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CONTENTS

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Variation of cyanobacteria with different environmental conditions in Nansi Lake, China

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Abstract

Nansi Lake is located on the east line of the South-to-North Water Diversion Project in China. A comprehensive study was carried out to investigate the spatial and temporal distribution of cyanobacteria in the lake from June 2008 to May 2011 based on monthly sample monitoring from five stations. The effect of environmental factors on cyanobacterial abundance was also evaluated. The cyanobacterial community contained 15 genera and 23 species. The cyanobacterial abundance of each monitoring station ranged from 0 to 1.53×10^7 cells/L with an average of 1.45×10^6 cells/L, which accounted for 11.66% of the total phytoplankton abundance. The dominant species of cyanobacteria were *Pseudanabaena* (32.94%) and *Merismopedia* (19.85%), not the bloom-forming algae such as *Microcystis* and *Anabaena*. In addition, the cyanobacterial community structure and water quality variables changed substantially over the survey period. Redundancy analysis (RDA) suggested that temperature and phosphorus were important environmental factors that affected cyanobacteria. Temperature was the most important factor affecting cyanobacterial abundance. The effect of phosphorus on cyanobacterial abundance was more notable in warm periods than in periods with low temperature.

Key words: cyanobacteria; Nansi Lake; cyanobacterial bloom; South-to-North Water Diversion Project

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Introduction

Cyanobacterial bloom is one of the most serious problems in eutrophic freshwater systems, because it forms surface scums that cause problems of taste and odor, and even produces toxins that threaten human health (Wu et al., 2010). The occurrence of heavy cyanobacterial blooms in eutrophic lakes has been a worldwide problem (Carmichael, 1992). Cyanobacterial blooms caused by eutrophication in freshwater lakes in China are increasingly serious, such as the intensive and large-scale algal blooms in Taihu Lake, Dianchi Lake and Chaohu Lake (Chen et al., 2009a; Liu et al., 2006; Zhang et al., 2011).

The South-to-North Water Diversion Project in China is the largest project to meet the increasing demand for water resources in northern China and is composed of three routes: east, center, and west (Shan et al., 2007). The construction of the project is designed to solve the water shortage problem and sustain economic and social development in the water-receiving areas (Feng et al., 2007). Nansi Lake is situated along the east route of the South-to-North Water Diversion Project for accommodating water storage and a water channel, making it a potential drinking water source for the water diversion project.

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Nansi Lake is located in the north of the Huai River Basin (34°27′–35°20′N, 116°34′–117°21′E), and it drains an area of 3.17×10^4 km^2, belonging to 32 counties of Jiangsu, Shandong, Henan and Anhui Provinces. The total water area is 1266 km^2 with an average water depth of 1.5 m. Accordingly, Nansi Lake is classified as a plain shallow lake. At present, Nansi Lake is being utilized for a variety of purposes, such as flood control, irrigation, water supply, aquatic breeding, navigation, and tourism. Nutrient load from the drainage area has increased dramatically in the last two decades due to sewage discharge, industrial effluents and overuse of agricultural fertilizer (Chen et al., 2007).

It is necessary to obtain in-depth information on the seasonal succession of phytoplankton composition. This information is useful for exploring the formation and developmental mechanisms of cyanobacterial blooming. The spatial distributions of cyanobacteria, species composition and abundance in Nansi Lake have not been studied intensively for the last 20 years. Shuai et al. (2006) found that the *Merismopdia glauca* was dominant in May 2002 and Gong et al. (2010) indicated that *Chroococcus* and *Phorimidium* were preponderant in May and August in 2007 and 2008, respectively. Both of these earlier studies sampled only once and not much attention has been paid to the spatial distribution and temporal variability of the abundance. It would be better to analyze the basic information of the phytoplankton to improve water quality and prevent the occurrence of cyanobacterial bloom (O'Farrell et al., 2002; Webber et al., 2005; Domingues et al., 2008).

In recent years multivariate statistical analysis, especially redundancy analysis (RDA), has been widely employed to examine patterns and relationships in large-scale ecological data sets. Additionally, RDA has proved useful for qualitative analysis of the interactions between the environmental factors that influence plankton communities in highly complex systems. This article concentrates on the long-term changes of cyanobacteria in Nansi Lake, using monthly monitoring data from June 2008 to May 2011. RDA was also applied to explore the correlation between multi-environmental variables and cyanobacteria. The objectives of this study were to analyze cyanobacteria species and abundance variability in relation to environmental factors so that this information can be used effectively to develop strategies for preventing cyanobacterial bloom in Nansi Lake.

1 Materials and methods

1.1 Station description

Nansi Lake, which is comprised of four connected lakes named Nanyang, Dushan, Zhaoyang and Weishan, is a long narrow lake running from north to south and is separated into an upper lake and a lower lake by a dam. Observations of water quality and cyanobacterial community structure were conducted at sites S1–S5 which are the national control monitoring sections. Nansi Lake and the sampling stations are shown in Fig. 1.

1.2 Sampling and frequency

Water samples were collected monthly with a Ruttner water sampler (436-131, Hydro-bios, Germany) at a depth of 0.5 m below the surface, as the average water depth of Nansi Lake was less than 5 m and the water was not stratified. Water samples were kept in a cool, dark environment and carried to the laboratory. The sampling campaign was interrupted from July to October in 2009.

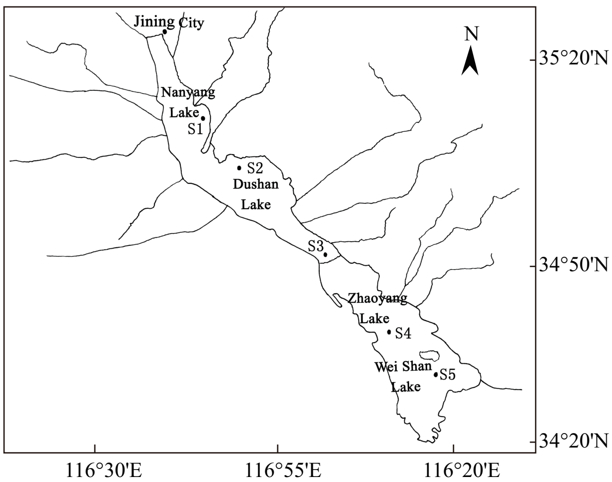

Fig. 1 Sampling stations in Nansi Lake.

1.3 Analysis methods

The physical and chemical parameters such as water temperature (Temp), pH, transparency (Trans) and dissolved oxygen (DO) were determined using *in situ* instruments with a thermometer (TES1316, Shanghai Precision Instruments Co., China), portable acidity meter (PH-HJ90, Aerospace Computer Company, China), Secchi disk (20 cm), and portable dissolved oxygen meter (YSI59, YSI Corporation in China, USA), respectively. Total phosphorus (TP) and total nitrogen (TN) were determined by the molybdate blue procedure and persulfate oxidation spectrometry (EPAC, 2002), respectively. Chemical oxygen demand (COD) was determined by the acidic potassium permanganate method, and biochemical oxygen demand (BOD_5 at 20°C) was analyzed with the dilution and seeding method (EPAC, 2002).

A sedimentation method was used for counting and species identification. The phytoplankton samples were kept in 1000 mL brown glass bottles, immediately preserved by adding 15 mL of Lugol's iodine solution and stored at 4°C. To optimize the counting process, the samples preserved with Lugol's solution were checked for high densities of phytoplankton, and the subsamples of water were settled over a period of 48 hr for enumeration using the microscope technique (CX31, OLYMPUS, Japan) (EPAC, 2002). The supernatant was siphoned off, resulting in a 25–100× concentration of the sample. In total, a volume of 10–40 mL of the sample was investigated for analysis, according to total phytoplankton abundance.

1.4 Statistical analysis

The CANOCO v4.5 computer program was used to perform all of the multivariate and ordination analyses (ter-Braak and Šmilauer, 2002). The first gradient length of detrended correspondence analysis (DCA) was used to select the appropriate model (ordination procedure) for the constrained ordinations. The RDA was appropriate for the analysis if the length of the ordination axes in DCA was relatively low (< 3); otherwise canonical correspondence analysis (CCA) was considered to be a more suitable method (Lepš and Šmilauer, 2003).

RDA, a constrained linear ordination method, was used to evaluate the effects of environmental variables on the phytoplankton community. The measured environmental factors, including Temp, Trans, pH, DO, BOD_5, COD, TP, TN and N:P ratio (mol/mol), were adopted as the explanatory variables. All of these environmental variables were $\log_{10}(X+1)$-transformed before analysis except for pH (Passy, 2007). In the data matrix of species biomass, only those taxa that occurred more than 3 times and accounted for greater than 1% of the total biomass in at least one sample were incorporated into the analysis. $\log_{10}(X+1)$ transformation was carried out on the abundance data of each of the genera before analysis to obtain consecutive distributions. Thus, two series of matrices were produced from the measured results, one for species abundance and the other for environmental factors.

The results of RDA were visualized in the form of ordination diagrams in the Canodraw for Windows program. Species scores are represented as triangles. Environmental variables are represented by arrows, pointing in the direction of maximal variation. Variables with lines close to each other and headed in the same direction are highly positively correlated, while those headed in opposite directions are highly negatively correlated. Two lines at a 90° angle indicate that the corresponding variables are uncorrelated.

Pearson correlations between phytoplankton abundance and environmental factors were done. A *t*-test was used to check the significance of parameters between two sites. Levels of significance used were 5% (significant) and 1% (highly significant). Statistical analysis was carried out using the SPSS 18.0 package.

2 Results

2.1 Basic physical and chemical environment factors in sampling stations

The concentration ranges and averages of water quality variables between June 2008 and May 2011 are shown in Table 1. Water temperature ranged from 0 to 28°C and pH from 7.06 to 8.87. Transparency had wide variations from 25 to 120 cm among the five sampling sites. DO concentrations varied indistinctly with time and ranged from 4.80 to 14.00 mg/L, with an average of 8.40 mg/L. BOD_5 and COD showed a similar changing trend, with ranges of concentrations 1.04–5.80 mg/L and 3.77–6.41 mg/L, respectively.

With regard to the trophic conditions of Nansi Lake, TN and TP covered a wide range of concentrations (from 0.29 to 4.70 mg/L TN, from 0.02 to 0.26 mg/L TP) and there were four pulses in both at the 5 sampling sites (Fig. 2). TN and TP concentrations exhibit an opposite trend, with high TN concentration occurring in winte, while that of TP occurred in summer. This kind of fluctuation leads to a wide variation of the N:P ratio in Nansi Lake (from 5.21 to 158.32).

2.2 Phytoplankton community composition

A total number of 15 genera and 23 species were identified in the cyanobacterial community (Table 2). The proportion of the community composition was *Pseudanabaena* 32.94%, *Merismopedia* 19.85%, *Microcystis* 11.42%, *Phorimidium* 10.19%, *Chroococcus* 6.97%, *Oscillatoria* 6.19%, and the remainder 12.44%. The species number ranged from 0 to 14 identified per sample. The maximal species number in a single sample was found at the station S1 in August 2010 and the minimal at station S4 in February 2009. The species of *Pseudanabaena* and *Merismopedia* were the main components of phytoplankton communities in Nansi Lake.

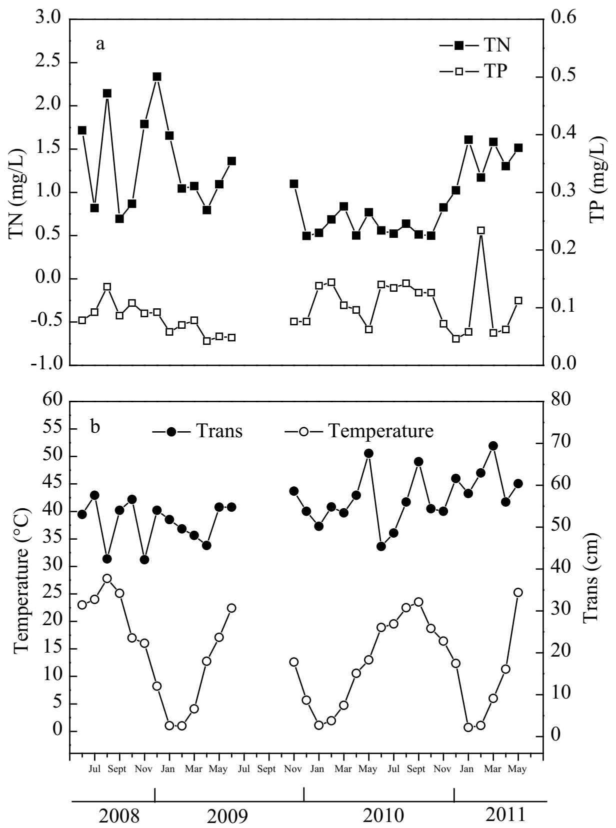

Fig. 2 Temporal variations of TN, TP (a); Trans, Temp (b) from June 2008 to May 2010 (each dot represents the mean of five sampling stations).

2.3 Phytoplankton variations in abundance

The distribution of cyanobacteria species varied in different stations (Fig. 3). The interannual variation of the cyanobacterial abundance ranged over seven orders of magnitude, from the winter minima of undetectable values to 1.53×10^7 cells/L in September 2010 at station S5.

Table 1 Summary of major water quality variables in Nansi Lake between June 2008 and May 2011

	No.	Mean	Min	Median	Max	StDev[a]	C.V.[b]
Temp (°C)	160	13.29	0	13	28	8.58	0.65
pH	160	7.57	7.06	7.56	8.87	0.24	0.032
Trans (cm)	160	54.75	25	55	120	11.30	0.21
DO (mg/L)	160	8.40	4.80	8.00	14.00	1.62	0.19
TN (mg/L)	160	1.06	0.29	0.86	4.70	0.68	0.64
TP (mg/L)	160	0.09	0.02	0.08	0.26	0.04	0.48
N:P (mol/mol)	160	34.43	5.21	25.68	158.32	29.53	0.86
BOD_5 (mg/L)	160	2.63	1.04	2.60	5.80	0.72	0.27
COD (mg/L)	160	5.08	3.77	5.05	6.41	0.57	0.11

[a]Standard deviation; [b]coefficient of variation (StDev/Mean).

Temp: temperature; Trans: transparency; DO: dissolved oxygen; TN: total nitrogen; TP: total phosphorus; N:P: total nitrogen/total phosphorus; BOD_5: biochemical oxygen demand; COD: chemical oxygen demand; No.: the number of water quality variables.

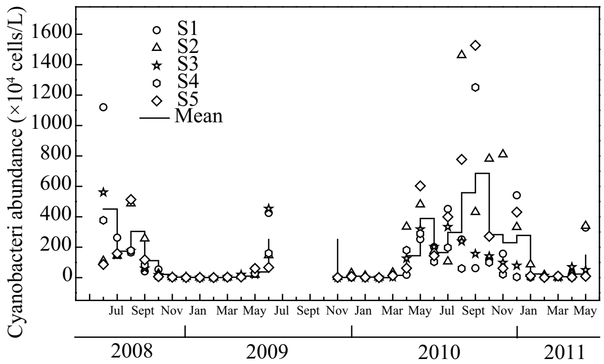

Fig. 3 Temporal variations of cyanobacterial abundance at five sampling stations.

Table 2 Cyanobacteria species recorded from Nansi Lake (June 2008–May 2011)

Genera	Species
Microcystis	*Microcystis aeruginosa*; *Microcystis incerta*
Aphanocapsa	*Aphanocapsa rivularis*
Gloeocapsa	*Gloeocapsa magma*
Chroococcus	*Chroococcus tenax*; *Chroococcus Minor*; *Chroococcus minutus*
Merismopedia	*Merismopedia sinica*; *Merismopedia elegans*; *Merismopedia glauca*; *Merismopedia punctata*; *Merismopedia tenuissima*
Dactyloccocopsis	*Dactyloccocopsis rhaphidioides*
Pleurocapsa	*Pleurocapsa fuliginosa*
Raphidiopsis	*Raphidiopsis curvata*
Aulosira	*Aulosira laxa*
Oscillatoria	*Oscillatoria princeps*; *Oscillatoria tenuis*
Phormidium	*Phormidium tenus*
Pseudanabaena	*Pseudanabaena limnetica*
Coelosphaerium	*Coelosphaerium dubium*
Rhabdoderma	*Rhabdoderma lineare*
Cylindrospermum	*Cylindrospermum stagnale*

The average cyanobacterial abundance of waters in the lower lake (S4 and S5) was 1.52×10^6 cells/L, which was higher than waters in the upper lake (S1, S2 and S3), at an average of 1.34×10^6 cells/L. Temporal variation in cyanobacterial abundance at the 5 stations took on a similar regularity. The most recurrent periods of increase took place from spring to summer (or autumn), when the highest peaks occurred, while winter was the period of the lowest abundance, except for the monsoon. There is a clear evidence of this trend from the mean annual cycles that showed a regular pattern common to each station (Fig. 3): a phase of phytoplankton increase from March to September, more or less variable in abundance, length and timing of peaks, followed by a decrease through to December, after which the lowest mean densities were observed. This result indicates that climatic factors are the principal driving factors for abundance fluctuation.

2.4 Change of species composition of phytoplankton

The species composition and abundance of dominant phytoplankton species during the period of investigation are shown in Fig. 4. The predominant phytoplankton species in the lake were classified into the genera of *Pseudanabaena*, *Merismopedia*, *Microcystis*, *Phorimidium*, *Chroococcus* and *Oscillatoria*. *Pseudanabaena* and *Merismopedia*, being widespread in the whole lake, were always the most abundant, with the highest mean abundance of 4.76×10^5 and 2.87×10^5 cells/L, respectively. They were the most dominant from spring to autumn, and less in winter (Fig. 4). *Merismopedia* and some species of *Microcystis* occurred dominantly during summer (June–August) in 2008 and 2010, and *Merismopedia* and *Pseudanabaena* became dominant during June 2009 and summer in 2010. *Merismopedia*, *Pseudanabaena* and *Phorimidium* were dominant during autumn in 2008 and 2010, respectively. The mean density of *Microcystis* exceeded 5.0×10^5 cells/L only in Jun 2008, May 2010 and June 2010, that is, the late spring and early summer of 2008 and 2010.

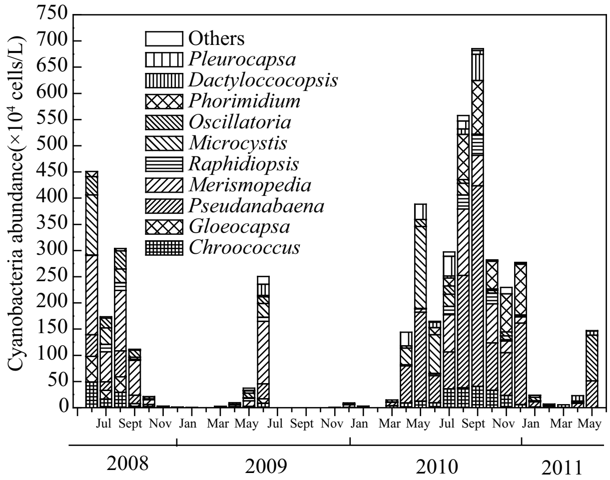

Fig. 4 Cyanobacterial community succession in Nansi Lake.

2.5 Relation between phytoplankton species and environmental factors

RDA was applied to evaluate the interactions between cyanobacteria variation and environmental variables. A close and significant relationship between algal taxon and environment was observed in RDA ordination. Ten species from all the samples met the data selection criteria over the entire period investigated, and were consequently summed as the species data matrix, 160×10 (Fig. 5a). In addition, 10 species from the warm period samples met the criteria and were summed as a 75×10 species matrix (Fig. 5b). The physicochemical variables explained 27.9% of the total variance of species distribution within all periods investigated, and 28.8% within the periods when the temperature exceeded 15°C (denoted as warm periods). Most of these species were clustered by the two-dimension graph of RDA. Each water-quality variable is represented by an arrow, which determines an axis. The projection of a taxon on this axis indicates the level of the variable where the taxon is most abundant. As an index of seasonal succession, water temperature is the most effective factor influencing both the community composition and distribution.

In all periods investigated, the eigenvalues (λ) for redundancy analysis (RDA) axis 1 (λ: 0.247) and RDA axis 2 (λ: 0.032) explained 27.9% of variance in the species data (Table 3). Variables such as temperature (r = –0.625), BOD_5 (r = –0.303), DO (r = 0.282), N:P ratio (r = 0.265) and TN (r = 0.230) related to axis 1, whereas N:P ratio (r =

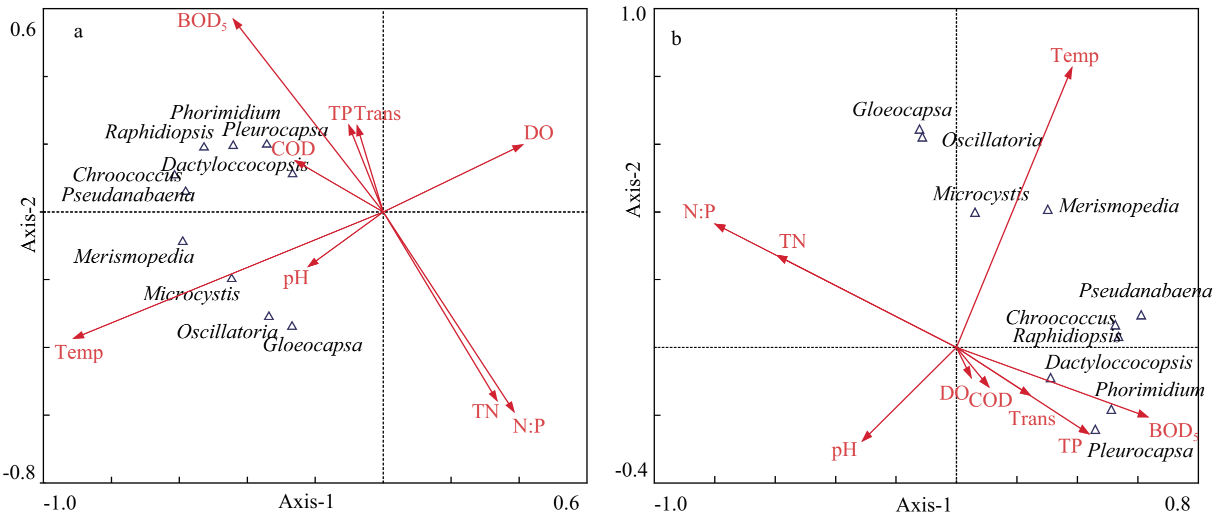

Fig. 5 The first two axes of RDA for environmental factors associated with the cyanobacteria variation in all periods investigated (a) and warm periods (b) at Nansi Lake.

Table 3 Summary of redundancy analysis between environmental factors and cyanobacterial abundance in Nansi Lake

Axes	All periods		Warm periods	
	1	2	1	2
Eigenvalues	0.247	0.032	0.168	0.120
Species-environment correlations	0.687	0.503	0.668	0.723
Cumulative percentage variance of species data	24.7	27.9	16.8	28.8
Cumulative percentage variance of species-environment relation	80.4	90.8	48.1	82.5
Sum of all eigenvalues	1.000		1.000	
Sum of all canonical eigenvalues	0.307		0.349	

–0.296), BOD_5 (r = 0.285) and TN (r = –0.279) associated significantly with axis 2 (Fig. 5a). In warm periods, the eigenvalues for RDA axis 1 (λ: 0.168) and RDA axis 2 (λ: 0.120) explained 28.8% of variance in the species data (Table 5). Variables such as N:P ratio (r = –0.532), BOD_5 (r = 0.422) and TN (r = –0.396) related strongly to axis 1, whereas Temp (r = 0.597) and N:P ratio (r = –0.215), were associated significantly with axis 2 (Fig. 5b).

The RDA ordination clearly showed that the cyanobacterial community experienced rapid and substantial changes. These changes are statistically related to many water quality variables, including Temp, DO, Trans, TN, TP, BOD_5 and COD. In all periods investigated, many genera cluster along the variable of temperature. *Pseudanabaena*, *Chroococcus*, *Dactyloccocopsis*, *Pleurocapsa*, *Phormidium* and *Raphidiopsis* cluster along the variables of BOD_5 and COD, indicating that these cyanobacteria were affected by the general water quality. In warm periods, *Gloeocapsa*, *Microcystis*, *Oscillatoria* and *Merismopedia* preferred a higher water temperature. *Pseudanabaena*, *Chroococcus*, *Dactyloccocopsis*, *Pleurocapsa*, *Phormidium* and *Raphidiopsis* were affected by the general water quality. More details about the interpretation of the triplot can be found in Lepš and Šmilauer (2003). Considering the complexity of the ecosystem and interactions between nutrients and the cyanobacterial community, it was easy to find that temperature was the limiting factor for most cyanobacteria species in Nansi Lake.

The data reveal several statistically significant correlations of interest. In all periods investigated, cyanobacterial abundance correlated positively with temperature and BOD_5, but negatively with DO (Table 4). *Pseudanabaena* abundance correlated positively with temperature, BOD_5 and transparency, but negatively with TN and N:P ratio. *Merismopedia* abundance correlated positively with temperature and BOD_5, but negatively with DO. *Microcystis* abundance only correlated significantly with temperature, which was a positive correlation (Table 4). In warm periods, cyanobacterial abundance correlated positively with temperature and BOD_5 (Table 4). *Pseudanabaena* abundance correlated positively with BOD_5, but negatively with transparency and N:P ratio. *Merismopedia* abundance correlated positively with temperature. *Phorimidium* abundance only correlated significantly with BOD_5, which was a positive correlation (Table 4). It is clear that temperature and BOD_5 correlated significantly with cyanobacterial abundance for a wide variety of species in Nansi Lake.

3 Discussion

In Nansi Lake, the abundance and the spatial distribution of the dominant species of cyanobacteria were greatly affected by water quality. From 1984 to 1990, water pollution became serious in Nansi Lake, and cyanobacteria species and their abundance have undergone great changes. Phytoplankton species that were adapted to grow in clean waters reduced or disappeared, while a variety of more hardy species gradually appeared (Jin and Liu, 1995). From Table 5, it can be seen that *Oscillatoria* was the dominant genus of cyanobacteria between 1987 and 1988, and *Microcystis* was the dominant cyanobacteria genus in May 1996. In this study, the cyanobacterial abundance accounted for 11.7% of the total phytoplankton abundance with 1.45×10^6 cells/L, much more than the historical

Table 4 Pearson correlation coefficients between parameters during warm periods and all periods investigated (unit: cells/L)

	CHA	GLA	PSA	MEA	RAA	MIA	OSA	PHA	DAA	PLA	CYA
All periods											
Temp	0.490**	0.354**	0.274**	0.498**	0.346**	0.228**	0.336**	0.198*	0.222**	0.087	0.459**
pH	0.024	–0.036	0.008	0.115	0.097	0.150	0.028	–0.031	0.081	0.072	0.074
Trans	–0.025	–0.111	0.185*	–0.037	0.046	0.143	0.068	0.095	0.081	0.102	0.135
DO	–0.202*	–0.141	–0.126	–0.192*	–0.148	–0.080	–0.060	–0.102	–0.094	–0.070	–0.187*
TP	0.109	–0.031	0.026	0.016	0.060	–0.018	–0.017	–0.018	0.050	0.055	0.023
TN	–0.115	0.207**	–0.198*	–0.038	–0.168*	–0.033	0.129	–0.164*	–0.098	–0.144	–0.151
BOD5	0.700**	0.015	0.363**	0.177*	0.399**	–0.051	–0.084	0.303**	0.407**	0.049	0.331**
COD	0.184*	0.050	0.042	0.049	0.049	–0.105	0.013	0.104	0.100	0.017	0.059
N:P	–0.217**	0.110	–0.159*	–0.086	–0.187*	–0.062	0.037	–0.071	–0.073	–0.143	–0.151
Warm periods											
Temp	CHA	GLA	PSA	MEA	RAA	MIA	OSA	PHA	DAA	PLA	CYA
Temp	0.181	0.360**	0.125	0.376**	0.178	0.145	0.333**	–0.038	0.184	–0.026	0.260*
pH	–0.282*	–0.209	–0.128	–0.093	–0.054	–0.054	–0.120	–0.120	–0.003	0.030	–0.161
Trans	0.003	–0.135	0.241*	0.031	0.166	–0.218	0.118	0.202	0.220	0.043	0.171
DO	0.037	–0.075	–0.020	–0.015	–0.032	0.071	0.143	0.022	–0.040	–0.006	0.012
TP	0.223	–0.152	0.140	–0.062	0.075	0.036	–0.075	0.034	0.117	0.210	0.083
TN	–0.107	0.306**	–0.205	–0.023	–0.213	0.080	0.211	–0.202	–0.132	–0.142	–0.134
BOD5	0.295*	–0.084	0.406**	0.052	0.354**	–0.138	–0.174	0.305**	0.415**	0.051	0 .299**
COD	0.102	–0.060	–0.040	–0.160	–0.086	–0.077	–0.084	–0.045	–0.002	0.124	–0.086
N:P	–0.211	0.313**	–0.229*	0.009	–0.208	0.055	0.169	–0.190	–0.087	–0.172	–0.145

* $P < 0.05$; ** $P < 0.01$.
A: abundance; CH: *Chroococcus*; GL: *Gloeocapsa*; PS: *Pseudanabaena*; ME: *Merismopedia*; RAA: *Raphidiopsis*; MI: *Microcystis*; OS: *Oscillatoria*; PHA: *Phorimidium*; DA: *Dactyloccocopsis*; PL: *Pleurocapsa*; CY: Cyanobacterial.

Table 5 Variation of cyanobacteria in Nansi Lake

Period	Ratio of cyanobacterial abundance of phytoplankton abundance (%)	Cyanobacterial abundance ($\times 10^5$ cells/L)	Dominant genus of cyanobacteria	Reference
Between 1983 and 1984	14.6	3.05	*Chroococcus*	Jin and Liu, 1995
Between 1987 and 1988	62.1	2.27	*Oscillatoria*	
1989	10.1	1.65	*Merismopedia* *Oscillatoria*	
1990	25.8	3.86	*Oscillatoria*	
1991	25.5	4.37	*Merismopedia* *Oscillatoria*	
May 1996	17.0	3.12	*Microcystis*	Liu et al., 1997
May 2002	23.8	5.84	*Merismopedia*	Shuai et al., 2006
Between June 2009 and May 2011	11.7	14.5	*Pseudanabaena* *Merismopedia*	This study

records between 1983 and 2002, with the dominant species being from the *Pseudanabaena* and *Merismopedia* genera.

Eutrophication has become the most widespread water quality problem in China and many other countries (Wang et al., 2004; Chen et al., 2004). The development of phytoplankton populations is dependant upon the concentration of nutrients and other ecological factors such as light, temperature, salinity, composition and quantity of organic matter, currents and grazing (Viličić, 1989). There will be an outbreak of cyanobacterial bloom when eutrophic water bodies are exposed to appropriate water temperature, air temperature, flow rate, radiation and other external conditions (Heisler et al., 2008). As shown in the RDA ordination, in all periods investigated and in warm periods, *Pseudanabaena*, *Chroococcus*, *Dactyloccocopsis*, *Pleurocapsa*, *Phormidium* and *Raphidiopsis* cluster along the variables of BOD_5 and COD, indicating that these cyanobacteria were affected by the general water quality (Fig. 5). Pearson correlation coefficients have similar results: *Pseudanabaena*, *Dactyloccocopsis*, *Phormidium*, *Raphidiopsis* and *Chroococcus* had a "highly significant" or a "significant" correlation between phytoplankton abundance and BOD_5 in all periods investigated and in warm periods (Table 4). Most species of cyanobacteria were affected by the general water quality or trophic state.

Overloading is the most important cause of lake eutrophication in China; as phosphorus is a critical element in biogeochemical cycles, numerous studies have shown that high loading of phosphorus leads to high phytoplankton biomass (An and Li, 2009). Hecky and Kilham (1988) reported that phosphorus has been considered as the primary limiting factor to algal growth. Based on the results of RDA, *Pseudanabaena*, *Chroococcus*, *Dactyloccocopsis*, *Pleurocapsa*, *Phormidium* and *Raphidiopsis* were significantly influenced by phosphorus (Fig. 5). The effect was more noticeable in warm periods. Hence, it was concluded that phosphorus significantly affected the cyanobacterial abundance, while the effect of TN concentration was barely observed based on the Pearson correlation coefficient and RDA (Tables 3 and 4). N:P ratios were proposed as an index to classify lakes into N- or P-limited categories, while the assessment criterion of nutrient limitation is proposed as 10–17 (Sakamoto, 1966). The N:P ratio proposed by Redfield (1958), which is 16:1 (atomic ratio), has been extensively used as the criterion to assess nutrient limitation. The N:P ratios ranged from 1.48 to 158.32 (atomic ratio) with a mean value of 34.34, while 65.63% of the N:P ratio was more than 16 during the research period. From this it could be concluded that Nansi Lake was a P-limited lake.

Water temperature is thought to be the most important environmental factor influencing the growth of phytoplankton. Tsuchida et al. (1984) reported that temperature was the limiting factor controlling the multiplication rate and standing stock of natural population of phytoplankton in the lake of Tsuchiura Harbor during the spring bloom of 1980. Masaki and Seki (1984) reported that the limiting factor for inducing the spring bloom of phytoplankton in 1980 at Tsuchiura Harbor on Lake Kasumigaura was temperature, and the concentration of inorganic nitrogen in the lake had a profound effect on the induction of the spring bloom as a non-limiting factor.

Previous studies reported that cyanobacteria access a dormant phase when the environment temperature is not suitable for growing, and will return to normal growth when the temperature is high (Barbiero et al., 1994; Hansson, 1996). Reynold (1973) reported that *Microcystis* began accelerated growth and floated to the top of the water column when the water temperature reached 15°C. Krüger and Eloff (1978) found a sharp decline in growth rate below about 15°C in four strains of *Microcystis*, though the exact critical temperature varied between strains. Jin et al. (2008) reported that *Microcystis flos-aquae* could not grow below 13°C, and grew slowly at 16°C. Furthermore, *Planktothrix mougeotii* could grow slowly at 10°C, and grew well above 16°C. Based on the above research, it can be concluded that *Microcystis* and other cyanobacteria can float from sediments to the top of the water column when the temperature exceeds 15°C. The period when the temperature exceeds 15°C was denoted as the warm period, and was selected for investigation in this study.

In all periods investigated, the abundance of most cyanobacteria correlated significantly and positively with temperature (Table 4). RDA could qualitatively, but not quantitatively (Gilbride et al., 2006), describe the relationship between cyanobacterial abundance and temperature. For that reason, the regression method was selected in the form of a Pearson correlation, where Y was log(cyanobacterial abundance ($\times$ 10^4 cells/L)) and X was log(temperature (°C)). The results of temperature-cyanobacterial abundance regression based on the data from all periods investigated illustrated that all the temperature–cyanobacterial abundance regressions had higher coefficients of determination ($Y = 1.969X^2 - 1.635X + 0.7086$; $R = 0.7412$; $n = 160$; $P < 0.0001$) (Fig. 6). Phytoplankton abundance varied from millions to billions for different water bodies. However, the exact concentration of phytoplankton abundance that could lead to water bloom could not be determined since water

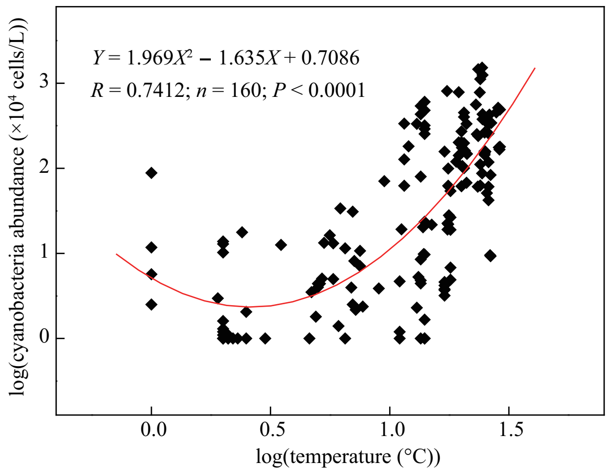

Fig. 6 Relationship between temperature and cyanobacterial abundance in Nansi Lake.

qualities varied greatly for different lakes. According to our observations, phytoplankton colored the water when cyanobacterial abundance reached 1.0×10^6 cells/L, with the critical temperature being 20.2°C in Nansi Lake. In general, the mean water temperature exceeds 20.2°C from May to October in Nansi Lake, and *Pseudanabaena* and *Merismopedia* were dominant during these months. The nontoxic *Pseudanabaena limnetica*, which could grow without much sunlight, was adaptable to environmental changes even in turbulence, and was often the dominant species in shallow lakes (Havens et al., 1998; Mischke, 2003; Casé et al., 2008). As a kind of ubiquitous species with strong environmental adaptability, *Merismopedia* could be found in lakes, rivers and estuaries and often was the dominant species in low-alkalinity clear water lakes in summer (Blomqvist et al., 1995; Blomqvist, 2001; Qin et al., 2007). The highest mean cyanobacterial abundance (6.85×10^6 cells/L) during all periods investigated appeared in September 2010. *Microcystis* bloom had not been seen in Nansi Lake, although the cyanobacterial abundance was very high in some warm periods. The reason might be that the dominant species of cyanobaceria were *Pseudanabaena* and *Merismopedia*, but not the bloom-forming algae such as *Microcystis* or *Anabaena*.

Most of the cyanobacterial blooms that have occurred in China were caused by *Microcystis* (Chen et al., 2009b; Deng et al., 2008; Gong et al., 2011). *Microcystis* has been comprehensively researched because of the threat to drinking water safety associated with its production of microcystins (Zilliges et al., 2011). It has been widely recognized that the growth of *Microcystis* would be limited in a low phosphorus condition, while cyanobacterial blooms occur at relatively high phosphorus concentrations (Olsen, 1989; Amano et al., 2002; Xie et al., 2003). Chen et al. (2009b) reported that the average concentration of TP was 0.17 and 0.13 mg/L during the period of July–December in 2003 and 2005, respectively, when a cyanobacterial bloom occurred in Meiliang Bay of Lake Taihu. The average TP concentration exceeded 0.20 mg/L in the west lake region of Chaohu from 2000 to 2006 (Zan et al., 2011). In this study, the mean TP concentration was 0.09 mg/L during all periods investigated. Based on this analysis it was expected that cyanobacterial blooms in Nansi Lake might not occur if the phosphorus pollution did not worsen.

Temperature was another important parameter influencing cyanobacterial blooms. *Microcystis* populations have been shown to be predominant at or above 25°C (Robarts and Zohary, 1987). Wang et al. (2008) reported that a water temperature between 24 and 30°C was necessary for cyanobacterial bloom, based on MODIS (Moderate Resolution Imaging Spectroradiometer) data in Taihu Lake. In this study, water temperature exceeded 25°C only in September 2008, May 2011 and August 2008, and the last time was so short that *Microcystis* bloom never occurred in Nansi Lake.

4 Conclusions

Based on a monthly sampling from five stations, 10 genera and 23 species of cyanobacteria were identified from June 2008 to May 2011 in Nansi Lake. The average cyanobacterial abundance was 1.44×10^6 cells/L, ranging from ~0 (undetectable) to 1.53×10^7 cells/L. The dominant species of cyanobacteria were the species of *Pseudanabaena* (32.94%) and *Merismopedia* (19.85%), not the bloom-forming algae such as *Microcystis* or *Anabaena*. RDA results indicated that temperature and phosphorus were important environmental factors that affected cyanobacterial community variation in Nansi Lake. In all periods investigated, temperature–cyanobacterial abundance regressions had the highest coefficients of determination, showing that temperature was the most important factor affecting cyanobacterial abundance. The effect of phosphorus on cyanobacterial abundance was more notable in warm periods than in the periods with low temperature.

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