection was used for the first time to evaluate the water quality. Then, the evaluation index and the concentration of cyanobacteria were studied together to investigate their relationship, to analyze the factors related to the concentration of cyanobacteria. Finally, by considering the relationship between cyanobacteria concentration and other water quality factors, PCA was selected to establish the calculation method of the cyanobacteria pollution index, which could provide a reference for the research of similar areas in the world.

## MATERIALS AND METHODS

### Study area

Shihe Reservoir in Qinhuangdao City is located on the Shihe River in the northwest of Shanhaiguan in Qinhuangdao City. This reservoir is located in the north temperate monsoon climate zone. Shihe Reservoir has a total reservoir capacity of 70 million $m^3$, and a dead reservoir capacity of 2.4 million $m^3$. The normal water level of the Shihe Reservoir is 56.70 m, and the design flood level is 56.989 m. Shihe Reservoir has a catchment area of 28.2 $km^2$. The flood season of the surrounding rivers is earlier than that of Shihe Reservoir, which makes the flow of the reservoir slower and creates favorable conditions for the growth and reproduction of algae and plankton; and because the population density in the plain area is large, so the pollution load into the reservoir is large. The water sampling site (119°71′28″E, 40°03′34″N) is the area under the dam, monitoring the water quality of the reservoir outlet. The reason for choosing this sampling site is that the water quality here is most closely related to the quality of water supply.

### Sample data collection

Based on the water environment monitoring norms and the local water environment, nine water quality testing items were selected, including chemical oxygen demand ($COD_{cr}$

and $COD_{Mn}$), ammonia nitrogen (AN), TP, TN, fluoride(F), Chl*a*, transparency depth (SD), chromium ion (Gr), and biological oxygen demand ($BOD_5$). These testing items were measured according to the methods described in the Standard for Surface Water Environmental Quality of China (GB3838-2002) and Water and Wastewater Monitoring and Analysis Method (fourth edition) published by the State Environmental Protection Agency. The detection principle of these parameters is consistent with other national water quality standards such as AHPA Standard Methods for the Examination of Water & Wastewater 2012. Other routine tests including temperature, pH, dissolved oxygen (DO), turbidity, conductivity were carried out by instruments (HACH, USA). Cyanobacteria concentration was detected by TriOS microFlu-blue (TriOS, Germany). The TriOS microFlu-blue cyanobacteria analyzer determines the concentration of cyanobacteria by detecting the amount of phycocyanin in the measured water. This method has been proved to be reliable in previous reports (Bastien *et al.* 2011). The average was calculated based on three repeated test results.

The samples were surface water (0.5 m underwater) from sampling site. The detection time was from January 2018 to December 2019. During the ice freezing period, after removing the snow covered on the ice, the samples were collected under the ice cap or tested *in situ*. In order to reflect the water quality changes more accurately, the detection frequency was once a day, sampling time was 12 pm (noon) (Beijing time). It should be noted that through the layered monitoring and analysis of water quality, the concentration of cyanobacteria was highest in the surface layer water. At the same time, the surface layer water was the flow out of the reservoir for water supply, so the surface layer water was selected for analysis. The detection of all parameters was completed within 10 days after sampling.

## Calculation of water quality assessment index

### Total pollution index of water quality

According to the surface water quality assessment specifications (Water conservancy standard of China; SL 395-2007), the comprehensive pollution index of water quality was calculated as follows:

$$\begin{aligned}\text{Comprehensive pollution index} &= (COD_i/COD_o + AN_i/AN_o + TP_i/TP_o \\ &+ TN_i/TN_o + F_i/F_o + Gr_i/Gr_o + BOD_i/BOD_o)/7 \end{aligned} \quad (1)$$

In this formula, $COD_i$ represented the measured value of COD; $COD_o$ represented the standard value of $COD_{cr}$; $AN_i$ represented the measured value of ammonia nitrogen; $AN_o$ represented the standard value of ammonia nitrogen; $TP_i$ represented the measured value of total phosphorus; $TP_o$ represented the standard value of total phosphorus; $TN_i$ represented the measured value of total nitrogen; $TN_o$ represented the standard value of total nitrogen; $F_i$ represented the measured value of fluoride; $F_o$ represented the standard value of fluoride; $Gr_i$ represented the measured value of chromium ion; $Gr_o$ represented the standard value of chromium ion; $BOD_i$ represented the measured value of biological oxygen demand; $BOD_o$ represented the standard value of biological oxygen demand.

According to surface water environmental standards of China (GB3838-2002), $COD_o$ was 15 mg/L, $AN_o$ was 0.5 mg/L, $TP_o$ was 0.025 mg/L, $TN_o$ was 0.5 mg/L, $F_o$ was 1 mg/L, $Gr_o$ was 0.05 mg/L and $BOD_o$ was 3 mg/L.

The classification of reservoir water quality based on comprehensive pollution index is shown in Table 1.

### Eutrophication index

The comprehensive nutritional status index (Trophic Level Index; TLI) recommended by the Ministry of Environmental Protection of China was adopted. According to the literature (Wang *et al.* 2002), Carlson's nutritional status index (Carlson 1977) was improved, and the specific method was as follows.

**Table 1** | The classification of comprehensive pollution index

| Comprehensive pollution index | $\leq 0.8$ | $0.8 < CPI \leq 1.0$ | $1.0 < CPI \leq 2.0$ | $CPI > 2.0$ |
|---|---|---|---|---|
| Water quality grade | Good | Qualified | Polluted | Heavily polluted |

Step 1: The nutritional status index of each water quality parameter was determined:

$$TLI(SD) = 10(5.118 - 1.94\ln SD) \quad (2)$$

$$TLI(TN) = 10(5.453 + 1.694\ln TN) \quad (3)$$

$$TLI(Chla) = 10(2.5 + 1.086\ln Chla) \quad (4)$$

$$TLI(TP) = 10(9.436 + 1.624\ln TP) \quad (5)$$

$$TLI(COD) = 10(0.109 + 2.661\ln COD_{Mn}) \quad (6)$$

The unit of Chl*a* was $mg/m^3$. The unit of TP, TN and $COD_{Mn}$ were mg/L, and the unit of transparency SD was m.

Step 2: The weight values of each water quality parameter were calculated as follows, and the correlation coefficients between Chl*a* and other parameters are shown in Table 2:

$$W_j = \frac{R_{ij}^2}{\sum_{j=1}^{n} R_{ij}^2} \quad (7)$$

in which $R_{ij}$ was correlation coefficient between the content of index J and Chl*a* concentration; $W_j$ was the weight value of index J; n was the number of parameters.

Step 3: The Eutrophication Index was calculated as follows:

$$TLI\left[\sum\right] = \sum_{j=1}^{m} W_j \times TLI(j) \quad (8)$$

in which TLI [∑] was the Eutrophication Index.

Step 4: The classification of eutrophication level was based on Table 3.

## Nitrogen and phosphorus index

According to the surface water environmental standard (GB3838-2002), through long-term environmental monitoring, it was found that Shihe Reservoir has been facing the problem of TN and TP exceeding the standard over a long time. Therefore, the nitrogen and phosphorus index was calculated in this study to better analyze the water quality of the reservoir and help managers make decisions. According to the surface water quality assessment specifications (Water conservancy standard of China; SL 395-2007), nitrogen and phosphorus index of water quality was calculated as follows:

$$\text{Nitrogen and phosphorus index} = (TP_i/TP_o + TN_i/TN)/2 \quad (9)$$

In this formula, $TP_i$ represented the measured value of total phosphorus; $TP_o$ represented the standard value of total phosphorus; $TN_i$ represented the measured value of total nitrogen; $TN_o$ represented the standard value of total nitrogen.

According to surface water environmental standards of China (GB3838-2002), $TP_o$ was 0.025 mg/L, and $TN_o$ was 0.5 mg/L. The classification of reservoir water quality based on nitrogen and phosphorus index was is shown in Table 4.

**Table 2** | The correlation coefficients between chlorophyll *a* and other parameters

| Parameter | Chl*a* | SD | TP | TN | COD |
|---|---|---|---|---|---|
| $R_{ij}$ | 1 | −0.83 | 0.84 | 0.82 | 0.83 |
| $R_{ij}^2$ | 1 | 0.6889 | 0.7056 | 0.6724 | 0.6889 |

**Table 3** | The classification of eutrophication level

| TLI (∑) | (0,30) | (30,50) | (50,60) | (60,70) | (70, +∞) |
|---|---|---|---|---|---|
| Eutrophication level | Oligotrophic | Mesotrophic | Light eutrophic | Middle eutrophic | Hyper eutrophic |

**Table 4** | The classification of nitrogen and phosphorus index

| | $NPI \leq 1.0$ | $1.0 < NPI \leq 2.0$ | $NPI > 2.0$ |
|---|---|---|---|
| Water quality grade | Qualified | Small amount exceeding standard | Several times exceeding the standard |

### Cyanobacteria pollution index based on principal component analysis

The pollution index of cyanobacteria was calculated by PCA. Principal component analysis is mainly based on dimensionality reduction to find the fewest indicators that have a great impact on the problem from multiple indicators. The calculation steps were as follows.

Step 1: All the test data were standardized by Z-score. For positive indicators such as DO value, reverse processing was performed first. The reverse processing formula was:

$$Z_x = \max\{X\} - X \quad (10)$$

Step 2: The correlation coefficient matrix (R) between the parameters was solved by SPSS 21.0 software. Kaiser–Meyer–Olkin (KMO) and Bartlett test was carried out at the same time:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (11)$$

$$r_{ij} = \frac{\sum_{k=1}^{n} (x_{km} - \bar{x}_m)(x_{km} - x_n)}{\sqrt{\sum_{k=1}^{n} (x_{ki} - \bar{x}_i)^2 \sum_{k=1}^{n} (x_{kn} - \bar{x}_n)^2}} \quad (12)$$

Step 3: The covariance matrix was used to obtain the explanatory variance, eigenvalue and cumulative variance contribution rate of each principal component.

Step 4: The score coefficient matrix of the main component was obtained.

### Parametric correlation analysis

The correlation analysis was based on the method of Karl Pearson. The Pearson correlation between two parameters was calculated using IBM SPSS 21.0 software.

The relationship between correlation coefficient and correlation degree is shown in Table 5.

## RESULTS AND DISCUSSION

### Conventional evaluation of reservoir water quality

The water quality change of Shihe Reservoir is shown in Figures 1 and 2. The comprehensive pollution index of reservoir water quality in 2018 maintained a relatively stable level throughout the year and the pollution index of each season was little different. The peak that appeared in May was very close to the peak of the eutrophication index, which shows that when the concentration of pollutants in water increased, eutrophication was also more likely to occur in water bodies (Wang *et al.* 2019). The overall change in the comprehensive pollution index in 2019 showed a slow growth trend with time. At the same time, through the calculation of monthly average comprehensive pollution index, it was found that, except for the lower comprehensive pollution index in May and June (<1.0; the water quality was qualified), the water pollution degree was higher at other times. The sewage discharged from the upstream villages by agriculture, animal husbandry, tourism and industry had a great impact on the water quality of the reservoir (Ding *et al.* 2019). But it should be noted that this situation was related not only to the entry of external pollutants, but also to other meteorological factors such as rainfall, temperature and so on (Howell *et al.* 2019).

The eutrophication index of reservoir water quality showed the change followed first increasing and then decreasing with the seasonal change. Its value reached the highest in summer and autumn. Eutrophication index was not only related to the concentration of nitrogen and phosphorus in water, but also to the concentration of chlorophyll in water (Yang *et al.* 2019). The flow rate in the dam area was lower than that in other places, and with slow flow rate, the algae found it easy to grow (Huang *et al.* 2006).

**Table 5** | The relationship between correlation coefficient and correlation degree

| Correlation coefficient | 0 | 0 ~ ± 0.3 | ± 0.3 ~ ± 0.5 | ± 0.5 ~ ± 0.8 | ± 0.8 ~ ± 1 |
|---|---|---|---|---|---|
| Correlation degree | No relevant | Weak correlation | Low correlation | Moderate correlation | High correlation |

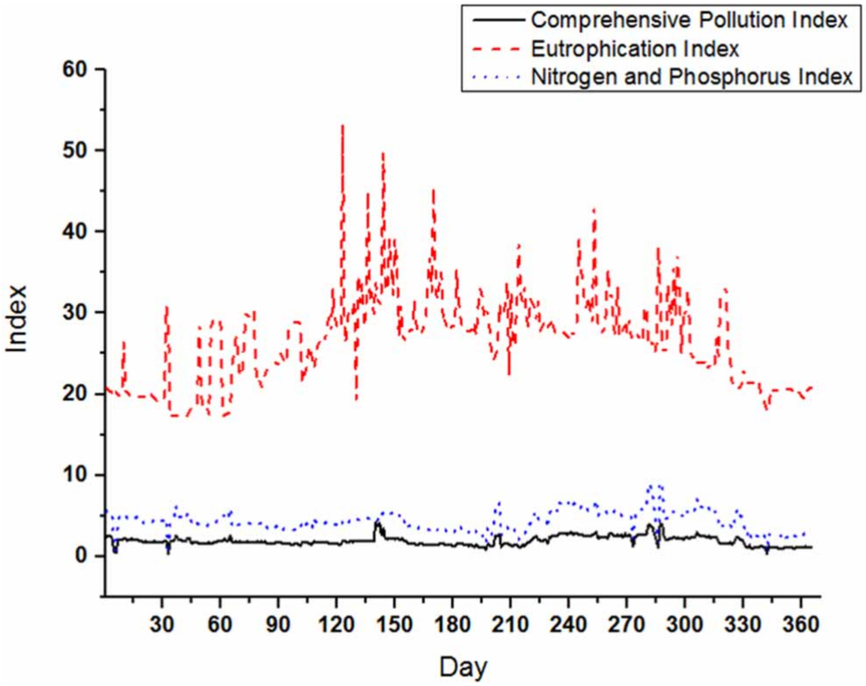



**Figure 1** | Water quality indexes changes of Shihe Reservoir in 2018.

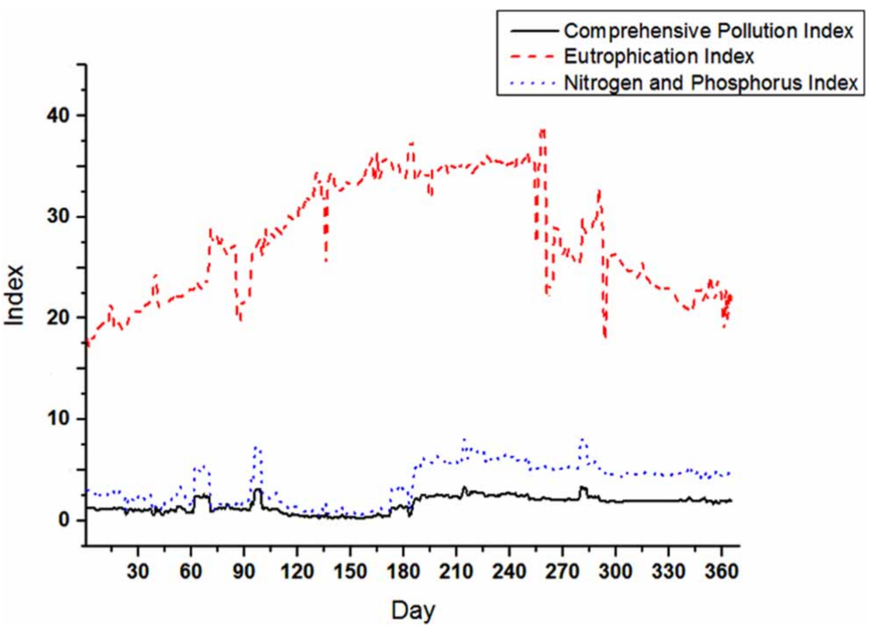



**Figure 2** | Water quality indexes changes of Shihe Reservoir in 2019.

Nitrogen and phosphorus index varied greatly throughout the year, with a maximum value of more than 6 and an average level of more than 3, which seriously exceeded the standard; and its changing trend was the same as the comprehensive pollution index. It can be seen that the nitrogen and phosphorus index of reservoir was maintained at a higher level and there was an urgent need to deal with various pollution sources. Reducing the input of pollutants from river basins to reservoirs is the basis for the improvement of water quality and ecology of reservoirs (Chen *et al.* 2018).

The long-term monitoring of the reservoir also showed that the water quality of the reservoir was basically in a stable state. The eutrophication index and nitrogen phosphorus index of the water body were high, so in the future biological pollution in the reservoir cannot be ignored. It is necessary to pay close attention to the algae reproduction in the water body, and the algae concentration should be monitored.

## Variation of cyanobacteria concentration with time

The monitoring results of cyanobacteria concentration are shown in Figure 3. The concentration of cyanobacteria showed obvious seasonal fluctuation and the concentration of cyanobacteria was the highest in summer. Increased water temperature and sunshine provide opportunities for cyanobacteria growth. Summer and autumn were the high occurrence periods of cyanobacteria outbreaks, which need to be monitored and prevented. This phenomenon also occurs in reservoirs in southern China. For example, the Jiuquwan Reservoir in Zhujiang City of Guangdong Province has experienced cyanobacteria blooms since 2009. The outbreak time generally occurs from April to October every year, with the most serious in July to September (Luo *et al.* 2018). In the autumn of 2019, the concentration of cyanobacteria increased sharply again but this situation did not appear in the autumn of 2018. This indicated that there was a possibility of cyanobacteria outbreak again in autumn. Therefore, it is imperative to monitor the concentration of cyanobacteria.

## The correlation between water quality evaluation index and cyanobacteria concentration

Based on the monitoring data, the Pearson correlation coefficient method was used to analyze the relationship between WQI and cyanobacteria concentration in Shihe Reservoir. If there is a strong positive correlation between a certain water quality evaluation index and the cyanobacteria concentration, it shows that this evaluation index can be used to represent the growth of cyanobacteria, and with the larger

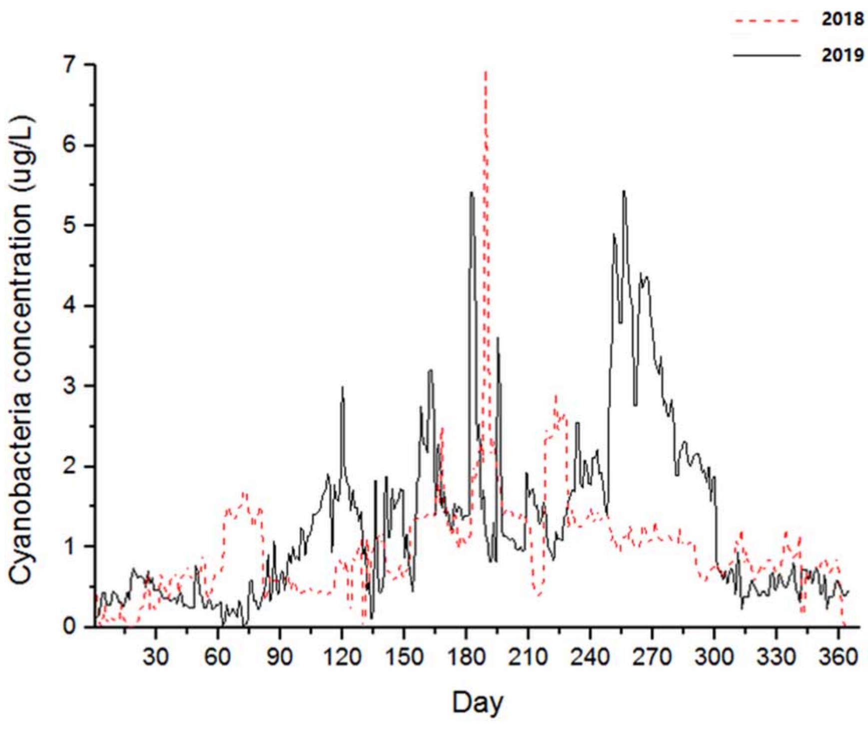



**Figure 3** | Changes of cyanobacteria concentration.

the index value, more cyanobacteria would be present in the water. At the same time, if there is a strong negative correlation between them, the higher the index, the less the growth of cyanobacteria, which can also be used to indicate the growth concentration of cyanobacteria. If the current water quality evaluation indicators cannot form a strong correlation with cyanobacteria concentration, then these indicators cannot be used to represent the cyanobacteria concentration. The results are shown in Table 6. The comprehensive pollution index was highly positively correlated with the nitrogen and phosphorus index, and can be basically replaced by the nitrogen and phosphorus index. This also provided a simpler way to evaluate water quality in the future and optimizes the evaluation system. There was no good correlation between comprehensive pollution index and eutrophication index, which also showed that there was no absolute relationship between pollutants and eutrophication. These two evaluation mechanisms not replaceable. There was a weak positive correlation between the comprehensive pollution index and the concentration of cyanobacteria, which also showed that the increase in the concentration of pollutants had a certain impact on the growth of cyanobacteria, but it was not a decisive factor. Eutrophication index and nitrogen and phosphorus index also showed a weak positive correlation, because the concentration of nitrogen and phosphorus was only a part of the index of eutrophication, and could not represent the whole index situation. There was only a weak positive correlation between nitrogen and phosphorus index and cyanobacteria concentration, because some types of cyanobacteria preferred low nitrogen and high phosphorus nutrients. For example, the nitrogen-fixing cyanobacteria such as *Dolichospermum* sp. do not need a nitrogen source in the process of reproduction. So the nitrogen and phosphorus index and cyanobacteria concentration could not establish a strong positive relationship. The correlation between eutrophication index and cyanobacteria concentration reached weak positive correlation. This also showed that it was not accurate to measure whether cyanobacteria blooms would occur using eutrophication index alone. High eutrophication index can promote algae reproduction, but it did not mean that cyanobacteria must be one of the dominant species. That was to say, reservoirs need to establish a comprehensive monitoring mechanism for cyanobacteria concentration, especially in summer, an automatic detection system for pollution cyanobacteria should be established. Therefore, we suggest that the cyanobacteria index should be added to the water quality evaluation system of reservoirs in order to evaluate the water quality more comprehensively.

## Cyanobacteria pollution index of reservoir based on principal component analysis

Because there is a certain correlation between the concentration of cyanobacteria and other water quality parameters, the change in water quality parameters in water would affect the growth of cyanobacteria. Nutrient content in water directly determines the increment rate of phytoplankton (Huang *et al.* 2017). At the same time, the increase in cyanobacteria concentration also can change other water quality parameters such as chlorophyll concentration, water turbidity and so on. Therefore, the influence of cyanobacteria on water quality cannot be evaluated only by the cyanobacteria concentration value.

**Table 6** | Correlation analysis of different indicators

| | | CPI | TLI | NPI | Cyanobacteria concentration |
|---|---|---|---|---|---|
| CPI | Pearson correlation | 1 | 0.209 | 0.930 | 0.042 |
| | Significance | | 0 | 0 | 0.421 |
| TLI | Pearson correlation | 0.209 | 1 | 0.132 | 0.242 |
| | Significance | 0 | | 0.011 | 0 |
| NPI | Pearson correlation | 0.930 | 0.132 | 1 | 0.016 |
| | Significance | 0 | 0.011 | | 0.766 |
| Cyanobacteria concentration | Pearson correlation | 0.042 | 0.242 | 0.016 | 1 |
| | Significance | 0.421 | 0 | 0.766 | |

When determining the cyanobacteria pollution index of a reservoir, the correlation between various water quality parameters and cyanobacteria concentration should be considered.

In this study, the PCA method was used to determine the cyanobacteria pollution index of the reservoir. This method can achieve the conversion of multiple variable indexes into a few evaluation indexes, so that the complexity of the original data is greatly reduced (Tabata *et al.* 2015). In order to obtain an accurate water quality evaluation of cyanobacteria pollution, all the parameters of water quality and cyanobacteria concentration were selected for correlation analysis, and KMO and Bartlett test was carried out. The results showed that the five parameters including chlorophyll ($Z_1$), turbidity ($Z_2$), cyanobacteria concentration ($Z_3$), TP ($Z_4$), and dissolved oxygen ($Z_5$) can be selected for reliable PCA. The KMO and Bartlett test result is shown in Table 7. KMO value was 0.676 and Sig. value in Bartlett's sphericity test was less than 0.05. The PCA can be carried out.

The characteristic value and cumulative contribution rate of the principal component are shown in Table 8. According to the PCA theory, if the characteristic value of a principal component is greater than 1, the principal component can replace the original data. According to Table 8, the first principal component and the second principal component were greater than 1, so the principal components were determined to be the first and second components. The total variance of the two main components was 77.106%, which can reflect most of the data information. The linear expressions of the main component score and comprehensive score were as follows:

$$F_1 = 0.343Z_1 + 0.381Z_2 + 0.407Z_3 - 0.097Z_4 + 0.288Z_5 \tag{13}$$

$$F_2 = -0.051Z_1 - 0.279Z_2 + 0.050Z_3 + 0.876Z_4 + 0.288Z_5 \tag{14}$$

$$W = 0.56251F_1 + 0.20856F_2 \tag{15}$$

**Table 7** | KMO and Bartlet test of principal component

| KMO | Approximate chi square | df | Sig. |
|---|---|---|---|
| 0.676 | 634.604 | 10 | 0.000 |

**Table 8** | Eigenvalues and contribution rates of each component in principal component analysis

| Component | Eigenvalues | Contribution rates of each component | Cumulative contribution rate |
|---|---|---|---|
| 1 | 2.813 | 56.251 | 56.251 |
| 2 | 1.043 | 20.855 | 77.106 |
| 3 | 0.666 | 13.322 | 90.428 |
| 4 | 0.363 | 7.256 | 97.684 |
| 5 | 0.116 | 2.316 | 100.000 |

in which, $Z_1$ represented chlorophyll concentration (standardized value); $Z_2$ represented turbidity (standardized value); $Z_3$ represented cyanobacteria concentration (standardized value); $Z_4$ represented TP (standardized value); and $Z_5$ represented dissolved oxygen (standardized value).

Finally, the main component score and comprehensive score were calculated, and the cyanobacteria pollution index was quantitatively described and ranked. As shown in Figure 4, the average cyanobacteria pollution index was the highest in April, June and October through comprehensive evaluation of two years. Through the evaluation of cyanobacteria index, the reservoir management department can formulate the corresponding management plan in advance to avoid the impact of cyanobacteria on water safety. Monitoring and emergency treatment also should be strengthened during these months. Because the standard concentration of cyanobacteria concentration, chlorophyll, and turbidity are not determined in the national standard, so the level of cyanobacteria pollution index cannot be determined. However, the cyanobacteria pollution index can be compared at different times and places. At the same time, in the reservoirs in other areas, similar parameters can also be selected to calculate the cyanobacteria pollution index, and to classify and compare the water quality. The water quality assessment system proposed in this paper can also be used in other similar reservoirs around the world.

## CONCLUSION

In view of the lack of biological factor evaluation in water quality evaluation at present, an evaluation system of reservoir water quality which included a comprehensive pollution

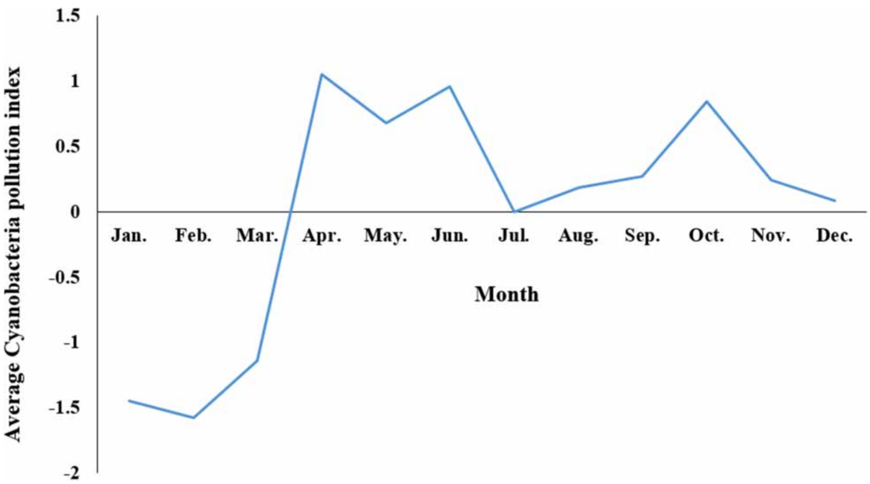



**Figure 4** | Changes of the average cyanobacteria pollution index.

index, eutrophication index, nitrogen phosphorus index and cyanobacteria pollution index was established. The correlation analysis between the indexes and the concentration of cyanobacteria showed that the comprehensive pollution index was highly positively correlated with the nitrogen phosphorus index, and the comprehensive pollution index can be basically replaced by the nitrogen and phosphorus index, which also provided a simpler way to evaluate water quality in the future and optimize the evaluation system. The correlation between eutrophication index and cyanobacteria concentration reached a weak correlation which also indicated that it was not accurate to measure whether cyanobacteria blooms would occur only by using eutrophication index. The PCA method can be used to determine the cyanobacteria pollution index of the reservoir. The cyanobacteria pollution index was the highest in April, June and October. Monitoring and emergency treatment should be strengthened. Through the evaluation of the cyanobacteria index, the reservoir management department can formulate the corresponding management plan in advance to avoid the impact of cyanobacteria on water safety. The water quality assessment system proposed in this paper can also be used in other similar reservoirs around the world.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the supports from Natural Science Foundation of Zhejiang Province (LQ20B060004) and Zhejiang Shuren University project (2019R017).

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## REFERENCES

APHA 2012 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington DC, USA.

Bastien, C., Cardin, R., Veilleux, É., Deblois, C., Warren, A. & Laurion, I. 2011 Performance evaluation of phycocyanin probes for the monitoring of cyanobacteria. *J. Environ. Monit.* **13**, 110–118.

Bordalo, A. A., Teixeira, R. & Wiebe, W. J. 2006 A water quality index applied to an international shared river basin: the case of the Douro River. *Environ. Manag.* **38**, 910–920.

Buratti, F. M., Manganelli, M. & Vichi, S. 2017 Cyanotoxins: producing organisms, occurrence, toxicity mechanism of action and human health toxicological risk evaluation. *Arch. Toxicol.* **91**, 1049–1130.

Carbajal-Hernandez, J. J., Sanchez-Fernandez, L. P., Hernandez-Bautista, I. & Hernandez-Lopez, J. 2017 A model based on an artificial neural network for assessing water quality on large shrimp farms. *Tec Cie del Agua.* **8**, 71–89.

Carlson, R. E. 1977 A trophic state index for lakes. *Limnol. Oceanogr.* **22**, 361–369.

Chen, L., Chen, J., Zhang, X. Z. & Xie, P. 2016 A review of reproductive toxicity of microcystins. *J. Hazard. Mater.* **301**, 381–399.

Chen, Y., Yu, K., Hassan, M., Xu, C., Zhang, B., Gin, K. Y.-H. & He, Y. 2018 Occurrence, distribution and risk assessment of pesticides in a river-reservoir system. *Ecotoxicol. Environ. Saf.* **166**, 320–327.

Chorus, E. I., Bartrum, J., Falconer, I. & Fitzgerald, J. 1999 *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*. E&P Spon, London.

Chou, J.-S., Ho, C.-C. & Hoang, H.-S. 2018 Determining quality of water in reservoir using machine learning. *Ecol. Inform.* **44**, 57–75.

Ding, W., Zhu, Q., Zhai, A. & Liu, L. 2019 Water quality safety prediction model for drinking water source areas in Three Gorges Reservoir and its application. *Ecol. Indic.* **101**, 734–741.

Hou, W., Sun, S., Wang, M., Li, X., Zhang, N., Xin, X., Sun, L., Li, W. & Jia, R. 2016 Assessing water quality of five typical reservoirs in lower reaches of Yellow River, China: using a water quality index method. *Ecol. Indic.* **61**, 309–316.

Howell, N. L., Butler, E. B. & Guerrero, B. 2019 Water quality variation with storm runoff and evaporation in playa wetlands. *Sci. Total Environ.* **652**, 583–592.

Huang, C., Zhong, C., Deng, C., Xing, Z., Li, Y., Wang, D. & Meng, W. 2006 Preliminary study on correlation between flow velocity and algae along Daning river's backwater region at sluice initial stages in the three gorges reservoir. *J. Agro-Environ. Sci.* **25**, 453–457.

Huang, J., Xu, C., Ridoutt, B. G., Wang, X. & Ren, P. 2017 Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. *J. Cleaner Production* **159**, 171179.

Liu, Z., Sun, G., Huang, S., Sun, W., Guo, J. & Xu, M. 2012 Water quality index as a simple indicator of drinking water source in the Dongjiang River, China. *Int. J. Environ. Prot.* **2**, 16–21.

Lumb, A., Sharma, T. & Bibeault, J. F. 2011 A review of genesis and evolution of water quality index (WQI) and some future directions. *Water Qual. Expo. Health.* **3**, 11–24.

Luo, H., Chen, H., Chen, W., Wu, Q. & Zhang, Y. 2018 Ecological treatment of cyanobacteria in reservoir and its effectiveness evaluation. *J. N. China Univ. Water Resour. Electric Power* **39**, 51–55.

Olsen, R. L., Chappell, R. W. & Loftis, J. C. 2012 Water quality sample collection, data treatment and results presentation for principal components analysis: literature review and Illinois River watershed case study. *Water Res.* **46**, 3110–3122.

Pomati, F., Sacchi, S. & Rossetti, C. 2000 The freshwater cyanobacterium *Planktothrix* sp. FPl: molecular identification and detection of paralytic shellfish poisoning toxins. *J. Phycol.* **36**, 553–562.

Qu, J. H., Meng, X. L. & Ye, X. Q. 2016 Characteristic variation and original analysis of emergent water source pollution accidents in China between 1985 and 2013. *Environ. Sci. Pollut. Res.* **23**, 19675–19685.

Slaughter, A., Hughes, D., Retief, D. & Mantel, S. 2017 A management-oriented water quality model for data scarce catchments. *Environ. Model. Softw.* **97**, 93–111.

Štambuk-Giljanović, N. 1999 Water quality evaluation by index in Dalmatia. *Water Res.* **33**, 3423–3440.

Tabata, T., Hiramatsu, K. & Harada, M. 2015 Assessment of the water quality in the Ariake Sea using principal component analysis. *J. Water Resour. Prot.* **7**, 41–49.

Taheri Tizro, A., Ghashghaie, M. & Nozari, H. 2016 Assessment of Carson trophic index in Dam Lake: a case study of Ekbatan Dam. *Iran. J. Health Sci.* **4**, 25–33.

Tomas, D., Čurlin, M. & Marić, A. S. 2017 Assessing the surface water status in Pannonian ecoregion by the water quality index model. *Ecol. Indic.* **79**, 182–190.

Tripathi, M. & Singal, S. K. 2019 Use of Principal Component Analysis for parameter selection for development of a novel Water Quality Index: a case study of river Ganga India. *Ecol. Indic.* **96**, 430–436.

Wang, M., Liu, X. & Zhang, J. 2002 Evaluate method and classification standard on lake eutrophication. *Environ. Monit. China* **18**, 47–49.

Wang, J., Fu, Z., Qiao, H. & Liu, F. 2019 Assessment of eutrophication and water quality in the estuarine area of Lake Wuli, Lake Taihu, China. *Sci. Total Environ.* **650**, 1392–1402.

Xin, X., Li, K., Finlayson, B. & Yin, W. 2015 Evaluation, prediction, and protection of water quality in Danjiangkou Reservoir, China. *Water Sci. Eng.* **8**, 30–39.

Xing, Y., Lu, Y., Dawson, R. W., Shi, Y., Zhang, H., Wang, T., Liu, W. & Ren, H. 2005 Aspatial temporal assessment of pollution from PCBs in China. *Chemosphere* **60**, 731–739.

Xu, D., Zhou, C., Sun, C. & Du, Y. 2016 Water temperature and pH prediction model of aquaculture based on particle swarm optimization BP neural network. *Fish. Modern.* **1**, 24–29.

Yang, Y., Chen, J., Tong, T., Li, B., He, T., Liu, Y. & Xie, S. 2019 Eutrophication influences methanotrophic activity, abundance and community structure in freshwater lakes. *Sci. Total Environ.* **662**, 863–872.

Zhang, X. F., Chang, L. X., Yong, Q. L. & Ding, F. S. 2014 Water environmental quality assessment and protection strategies of the Xinlicheng Reservoir, China. *Appl. Mech. Mater.* **501**, 1863–1867.

First received 4 June 2020; accepted in revised form 20 November 2020. Available online 2 December 2020