Assessment of phytoplankton community structure and water quality in the Hongmen Reservoir

Chenwei Liu, Xu Sun, Lianghu Su, Jinbang Cai, Longjiang Zhang and Liyun Guo

ABSTRACT

To find effective measures to control the water quality of the Hongmen Reservoir, it is necessary to better understand its phytoplankton composition, abundance and spatial and temporal distribution. Samples were collected at three sampling sites in January (dry season), May (wet season) and September (normal season) in 2019. Trophic level and stability status were assessed on the basis of the Shannon diversity index (H), species richness (S) and evenness (J) index. The different relationships between phytoplankton and the concentrations of several physicochemical parameters and the main soluble nutrients were evaluated by statistical tests. The results showed that there were 75 species belonging to seven groups of phytoplankton, including Chlorophyta (44 species), Bacillariophyta (12 species), Cyanophyta (9 species) and others (10 species). The phytoplankton community composition belongs to the Chlorophyta–Bacillariophyta–Cyanobacteria type structure; and *Microcystis*, *Anabaena azotica Ley*, *Aphanizomenon*, *Melosira granulata* were the main contributors to the dissimilarities in the temporal distributions of their communities. The phytoplankton density ranged from 4.42×10^6 to 8.99×10^6 particles/L, with an average of 6.45×10^6 particles/L, and the biomass was $4.42 \times 10^6 \sim 8.99 \times 10^6$ particles/L, with an average of 6.45×10^6 particles/L. The variation ranges of the Shannon–Wiener index (H'), Margalef index (D) and Pielou evenness index (J) were $2.05 \sim 2.85$, $4.12 \sim 6.60$ and $0.61–0.78$, respectively. This research shows that the water in the Hongmen Reservoir is clean and that the pollution level is light. The correlation analysis shows that total phosphorus and dissolved oxygen are the main factors affecting phytoplankton community structure in the Hongmen Reservoir.

Key words | environmental factors, Hongmen Reservoir, phytoplankton

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HIGHLIGHTS

- Total phosphorus and dissolved oxygen were the main factors affecting the Hongmen Reservoir phytoplankton community structure.
- The community structure of the Hongmen Reservoir had seasonal differences, and the changes in environmental factors reflected the community structure changes in the Hongmen Reservoir in our time scale.
- The abundance and diversity of phytoplankton were influenced by environmental factors.

INTRODUCTION

Phytoplankton are one of the key components of aquatic ecosystems and play an important role in maintaining the balance of aquatic ecosystems (Padedda *et al.* 2017). Phytoplankton community structure is now accepted to be closely related to environmental factors (Kozak *et al.* 2015; Yuan *et al.* 2017; Sabater-Liesa *et al.* 2018; Mishra *et al.* 2019). Phytoplankton exhibit particular sensitivity to changes in the biotic (e.g., grazing pressure), physical (e.g., temperature, water level fluctuation) and chemical (e.g., nutrient content) characteristics of aquatic environments (Zhang *et al.* 2020). Many researchers have conducted studies on the succession of phytoplankton in seas, lakes and reservoirs and have found that nutrients, water temperature and light availability are the main influencing factors (Liu *et al.* 2010; Dantas *et al.* 2012; Sabater-Liesa *et al.* 2018).

Phytoplankton biomass is the key parameter reflecting the ecological effect of eutrophication in lakes and reservoirs (Dantas *et al.* 2012; Fetahi *et al.* 2014). Therefore, monitoring, simulation and forecasting of the phytoplankton community are of great importance in anthropogenically affected areas, protected areas and reservoirs serving as drinking water supplies or recreation, especially currently, when changes are affected by human activities. While the main causes of reservoir eutrophication are agricultural fertilizers, other nutrient sources, such as livestock, wastewater, urban runoff, river flow and aquaculture also affect ecosystem health. Therefore, reservoir ecosystems are under threat from both human activities and natural processes (Zhu *et al.* 2013; Bartozek *et al.* 2014; Lv *et al.* 2014; Fadel *et al.* 2015). The Hongmen Reservoir, located in Fuzhou city, Jiangxi Province, is a comprehensive water conservancy project, mainly for power generation, flood control, irrigation, shipping, aquaculture, etc. In the past ten years, a few studies have found that the nutrient levels of reservoirs have increased, resulting in cyanophyta becoming the dominant population in the high-temperature season (Zhou *et al.* 2008). Rapid economic development and human activities in and near the Hongmen Reservoir have changed estuarine dynamics, increasing the pressure on ecosystem management (Gong *et al.* 2019). However, the relationship between phytoplankton and environmental factors in the Hongmen Reservoir has not yet been reported.

Here, we use monitoring data to explore the general patterns in anthropogenic forces on the environmental drivers of the phytoplankton community. The main objectives of this work are to investigate: (1) the qualitative and quantitative analysis of phytoplankton, (2) the temporal and spatial organization of phytoplankton, (3) the influence of some abiotic parameters and (4) the assessment of trophic status. The results obtained will be helpful to assess and predict the growth and development of phytoplankton blooms and would be a reference for further strengthening the protection of water resources and water environment management.

METHODOLOGY

Sampling point location and sampling time

The Hongmen Reservoir is located in the lower reaches of the Litan River, which belongs to the Fuhe River system. The main tributaries of the Hongmen Reservoir include the Zifu River, Longan River and Longhu River. The Hongmen Reservoir has a typical subtropical monsoon humid climate with four distinct seasons, abundant rainfall and sufficient sunshine. The river basin above the dam site of the Hongmen Reservoir covers an area of 2,376 km^2, with an average annual runoff of 2.458 billion m^3 and a surface area of 69.58 km^2. The total length of the reservoir is 36.5 km, with a maximum width of 1.5 km and an average width of 0.3 km. The average water depth of the reservoir is approximately 17.5 m. The total storage capacity of the reservoir is 1.214 billion m^3, and the average water change cycle is 178 days. According to the morphological characteristics of the Hongmen Reservoir and the inlet location of the main tributaries, four sampling points were set up in the main channel inlet and reservoir core (Figure 1), including the Cifu water inlet (S1), reservoir core (S3) and dam front (S4).

Sample collection and processing

Samples were taken at a station located in the deeper portion of the reservoir in December 2018, May 2019 and September 2019. Water samples were collected at the surface, middle and
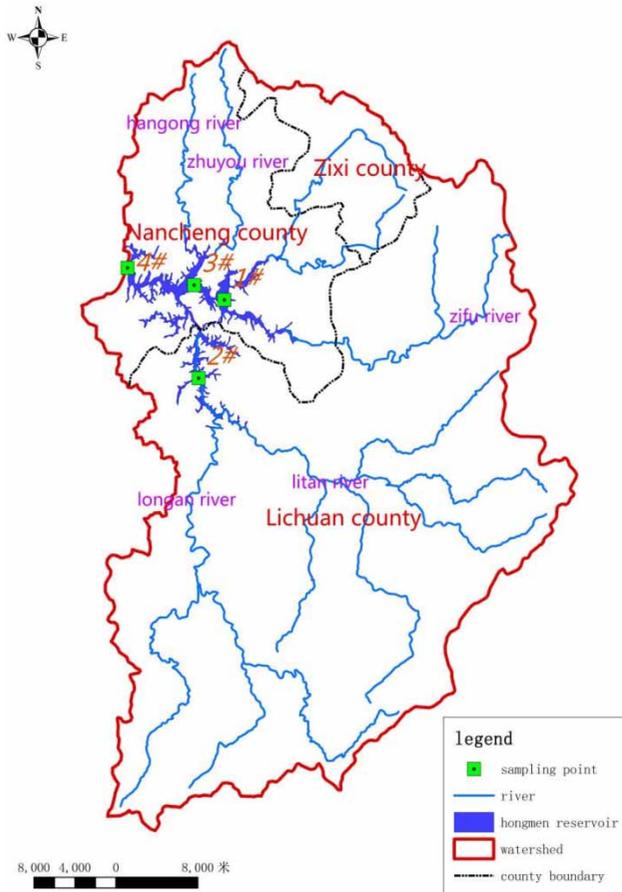
Figure 1 | Location of reservoir sampling point.

bottom of the water and then mixed for determination using a Niskin bottle. Before the collection of samples, an oxygen–temperature meter (YSI 6200) was used to measure the pH, dissolved oxygen (DO), water temperature, electrical conductivity (EC) and salinity *in situ*. The water transparencies of the lakes were determined with the aid of a 20-cm Secchi disk. The samples were stored in a cold, dark environment for laboratory analyses of ammonium (NH_4^+-N), nitrate (NO_3^--N), nitrite (NO_2^--N), total nitrogen (TN), permanganate index (COD_{Mn}), biochemical oxygen demand (BOD_5), total phosphorus (TP) and chlorophyll *a* (Chl *a*) following the water and wastewater monitoring and analysis method (4th).

For the phytoplankton analyses, the one-liter water samples were preserved using 1% Lugol's iodine solution for identification and counting of phytoplankton species. Algal analysis involved sample concentration through several settling steps from an original volume of 1 L to 50 mL

(settling time was 24 h) and to a final volume of 10 mL (settling time was also 24 h). Thereafter, the units were counted under 400× magnification for at least 200 specimens (Zhang *et al.* 2020). The examination of samples under a microscope (CX31, Olympus, Japan) was usually completed within a few hours of collection, and taxonomic identification of the phytoplankton species was performed according to international websites, for example, the NBN atlas, WoRMS and one book, 'Freshwater algae in China (System, Classification and Ecology)' (Hu & Wei 2006).

Data analysis

Environmental data are given as the mean and standard deviation (mean ± SD) after performing the descriptive analysis (SPSS version 15.0, Chicago, USA). Duncan's multiple range test was used to distinguish environmental variables among samples. The comprehensive trophic status index (TSI) is used to evaluate the trophic status of reservoirs, and the evaluation parameters include chlorophyll *a*, TN, TP, permanganate index and transparency (Effendi *et al.* 2016).

(Y) represents the dominant species of zooplankton. (Y) is determined according to the occurrence frequency of species and the density of individuals and the calculation formula is as follows:

$$Y = f_i \times p_i$$

where Y is the dominance degree, f_i is the occurrence frequency P_i of the ith species and P_i is the proportion of the individual density of the ith species in the total individual density. When $Y > 0.02$, it is the dominant species (Shen *et al.* 2019).

The Shannon–Weiner diversity index (H'), Margalef species richness index (D) and Peilou evenness index (J) were selected to evaluate species diversity (Belokda *et al.* 2019). The formula is as follows:

$$H' = -\sum\nolimits_{i=1}^{S} P_i \times \log_2 P_i$$

$$d = \frac{S - 1}{\ln N}$$

$$J = \frac{H'}{\log_2 S}$$

where S is the total number of species, n_i is the individual density of the ith species, N is the total individual density of organisms in the sample and P_i in the H' formula is the proportion of the individual density (n_i) of the ith species in the total individual density (N).

Gradient lengths of detrended correspondence analysis for the first two axes justified the use of unimodal models. Thus, CCA-canonical correspondence analysis (CANOCO 4.5 software) was used to assess phytoplankton–environment relationships in the samples from the three periods. Logarithmic transformation was applied to the environmental data except pH to decrease skewness. The Monte Carlo permutation test with forward selection was used to test which stressors had significant roles in the distribution of phytoplankton species. The CCA ordination consisted of 75 phytoplankton taxa gathered from the reservoir in three seasons and nine environmental variables. A weighted averaging (WA) regression model was carried out to estimate the optimal values of phytoplankton species for stressors by using the Calibrate program. Phytoplankton taxa with biovolumes greater than 1% and found at least two times were used in the multivariate analyses (Çelekli *et al.* 2020).

RESULTS

Eutrophication status of reservoir

As shown in Figure 2, according to the comprehensive nutrient status index of the water body, the comprehensive nutrient status index of the Hongmen Reservoir was 32.4 to 45.1 during the survey period from December 2018 to September 2019, indicating that the reservoir was in the middle nutritive state ($30 < TSI < 50$), with the highest nutrient index in the flat period, followed by the dry period and the wet period. The nutrient index has obvious seasonal characteristics.

Phytoplankton community composition

In this survey, a total of 75 species of phytoplankton from 7 families were identified (only 1 species of the genus was identified), among which 44 species were chlorophyta, 12 species were Bacillariophyta, 9 species were cyanobacteria,
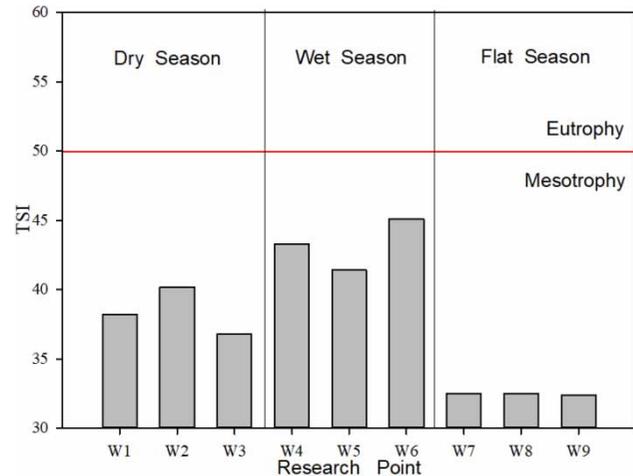

Figure 2 │ Comprehensive nutrient status index of the water body of the Hongmen Reservoir.

4 species were Euglenophyta, 3 species were Pyrrophyta, 2 species were Cryptophyta and 1 species was Chrysophyta. The proportion of chlorophyta in the Hongmen Reservoir is 58.7%, followed by Bacillariophyta at 16.0% and cyanobacteria at 12.0%, and the proportion of the three reaches 86.7% (Table 1), indicating that the reservoir shows typical characteristics of chlorophyta–Bacillariophyta–cyanobacteria. Figure 3 shows that the species composition of phytoplankton varies greatly in different periods, with the most abundant and diverse species in the dry period and the fewest species in the wet period.

Phytoplankton density and biomass

During the survey period, the average phytoplankton density in the Hongmen Reservoir was 6.6×10^6 cells/L.

Table 1 │ Phytoplankton species composition in the Hongmen Reservoir

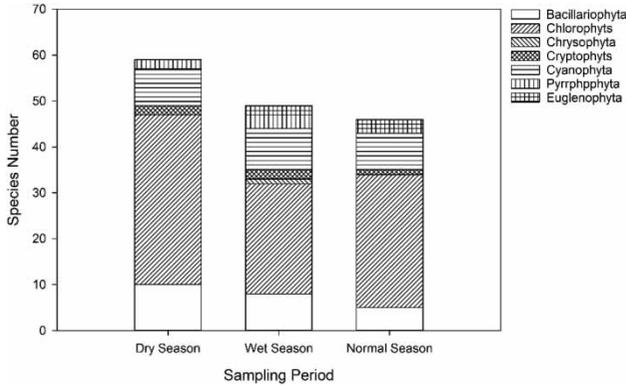| Phytoplankton	Species number	Proportion (%)
Bacillariophyta	12	16.0
Chlorophyta	44	58.7
Chrysophyta	1	1.3
Cryptophyta	2	2.7
Cyanophyta	9	12.0
Pyrrohophyta	3	4.0
Euglenophyta	4	5.3
Total	75	100

Figure 3 | Composition of the plankton community in different seasons in the Hongmen Reservoir.

According to the relevant density classification standard, the Hongmen Reservoir was at the level of mesotrophication, which was consistent with the analysis results of the total nutrient index. As shown in Figure 4, the change trend of phytoplankton density in different periods is $(7.55 \pm 1.81) \times 10^6$ (in normal season) $> (7.37 \pm 0.72) \times 10^6$ (in wet season) $> (4.91 \pm 0.36) \times 10^6$ (in dry season), among which there is a significant difference ($P < 0.05$) in the density of phytoplankton between dry season and wet season. The temperature in the dry season is significantly lower than the temperature in the wet season and normal season, which is not conducive to the growth of phytoplankton,
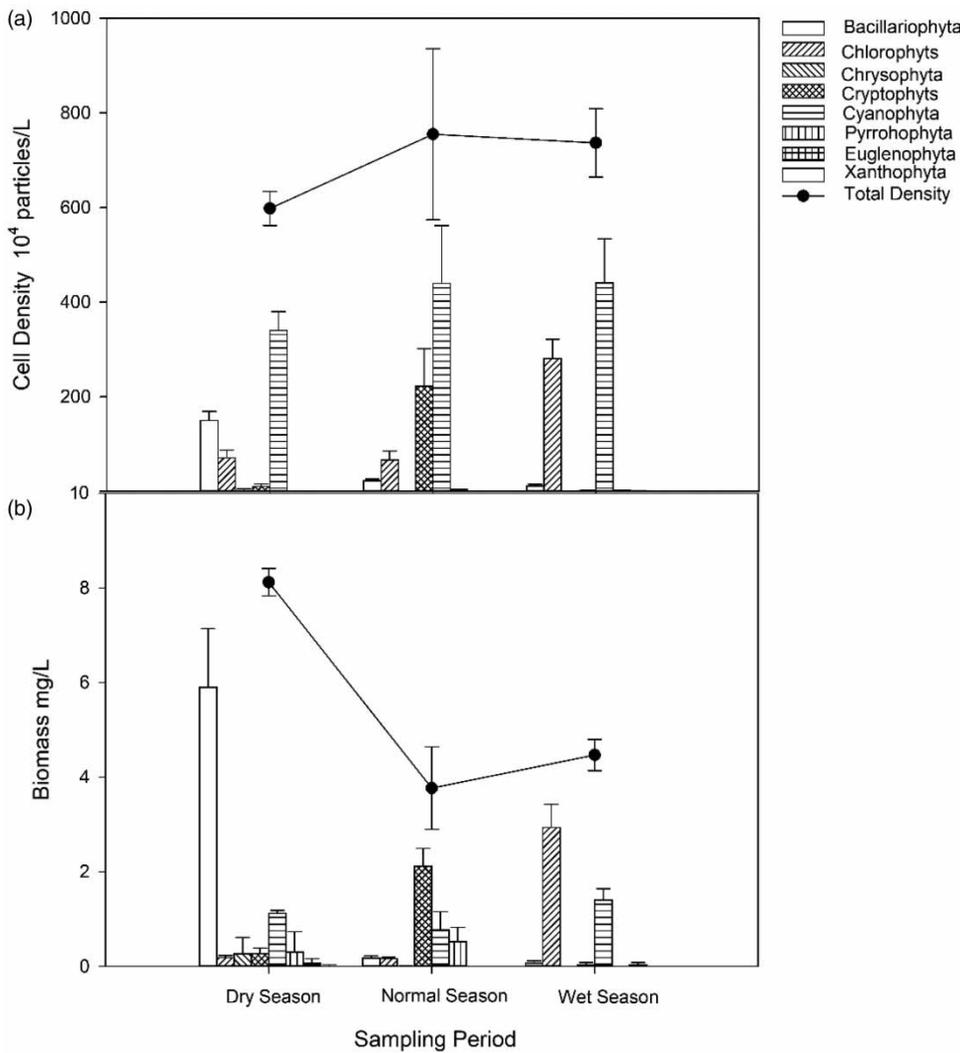

Figure 4 | Changes in phytoplankton density and biomass in the Hongmen Reservoir.

which may be one of the reasons for the low density of phytoplankton in the dry season. The density composition of phytoplankton phyla in different periods was also different. Ordered by density, the main algae were cyanobacteria > Bacillariophyta > chlorophyta in the dry season, cyanobacteria > cryptophyta in the normal season and cyanobacteria > chlorophyta in the wet season. The average biomass of phytoplankton was 4.1 mg/L, and the variation trend of phytoplankton biomass in different periods was 4.51 ± 0.33 mg/L (in the wet season) > 4.0 ± 1.23 mg/L (in the dry season) > 3.85 ± 0.87 mg/L (in the normal season). The order of biomass composition of phytoplankton in different periods is as follows: Bacillariophyta > cyanobacteria in the dry season, cryptophyta > cyanobacteria > pyrrhophyta in the normal season, chlorophyta > cyanobacteria in the wet season.

Dominant species of phytoplankton

There are 12 dominant species of phytoplankton in the Hongmen Reservoir, including 1 species of Bacillariophyta, 2 species of chlorophyta, 2 species of cryptophyta and 7 species of cyanobacteria (Table 2). Among them, the algae *Microcystis*, *Anabaena azotica Ley*, *Oscillatoria tenuis*, *Aphanizomenon* and *Pseudoa abaena* sp. are the dominant species in the reservoir in the three survey periods, and the other seven phytoplankton are distributed in a certain period. The dominant species of phytoplankton in the wet season are cyanobacteria, the dominant species in the

normal season are cyanobacteria and chlorophyta and the dominant species in the dry season are cyanobacteria, Bacillariophyta and cryptophyta, which indicates that there are significant differences in the dominant species of phytoplankton in different periods.

Phytoplankton diversity

Based on the data collected from the Hongmen Reservoir in different investigation periods, the Shannon–Wiener diversity index (H') is 2.05–2.85 with an average value of 2.44, the Margalef index (D) is 4.12–6.60 with an average value of 5.16 and the Pielou evenness index (J) is 0.61–0.78 with an average value of 0.69 (Figure 5). Therefore, the overall pollution in the Hongmen Reservoir is light, and the water quality is good. According to the values of different index types, the diversity, richness and evenness of the phytoplankton community in the dry season were significantly higher than the diversity, richness and evenness of the phytoplankton community in the normal and wet seasons ($P < 0.05$).

Effects of water environmental factors on phytoplankton community structure

Pearson correlation analysis was conducted for phytoplankton abundance, diversity and aquatic environmental factors in the Hongmen Reservoir. The results are shown in Table 3, indicating that phytoplankton density is closely related to water environmental factors in the Hongmen Reservoir.

Table 2 | Dominant species of phytoplankton in different periods in the Hongmen Reservoir

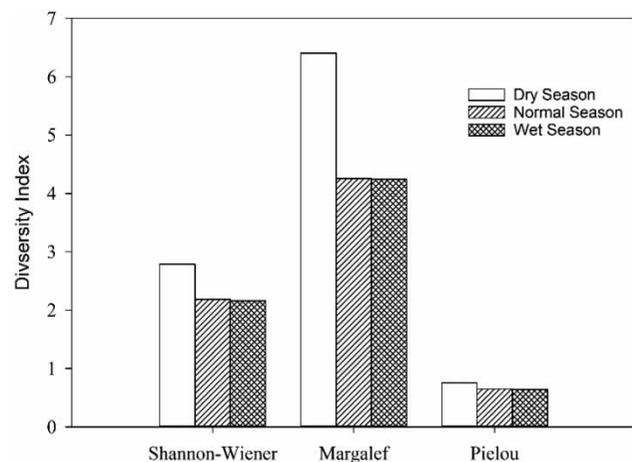| Dominant species	Dry season	Wet season	Normal season
Melosira granulata	0.173	0	0
Mougeoti	0	0	0.257
Cryptomonas erosa	0.027	0	0
Merismopedia minima	0	0.073	0
Microcyst	0.021	0.309	0.024
Anabaena azotica Ley	0.165	0.031	0.3
Anabeana circinalis	0.038	0	0
Aphanizomenon	0	0.027	0.042
Oscillatoria temuis	0.154	0.023	0.126
Pseudoanabaena sp.	0.182	0.089	0.083

Figure 5 | Phytoplankton diversity index in the Hongmen Reservoir.

Table 3 | Correlation between phytoplankton abundance and water quality

	Tem	DO	COD	BOD5	NH3	TP	TN	SD	Chl *a*	Shanoon	Bacillariophyta	Chlorophyta
Shanoon	−0.69									1		
Bacillariophyta	−0.95								0.79	0.71	1	
Chlorophyta			−0.85	−0.9	−0.9		−0.8	0.8				1
Chrysophyta												
Cryptophyta			0.83	0.9	0.9		0.83	−0.88				−0.9
Cyanophyta												
Pyrrohophyta		0.77				0.86						
Euglenophyta												

$R > 0.5$, $P < 0.05$.

Diatom density is significantly negatively correlated with the environmental temperature and positively correlated with chlorophyll *a* (Chl *a*). The density of green algae is negatively correlated with the permanganate index (COD_{Mn}), BOD_5, ammonia nitrogen and TN. Cryptophycea density was positively correlated with COD_{Mn}, BOD_5, ammonia nitrogen and total nitrogen concentrations and negatively correlated with transparency (SD). Phytoplankton diversity is negatively correlated with environmental temperature. The results indicate that environmental temperature, TP, COD_{Mn}, BOD_5, ammonia nitrogen and TN concentration are the main environmental factors affecting phytoplankton abundance.

The CCA analysis results of the phytoplankton community structure and water environmental factors in the reservoir are shown in Figure 6. The two-dimensional projection of nine samples in different periods can be grouped into three categories, and the samples in the dry season, normal season and wet season can be classified into one category, which indicates that there are obvious seasonal differences in phytoplankton community structure. Some water environmental factors explain the variation in phytoplankton community structure to some extent: the first axis information explains 37.8% of the species, the second shaft information explains 30.1% of the species and the differences between the first two axes explain 67.9% of the species. In conclusion, temperature, nutrient concentration, transparency, DO in water and other environmental factors significantly affect the community structure of phytoplankton.
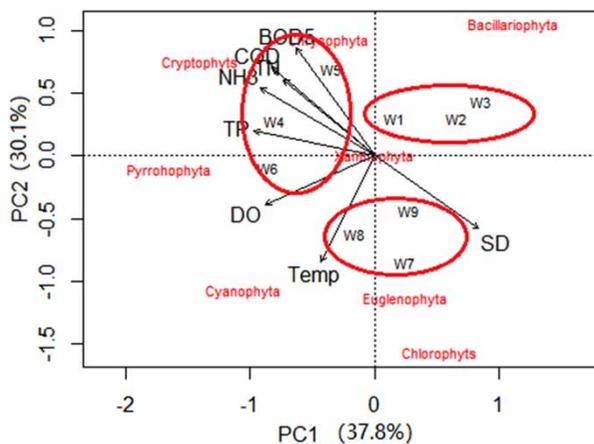

Figure 6 | Canonical correspondence analysis of the physical and chemical properties of the reservoir water and the composition of the phytoplankton community.

DISCUSSION AND CONCLUSIONS

Phytoplankton community in Hongmen reservoir

Phytoplankton are an important part of water ecosystems. As the primary producers of material metabolism and the energy cycle, phytoplankton play an important role in maintaining ecological balance. According to the investigation of phytoplankton species composition, there are 75 species of phytoplankton in 7 families in the Hongmen Reservoir, of which most species are chlorophyta (58.7%), followed by Bacillariophyta (16.0%) and cyanobacteria (12.0%), accounting for 86.7% of the total, belonging to the typical chlorophyll–Bacillariophyta–Cyanobacteria type. The characteristics of the phytoplankton community

are related to temperature factors. The composition and structure of planktonic algae are different, and the most suitable temperature for their growth and reproduction is also quite different. The annual water temperature of the Hongmen Reservoir ranges from 6 to 32 °C, and the average annual water temperature in the reservoir area is approximately 18.5 °C. Generally, it is suitable for the growth of chlorophyta and Bacillariophyta (Zheng *et al.* 2018). From the perspective of the dominant species of phytoplankton in the reservoir, Bacillariophyta and cyanobacteria are in the dry season, cyanobacteria and chlorophyta are in the normal season and cyanobacteria are in the wet season. Bacillariophyta is suitable for water with low temperature and easily grows in winter and early spring, which is consistent with the research results showing a negative correlation between diatom density and environmental temperature (Lira *et al.* 2011; Basavaraja *et al.* 2013). Cyanobacteria and chlorophyta are suitable for higher water temperatures and are prone to form an advantage in summer and early autumn (Varol 2019). The dominant species in the reservoir in different periods all contain cyanobacteria, especially in the high-temperature season, because high temperature helps cyanobacteria become the dominant population. The dominant species of cyanobacteria are the most abundant in the normal season, followed by the dry season and the least abundant in the wet season. Zhou Yaping's study in 2007 found that the composition of phytoplankton in the Hongmen Reservoir was dominated by chlorophyta, Bacillariophyta and cyanobacteria, accounting for 87.6% of the total. Gong *et al.* (2019) found that the dominant species in the Hongmen Reservoir were chlorophyta and Bacillariophyta, and the water quality of the reservoir was characterized by moderate eutrophication. In the high-temperature season, the nutrient status of the reservoir would help phyla cyanophyta become the dominant population, and the water body had a tendency toward eutrophication. Since 2017, the phytoplankton community in the Hongmen Reservoir has changed from chlorophyta and cyanophyta to Bacillariophyta, chlorophyta and cyanophyta, which may be related to the decrease in nutrient salt levels in the reservoir in recent years and the change in the characteristics of the water quality from middle eutrophication to middle eutrophication (Zhou *et al.* 2008; Gong *et al.* 2019).

The average density of phytoplankton in the reservoir is 6.96×10^6 particles/L, which is higher than the previous study results of 2.83×10^6 particles/L. The change trend in phytoplankton density at different periods, in the normal season > in the wet season > in the dry season, may be associated with the temperature of the reservoir. The average water temperature of the reservoir in the normal and wet seasons was 18.4 and 27.1 °C, respectively ($P < 0.05$), which was significantly higher than the average temperature in the dry season (6.2 °C, $P < 0.05$). The prolonged illumination time is conducive to the growth of algae. In the dry season, the water temperature is low, which is the leading factor in low phytoplankton density. The density of cyanobacteria in phytoplankton is the highest in the normal season, followed by cryptophyta, which is related to the increased water temperature, relatively less precipitation, and the lower water level in the reservoir area due to irrigation. Although the temperature is higher in the wet season, a large amount of exogenous water enters the reservoir, diluting the algae in the water.

Effects of environmental factors on phytoplankton community composition in the Hongmen Reservoir

The Pearson correlation analysis and the CCA analysis results of phytoplankton abundance, diversity and water environmental factors in the Hongmen Reservoir show that temperature, nutrients and transparency are the main environmental factors affecting phytoplankton community structure change, which is consistent with many studies on the influencing factors of phytoplankton community structure (Fadel *et al.* 2015; Gogoi *et al.* 2020).

The diversity, abundance and biomass of phytoplankton are closely related to the composition and concentration of nutrients. Nitrogen and phosphorus nutrients are essential for the survival and propagation of phytoplankton. The TP concentration in the Hongmen Reservoir is basically within 0.01–0.03 mg/L, and in the low nutrient state, the nitrogen–phosphorus ratio may become a limiting factor for the growth of phytoplankton. The mean annual values of TP and TN in the reservoir area are 0.025 and 0.56 mg/L, respectively. The optimal nitrogen–phosphorus ratio for the growth of planktonic algae was 16; when the nitrogen–phosphorus ratio was greater than 16, the growth was

restricted mainly by phosphorus, and when the nitrogen–phosphorus ratio was less than 16, the growth was mainly restricted by nitrogen (Grover 2002; Il'iash & Zapara 2006; Yang *et al.* 2016). The average nitrogen–phosphorus ratio in the Hongmen Reservoir is 23, so the TP is the main limiting factor for the growth of phytoplankton. The mean monthly value of TP in Hongmen Reservoir fluctuates greatly, and the concentration of TP is different, in normal season > wet season > dry season. In particular, the TP in the surface water of the storage and the monitoring points in the center of the reservoir exceed the standard in the normal season. In the Hongmen Reservoir basin, the population density is small, the degree of human construction development is relatively light and phosphorus pollution shows obvious characteristics of agricultural nonpoint source pollution. At the same time, the Danxia landform is not conducive to the growth of coastal vegetation attached to the surface, and soil and water loss still exists. The soluble phosphate from the area along the river flowed into the reservoir and increased the content of phosphorus in the water. Phosphorus can be absorbed into cells by phytoplankton, leading to an increase in phytoplankton biomass.

The transparency of the Hongmen Reservoir is 1.2–1.5 m, which is significantly lower in the normal season than in the dry season and wet season. In the normal season, the density of algae is relatively high, which is due to the influence of the intensity of light radiation conditions on the quantity of phytoplankton, which is consistent with the conclusion of most studies on phytoplankton populations in subtropical reservoirs; that is, transparency is also a key factor affecting the phytoplankton community structure in the Hongmen Reservoir. In biological monitoring, there is a good linear relationship between chlorophyll *a* concentration and the density of phytoplankton and algae (Bowes *et al.* 2012; Zhang *et al.* 2017; Liu *et al.* 2019), and the chlorophyll concentration can basically reflect the biomass of phytoplankton. Cyanobacteria are found as the dominant species in the reservoir in different periods, and the number is the highest, especially in the normal season. The change in chlorophyll *a* concentration is opposite to the change in transparency. In the normal season, the transparency decreases, the chlorophyll concentration increases and the eutrophication index of the water is relatively high.

Water quality characteristics of Hongmen reservoir

The phytoplankton diversity index is related to species number, individual richness and evenness. Generally, the more stable the phytoplankton community structure is, the higher the biodiversity index, richness index and evenness index are and the cleaner the water is (Duarte *et al.* 2017; Lu *et al.* 2017; Dondajewska *et al.* 2019). Using biological indicators to evaluate the degree of water pollution, the diversity index (H') of Shannon–Wiener in the Hongmen Reservoir is 2.05–2.85, the Margalef index (D) is 4.12–6.60 and the Pielou evenness index (J) is 0.61–0.78. The overall water quality evaluation results are in a state of clean to mild polluted. According to the results of the comprehensive nutrient salt index evaluation, the whole reservoir is in the middle nutrient state during the survey period, which is in good agreement with the results of the phytoplankton index evaluation.

From the perspective of time, the community structure of the Hongmen Reservoir has seasonal differences. The decrease in phytoplankton species, the increase in density and the decrease in evenness all mean that the water quality worsens. According to the comparison of phytoplankton diversity and density, the diversity index, richness index and evenness index in the normal season are the lowest, while the density of algae is the highest, indicating that the water quality in the normal season is poor, which is consistent with the conclusion that the eutrophication index is the highest in the normal season. The water diversity index and richness index in the dry season are significantly higher, while the eutrophication index in the wet season is significantly lower than the eutrophication index in the dry season and normal season because in the period of high precipitation, the dilution of external water sources helps to slow down the eutrophication degree of the reservoir.

The Hongmen Reservoir is an important lake for fishery production. The temperature of water in the reservoir is very favorable to the growth of farmed fish. Since 1976, people have tried to develop construction projects for blocking rivers in the Hongmen Reservoir. Since then, the blocking culture model has developed rapidly in reservoir areas. However, there are also many problems in the cage culture fishing model. The application of nitrogen fertilizer and phosphate fertilizer leads to water pollution and weakens

the balance ability of water ecosystems. In 2017, the net cage aquaculture of the Hongmen Reservoir was completely cleaned up, and the third party company implemented natural aquaculture uniformly. During this survey, the concentrations of TN and TP in the reservoir were 0.56 and 0.025 mg/L, respectively, which were significantly lower than the levels of TN (1.45 mg/L, $P < 0.05$) and TP (0.17 mg/L, $P < 0.05$) in the reservoir in 2017. The dominant species of phytoplankton also changed from chlorophyta and cyanophyta to chlorophyta, Bacillariophyta and cyanophyta, and the water quality was better. However, under adverse environmental factors, reservoirs still have the risk of algae proliferation and water quality deterioration.

Based on the investigation of water quality in Hongmen Reservoir, the structural characteristics of the phytoplankton community and its relationship with environmental factors were studied in this paper, and the main conclusions are drawn as follows.

In the phytoplankton survey of the Hongmen Reservoir, there were 75 species in 7 families, among which 44 species were chlorophyta (58.7%), 12 species were Bacillariophyta (16.0%) and 9 species were cyanobacteria (12.0%), with a proportion of 86.7%. The reservoir shows typical chlorophyll–bacillariophyta–cyanobacteria characteristics, and the dominant species are *Microcystis*, *Anabaena azotica Ley*, *Aphanizomenon*, *Melosira granulata*, etc. The dominant species in the reservoir in different periods all contained cyanobacteria, and the composition of phytoplankton species varied greatly in different periods. There are seasonal differences in the abundance and density composition of different phytoplankton species. In the dry season, phytoplankton are the most abundant and diverse. The density of phytoplankton in the normal season and wet season was significantly higher than that in the dry season.

The characteristics of the phytoplankton community in the Hongmen Reservoir are closely related to environmental factors. The results of statistical analysis show that the abundance and diversity of phytoplankton are influenced by environmental factors such as water temperature, water nutrient level, nitrogen and phosphorus composition and transparency. The comprehensive nutrition status index of the Hongmen Reservoir is medium, and the biological evaluation results of the phytoplankton diversity index, richness

index and evenness index show that the water quality of the reservoir is clean to β-polluted; the two evaluation results show good consistency. The community structure of the Hongmen Reservoir has seasonal differences, and the change in environmental factors reflects the change in the community structure in the Hongmen Reservoir on a time scale.

DATA AVAILABILITY STATEMENT

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

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