Aims and scope

*Journal of Environmental Sciences* is an international academic journal supervised by Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. The journal publishes original, peer-reviewed innovative research and valuable findings in environmental sciences. The types of articles published are research article, critical review, rapid communications, and special issues. The scope of the journal embraces the treatment processes for natural groundwater, municipal, agricultural and industrial water and wastewaters; physical and chemical methods for limitation of pollutants emission into the atmospheric environment; chemical and biological and phytoremediation of contaminated soil; fate and transport of pollutants in environments; toxicological effects of terrorist chemical release on the natural environment and human health; development of environmental catalysts and materials.

For subscription to electronic edition

Elsevier is responsible for subscription of the journal. Please subscribe to the journal via [http://www.elsevier.com/locate/jes](http://www.elsevier.com/locate/jes).

For subscription to print edition

China: Please contact the customer service, Science Press, 16 Donghuangchenggen North Street, Beijing 100717, China. Tel: +86-10-64017032; E-mail: journal@mail.sciencep.com, or the local post office throughout China (domestic postcode: 2-580).

Outside China: Please order the journal from the Elsevier Customer Service Department at the Regional Sales Office nearest you.

Submission declaration

Submission of an article implies that the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere. The submission should be approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If the manuscript accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Submission declaration

Submission of the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere. The publication should be approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If the manuscript accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Editorial

Authors should submit manuscript online at [http://www.jesc.ac.cn](http://www.jesc.ac.cn). In case of queries, please contact editorial office, Tel: +86-10-62920553, E-mail: jesc@263.net, jesc@rcees.ac.cn. Instruction to authors is available at [http://www.jesc.ac.cn](http://www.jesc.ac.cn).

Copyright

© Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V. and Science Press. All rights reserved.
CONTENTS

Aquatic environment

Three-dimensional hydrodynamic and water quality model for TMDL development of Lake Fuxian, China
Lei Zhao, Xiaoling Zhang, Yong Liu, Bin He, Xiang Zhu, Rui Zou, Yanguan Zhu

Removal of dispersant-stabilized carbon nanotubes by regular coagulants
Ni Liu, Changli Liu, Jing Zhang, Daohui Lin

Effect of environmental factors on the effectiveness of ammoniated bagasse in wicking oil from contaminated wetlands
Seungjoon Chung, Makram T. Suidan, Albert D. Venosa

Cationic content effects of biodegradable amphoteric chitosan-based flocculants on the flocculation properties
Zhen Yang, Yabo Shang, Xin Huang, Yichun Chen, Yuobo Lu, Aimin Chen, Yuxiang Jiang, Wei Gu

Biosorption of copper and zinc by immobilised and free algal biomass, and the effects of metals biosorption on the growth and cellular structure of Chlorella sp. and Chlamydomonas sp. isolated from rivers in Penang, Malaysia
W. O. Wan Maznah, A. T. Al-Fawwaz, Misni Surif

Variation of cyanobacteria with different environmental conditions in Nansi Lake, China
Chang Tian, Haiyan Pei, Wensong Hu, Jun Xie

Enhancing sewage sludge dewaterability by biocaching approach with comparison to other physical and chemical conditioning methods
Fenwu Liu, Jun Zhou, Dianzhan Wang, Lixiang Zhou

Effect of chloride content of chlorophenols on their adsorption by mesoporous SBA-15
Qingdong Qin, Ke Liu, Dalang Fu, Haoying Gao

Surface clogging process modeling of suspended solids during urban stormwater aquifer recharge
Zijia Wang, Xinqiang Du, Yuesuo Yang, Xueyan Ye

Adsorptive removal of iron and manganese ions from aqueous solutions with microporous chitosan/polyethylene glycol blend membrane
Neama A. Reid, Omar E. Abdel Salam, Ehab F. Abadir, Farid A. Harraz

Polyphenylene sulfide based anion exchange fiber: Synthesis, characterization and adsorption of Cr(III)
Jiajia Huang, Xin Zhang, Lingling Bai, Siguang Yuan

Atmospheric environment

Removal characteristics and kinetic analysis of an aerobic vapor-phase bioreactor for hydrophobic alpha-pinene
Yifeng Jiang, Shanshan Li, Zhuowei Cheng, Runye Zou, Juanmei Chen

Characterization of polycyclic aromatic hydrocarbon emissions from diesel engine retrofitted with selective catalytic reduction and continuously regenerating trap
Asad Naem Sham, Yunshun Ge, Jianwei Tan, Zhihua Liu, Chao He, Tao Zeng

Size distributions of aerosol and water-soluble ions in Nanjing during a crop residue burning event
Honglei Wang, Bin Zhu, Lijuan Shen, Hanqing Kang

Aerosol structure and vertical distribution in a multi-source dust region
Jie Zhang, Qiang Zhang, Congguo Tang, Yongxiang Han

Terrestrial environment

Effect of organic wastes on the plant-microbe remediation for removal of aged PAHs in soils
Jing Zhang, Xiangui Lin, Weiwei Liu, Yiming Wang, Jun Zeng, Hong Chen

Nitrogen deposition alters soil chemical properties and bacterial communities in the Inner Mongolia grassland
Ximei Zhang, Xingguo Han

Environmental biology

Augmentation of tribenuron methyl removal from polluted soil with Bacillus sp. strain BS2 and indigenous earthworms
Qiang Tang, Zhiping Zhao, Yajun Liu, Nanxi Wang, Baqiu Wang, Yingyi Zhou, Shuangjiong Liu

Microbial community changes in aquifer sediment microcosms for anaerobic anthracene biodegradation under methanogenic condition
Rui Wan, Shuying Zhang, Shuangxiao Han

Environmental health and toxicology

Molecular toxicity of earthworms induced by cadmium contaminated soil and biomarkers screening
Xiaohui Mo, Yuhui Qiao, Zhenjun Sun, Xiaofei Sun, Yang Li

Effect of cadmium on photosynthetic pigments, lipid peroxidation, antioxidants, and artemisinin in hydroponically grown Artemisia annua
Xuan Li, Manxi Zhao, Lanping Guo, Luqi Huang

Environmental catalysis and materials

Influences of pH value in deposition-precipitation synthesis process on Pt-doped TiO2 catalysts for photocatalytic oxidation of NO
Shuzhen Song, Zhongyi Sheng, Yue Liu, Haoqiang Wang, Zhongbiao Wu

Adsorption of mixed cationic-nonionic surfactant and its effect on bentonite structure
Yaxin Zhang, Yan Zhao, Yong Zhu, Huayong Wu, Hongtao Wang, Wenjing Lu

Municipal solid waste and green chemistry

Recovery of phosphorus as struvite from sewage sludge ash
Huacheng Xu, Pinjing He, Weimei Gu, Guanzhao Wang, Liming Shao
Variation of cyanobacteria with different environmental conditions in Nansi Lake, China

Chang Tian¹, Haiyan Pei¹,²*, Wenrong Hu¹,², Jun Xie³

¹. School of Environmental Science and Engineering, Shandong University, Jinan 250061, China. E-mail: yztianchang@163.com
². Shandong Provincial Engineering Center on Environmental Science and Technology, Jinan 250061, China
³. Shandong Environmental Monitoring Central Station, Jinan 250013, China

Received 15 October 2011; revised 22 December 2011; accepted 01 February 2012

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 1.53×10⁷ cells/L with an average of 1.45×10⁶ 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 cyanobacterial temperature. 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
DOI: 10.1016/S1001-0742(11)60964-9

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.

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 3.17×10⁴ km², belonging to 32 counties of Jiangsu, Shandong, Henan and Anhui Provinces. The total water area is 1266 km² 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 well studied in the last 20 years. Shuai et al. (2006) found that the Merismopedia glauca was dominant in May 2002 and Gong et al. (2010) indicated that Chroococcus and Phormidium 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 (BOD₅ 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, BOD₅, COD, TP, TN and N:P ratio (mol/mol), were adopted as the explanatory variables. All of these environmental variables were log₁₀(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. log₁₀(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 winter, 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 4.70 mg/L 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 winter, 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 4.70 mg/L TP) and there

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.

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 $1.53 \times 10^7$ 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

<table>
<thead>
<tr>
<th></th>
<th>No.</th>
<th>Mean</th>
<th>Min</th>
<th>Median</th>
<th>Max</th>
<th>StDev$^a$</th>
<th>C.V.$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>160</td>
<td>13.29</td>
<td>0</td>
<td>13</td>
<td>28</td>
<td>8.58</td>
<td>0.65</td>
</tr>
<tr>
<td>pH</td>
<td>160</td>
<td>7.57</td>
<td>7.06</td>
<td>7.56</td>
<td>8.87</td>
<td>0.24</td>
<td>0.032</td>
</tr>
<tr>
<td>Trans (cm)</td>
<td>160</td>
<td>54.75</td>
<td>25</td>
<td>55</td>
<td>120</td>
<td>11.30</td>
<td>0.21</td>
</tr>
<tr>
<td>DO (mg/L)</td>
<td>160</td>
<td>8.40</td>
<td>4.80</td>
<td>8.00</td>
<td>14.00</td>
<td>1.62</td>
<td>0.19</td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>160</td>
<td>1.06</td>
<td>0.29</td>
<td>0.86</td>
<td>4.70</td>
<td>0.68</td>
<td>0.64</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>160</td>
<td>0.09</td>
<td>0.02</td>
<td>0.08</td>
<td>0.26</td>
<td>0.04</td>
<td>0.48</td>
</tr>
<tr>
<td>N:P (mol/mol)</td>
<td>160</td>
<td>34.43</td>
<td>5.21</td>
<td>25.68</td>
<td>158.32</td>
<td>29.53</td>
<td>0.86</td>
</tr>
<tr>
<td>BOD$_5$ (mg/L)</td>
<td>160</td>
<td>2.63</td>
<td>1.04</td>
<td>2.60</td>
<td>5.80</td>
<td>0.72</td>
<td>0.27</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>160</td>
<td>5.08</td>
<td>3.77</td>
<td>5.05</td>
<td>6.41</td>
<td>0.57</td>
<td>0.11</td>
</tr>
</tbody>
</table>

$^a$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.
The average cyanobacterial abundance of waters in the lower lake (S4 and S5) was $1.52 \times 10^6$ cells/L, which was higher than waters in the upper lake (S1, S2 and S3), at an average of $1.34 \times 10^6$ 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 took place from spring to summer (or autumn), when the temperature exceeded 15°C (denoted as warm periods). The physicochemical variables explained 27.9% of variance in 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 phyicochemical 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.

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 $4.76 \times 10^5$ and $2.87 \times 10^5$ 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 $5.0 \times 10^5$ cells/L only in Jun 2008, May 2010 and June 2010, that is, the late spring and early summer of 2008 and 2010.

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 phyicochemical 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 ($\lambda$) for redundancy analysis (RDA) axis 1 ($\lambda$: 0.247) and RDA axis 2 ($\lambda$: 0.032) explained 27.9% of variance in the species data (Table 3). Variables such as temperature ($r = -0.625$), BOD$_2$ ($r = -0.303$), DO ($r = 0.282$), N:P ratio ($r = 0.265$) and TN ($r = 0.230$) related to axis 1, whereas N:P ratio ($r$ =
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

<table>
<thead>
<tr>
<th>Axes</th>
<th>All periods</th>
<th>Warm periods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Eigenvalues</td>
<td>0.247</td>
<td>0.032</td>
</tr>
<tr>
<td>Species-environment</td>
<td>0.687</td>
<td>0.503</td>
</tr>
<tr>
<td>correlations</td>
<td>Cumulative percentage of species data</td>
<td>24.7</td>
</tr>
<tr>
<td>Cumulative percentage</td>
<td>Cumulative percentage of species-environment relation</td>
<td>80.4</td>
</tr>
<tr>
<td>Sum of all eigenvalues</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Sum of all canonical</td>
<td>0.307</td>
<td>0.349</td>
</tr>
<tr>
<td>eigenvalues</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

−0.296), BOD$_3$ ($r = 0.285$) and TN ($r = -0.279$) associated significantly with axis 2 (Fig. 5a). In warm periods, the eigenvalues for RDA axis 1 ($\lambda$: 0.168) and RDA axis 2 ($\lambda$: 0.120) explained 28.8% of variance in the species data (Table 5). Variables such as N:P ratio ($r = -0.532$), BOD$_3$ ($r = 0.422$) 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$_3$ and COD. In all periods investigated, many genera cluster along the variable of temperature. *Pseudanabaena, Chroococcus, Dactylococcus, Pleurocapsa, Phormidium and Raphidiopsis* cluster along the variables of BOD$_3$ 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, Dactylococcus, 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$_3$, but negatively with DO (Table 4). *Pseudanabaena* abundance correlated positively with temperature, BOD$_3$ and transparency, but negatively with TN and N:P ratio. *Merismopedia* abundance correlated positively with temperature and BOD$_3$, 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$_3$ (Table 4). *Pseudanabaena* abundance correlated positively with BOD$_3$, but negatively with transparency and N:P ratio. *Merismopedia* abundance correlated positively with temperature. *Phormidium* abundance only correlated significantly with BOD$_3$, which was a positive correlation (Table 4). It is clear that temperature and BOD$_3$ 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...
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 quality and BOD5 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, Dactylococcopsis, 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 a "highly significant" or a "significant" correlation between phytoplankton abundance and BOD5 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, Dactylococcopsis, 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 a "significant" or a "highly significant" correlation between phytoplankton abundance and BOD5 in all periods investigated and in warm periods (Table 4). Most species of cyanobacteria were affected by the general water quality or trophic state.
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 maugeotii 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 \( \log(\text{cyanobacterial abundance} \times 10^6 \text{cells/L}) \) and \( X \) was \( \log(\text{temperature} \, ^\circ C) \). 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 qualities varied greatly for different lakes. According to our observations, phytoplankton colored the water when cyanobacterial abundance reached \( 1.0 \times 10^6 \text{cells/L} \), 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 (6.85x10^6 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 cyanobacteria 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.

Acknowledgments

This work was supported by the International Cooperation research of Shandong Province (No. 2008GJHZ20601), the International Science and Technology Cooperation Program of China (No. 2010DFA91150), and the Policy and Technology Research Center of South-to-North Diversion Project Office, State Council (No. 20080521). The authors thank the staff of Shandong Environmental Monitoring Central Station and Jining Environmental Monitoring Station for the sampling program. We thank David I. Verrelli and Findlay A. Nicol for improving the English of this manuscript.

References


