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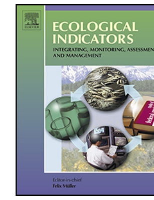

Relationship between phytoplankton and environmental factors in landscape water supplemented with reclaimed water

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ABSTRACT

The water quality of Feng-qing Lake, which is a landscape lake supplemented with reclaimed water, was surveyed to investigate the relationship between phytoplankton and environmental variables. A total of 29 water samples were collected to analyze temporal variations of phytoplankton and environmental factors from July 2013 to June 2014. Six phyla and 39 genera of phytoplankton were identified when the lake was supplied with reclaimed water. Among these, Cyanophyta and Chlorophyta account for 38.46% and 30.77% of phytoplankton, respectively. The dominant species in the lake are *Pseudanabaena limnetica* and *Chlorella vulgaris*, which are present the entire year. Other leading species include *Cosmarium* sp. and *Raphidiopsis curvata*. Principal component analysis (PCA) was conducted to analyze the relationship among environmental factors. Canonical correspondence analysis (CCA) was performed to investigate the relationship between environment factors and dominant species. The PCA result showed that temperature (*T*), total phosphorus (TP), total nitrogen (TN), transparency, and dissolved oxygen are the main factors that affect the eutrophication level of the lake. The CCA result revealed that TN, PO_4^{3-}–P, chemical oxygen demand (COD), *T*, and chlorophyll a exhibit a close relation with dominant species. In particular, TN, salinity, and COD influence the growth of *P. limnetica*; *T* and COD influence the growth of *R. curvata*; and T, PO_4^{3-}–P, NH_3–N, and pH influence the growth of *C. vulgaris* and *Cosmarium* sp.

1. Introduction

Urban rivers and lakes play important roles in landscaping and local weather modification. Xi'an, the capital of Shaanxi province, located in northwestern China, has a population of 843 million at the end of 2009. The increasing population and changing climatic conditions have made the urban district of the city very often extremely hot in recent years. Thus, the government of Xi'an has released a 571028 Plan in 2012 that will make 28 artificial lakes in the urban district to improve ecological conditions and alleviate the heat island effect in the metropolitan area of Xi'an. To realize its normal scenic environment function, landscape water requires an adequate and reliable water supply.

Water scarcity in China is becoming increasingly severe (Jiang, 2009). China is among the 13 countries in the world with the lowest water availability, and the per capita water availability of China is about a quarter of the world average (Yi et al., 2011). Moreover, a majority of the available water is concentrated in the south, leaving the northern and western China to experience perpetual droughts. Xi'an, being a semi-arid city, has an estimated total water resource availability of 24.22 hundred million cubic meters per year. Although Xi'an is facing severe water shortage, the city is also being planned to be developed into the third international metropolis of China by 2020. By then, one of the dominant social and economic problems in rapid urbanization of Xi'an will be its population, which is estimated to be more than 1280 million. When huge population and high population density is considered, its average annual water availability per capita will decline greatly. Therefore, Xi'an will not be able to meet the water demand in the near future.

Wastewater reclamation and reuse have drawn increasing attention as integral components of water resource management to address the water resource crisis (Chu et al., 2004). Reclaimed water is widely used nowadays, resulting in a trend in which landscape lakes are supplemented with reclaimed water (Wei et al., 2011), such as the main lake of SOF Park in Beijing, China. As early as 2002, faced with water shortage, Xi'an has begun conveying and utilizing reclaimed wastewater in industrial cooling systems. However, the amount of reclaimed wastewater in industry is still very limited compared with the production capacity of $17.5 \times 10^4\ m^3/d$ in the

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Table 1
Water quality standard for scenic environment reuse of urban wastewater and the quality of reclaimed water in this study.

Water quality items of reclaimed water	BOD_5 (mg/L)	pH value	Residual chlorine (mg/L)	DO (mg/L)	TP (mg/L)	TN (mg/L)	NH_3–N (mg/L)
Standard	6	6–9	0.05	2.0	0.5	15	5
Actual application	0.07–5.02	6.82–7.57	0.01–0.29	1.63–7.51	0.08–0.28	4.58–27.41	0.21–17.18

The People's Republic of China State Administration of Quality Supervision Inspection and Quarantine (2002).

centralized location of Xi'an. To expand the market of reclaimed wastewater, the potential users, ornamental lakes in public parks, were selected for replenishment with recycled water according to the Wastewater Reclamation and Reuse Plan during the Twelfth Five-Year Period (2011–2015) of Xi'an. Given that the scenic environment water are scattered across the entire city, the necessary pipeline networks for reclaimed water distribution, approximately 55 km, have been finished. Our research site, Feng-qing Lake, is one of the demonstration projects in Xi'an and is replenished with reclaimed wastewater from Qingyuan Wastewater Treatment and Reuse Ltd. Co. through a pipeline of 8 km.

However, the safety of reclaimed water has become a source of dispute since the beginning of wastewater reuse because various toxic chemicals and nutrient elements remain in wastewater even after traditional reclamation treatment processes. These chemicals cannot be completely eliminated, and they can accumulate and pose potential risk to human health and the ecological system (Asano et al., 2007; Wang et al., 2014; Rizzo et al., 2013). Furthermore, a high concentration of nutrients in reclaimed water can cause eutrophication because most urban lakes are shallow with low-velocity water flow. For example, previous researchers found that landscape water supplemented with reclaimed water faces a high risk of algal bloom during summer through simulation experiments (Li et al., 2011). Some investigators also found that the dominant alga phyla in eutrophicated lakes supplemented with reclaimed water are Cyanophyta and Chlorophyta (Li et al., 2005). Currently, knowledge on reclaimed water reuse in scenic environment is still insufficient.

New technologies in multivariate environmental studies have been reported in recent years. Environmental flow diagram (EFD) is a user-friendly software that can be used in all industrial companies and civil and energy projects for gathering detailed knowledge of pollution level of an area to solve environmental crises (Valipour et al., 2012a,b). EFD is a necessary and useful multivariate statistical technique for the evaluation and interpretation of data with a view to obtain better information about the water quality (Valipour et al., 2013). Principal component analysis (PCA), one of the multivariate methods, is often used to obtain a few independent variables that can explain most of the variance from the original variables (Jagadamma et al., 2008; Qiu et al., 2010). Another analysis technique is canonical correspondence analysis (CCA), which is a direct gradient analysis technique and always used in aquatic ecological studies (Çelekli et al., 2014).

In the present study, an urban landscape lake supplemented with reclaimed water was selected to investigate the relationship between environmental factors and phytoplankton community structure. Water quality and phytoplankton communities were continuously monitored for a year. PCA and CCA were conducted to analyze the relationships among environmental factors as well as between environmental factors and dominant species, respectively.

2. Materials and methods

2.1. Landscape water and reclaimed water

The landscape water selected for this study was Feng-qing Lake, an artificial lake with an area of 38,000 m^2 and an average water depth of 1.0 m. The lake is located in Feng-qing Park, Xi'an City, China. This lake is an ideal site for recreation and sightseeing. The volume of water in the lake is approximately 38,000 m^3, which is provided by a reclaimed water pipeline from a wastewater reclamation treatment plant in Xi'an. The quality of the reclaimed water is presented in Table 1, and the total volume of reclaimed water provided to the lake was 41,643 m^3 for one year during this study.

2.2. Sampling methods

The samples were collected using a water sampler (1000 mL) at a depth of 0.5 m around the lake. Four sites (Fig. 1) were chosen for each sampling from July 2013 to June 2014, in accordance with the Standard Methods for Observation and Analysis in Lake Eutrophication (Jin and Tu, 1990). The samples were collected five times a month in summer (July, August, and September), twice a month in spring and autumn (October, November, April, May, and June), and once a month in winter (December, January, February, and March). All samples were collected at approximately 11:00 AM to 11:30 AM.

The physicochemical characteristics of surface water, including water temperature (T), dissolved oxygen (DO), pH value, and transparency (Secchi disk clarity, SD), were measured in situ using a DO meter (HI9146, HANNA in China, Italy), a portable pH meter (PH-HJ90 MODELB, Aerospace Computer Company, China), and a Secchi disk (diameter: 20 cm). Phytoplankton samples were immediately preserved in Lugol's iodine solution and concentrated to approximately 50 mL. Then, the phytoplankton samples were kept for further taxonomic analysis and counting under a microscope (ECLIPSE 90i, Nikon, Japan) in the laboratory. Meanwhile, a water sample of approximately 2 L was kept in a cool and dark environment was and then transferred to the laboratory to measure the concentrations of nutrients and organic matter.

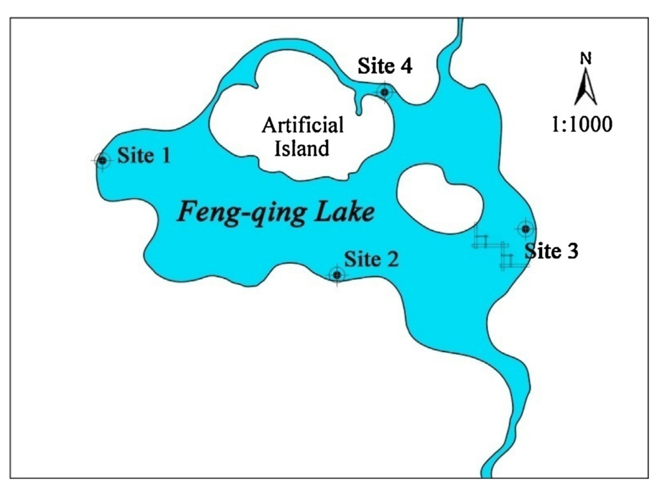

Fig. 1. Four sampling sites around Feng-qing Lake. Water sample was collected simultaneously from four sites around Feng-qing Lake and mixed together as the final sample for measurement.

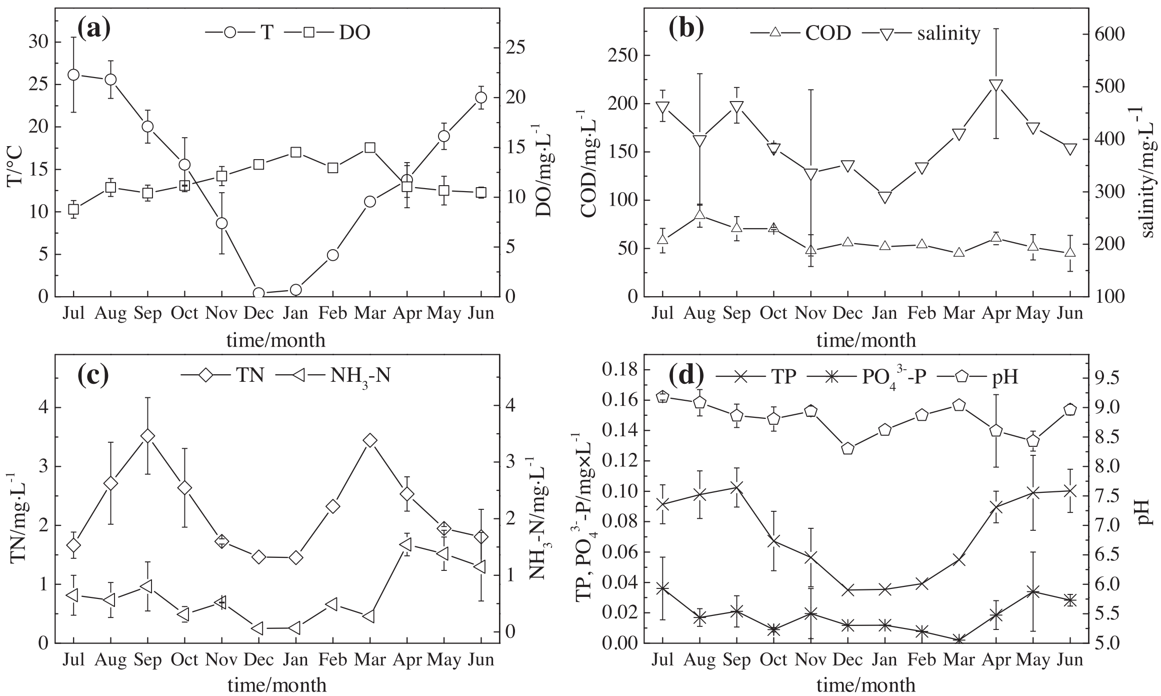

Fig. 2. Time course of physical and chemical indexes in water body of Feng-qing Lake. The concentration of nutrient substance showed a seasonal variation, and pH value, as well as DO maintained a high level in Feng-qing Lake.

2.3. Analytical methods

The samples were directly analyzed for total phosphorus (TP), total nitrogen (TN), chroma, turbidity, heterotrophic plate counts (HPC), chlorophyll a (Chla), and chemical oxygen demand (COD), whereas the filtered samples were analyzed for orthophosphate (PO_4^{3-}–P), ammonium (NH_4^+–N), and salinity. All of the analytical measurements were obtained in accordance with standard methods (EPAC, 2002).

The concentrated phytoplankton samples were directly counted in a plankton counting chamber (0.1 mL) using a Nikon ECLIPSE 90i optical digital microscope (ECLIPSE 90i, Nikon, Japan) at an eyepiece magnification of 10× and an objective magnification of 40×. The cell numbers of different phytoplankton species in 100 random fields were determined. Phytoplankton species were identified according to *Freshwater Algae in China* (Hu et al., 1980) and *Atlas of Common Freshwater Algae in China* (Weng and Xu, 2010).

2.4. Statistical analysis

The relationship between phytoplankton community and environmental factors was analyzed via CCA using Canoco for Windows 4.5. Meanwhile, the relationship among environmental factors was analyzed via PCA. Processing and graphing of data, as well as ANOVA, were performed using Origin 9.0. The Pearson correlations among environmental factors were determined using SPSS 20.0 software. Finally, *t*-test was conducted to check the significance of parameters between two factors. The levels of significance used were 0.05 (significant) and 0.01 (highly significant).

3. Results and discussion

3.1. Variations of the environmental factors

3.1.1. Physical and chemical indices

The physical and chemical indices in Feng-qing Lake over time are shown in Fig. 2. Fig. 2(a)–(d) shows the time course of T and DO concentration, COD and salinity, TN and NH_3–N concentration, and phosphorus concentration and pH value, respectively.

As shown in Fig. 2(a), *T* of Feng-qing Lake was 26.14 ± 4.42 °C in summer (July 2013), 20.04 ± 1.93 °C in autumn (September 2013), 18.90 ± 1.56 °C in spring (May 2014), and approximately 0.40 °C in winter (December 2013), with a total annual average temperature of 18.5 °C. A large variation of temperature occurred in the lake due to the extreme shallowness of the lake, which is easily influenced by atmospheric temperature. DO concentration varied from 7.80 mg/L to 14.97 mg/L, with the highest value reaching 14.97 mg/L in late March and the lowest value (7.80 mg/L) was recorded in July when the highest temperature occurred. DO concentration in winter was significantly higher than those in other seasons and frequently exceeded the saturation value, with an annual average value of 10.95 mg/L. A high DO concentration in water may be attributed to two aspects. The first reason lies in sample time, i.e., 11:00 AM to 11:30 AM, which is the time of day during which the oxygen produced by photosynthesis is higher than that consumed by respiration (Xue et al., 2014). The second reason is that the lake is extremely shallow, and thus, atmospheric restoration is the main approach to supplying oxygen in water.

The salinity of Feng-qing Lake significantly changed, with the lowest value of 292 mg/L in January and the highest value of 506 ± 106 mg/L in April. This phenomenon can be related to the change in solubility caused by *T* and phytoplankton growth. Salinity increased from January to April with the increasing temperature, and reached a peak in April (Fig. 2(b)), when quantities of phytoplankton began to develop in the lake. The monthly average COD concentration fluctuated considerably in April and August. The COD concentration was relatively stable, with an annual average value of 58 ± 12 mg/L, which is higher than the class V standard of the Surface Water Environment Quality Standards (State Environmental Protection Administration, 2002).

The concentrations of TN and NH_3–N significantly varied with the seasons. The monthly mean concentrations of TN and NH_3–N reached up to 3.52 ± 0.65 mg/L in autumn (September 2013) and 1.54 ± 0.2 mg/L in spring (April 2014). The lowest concentrations of

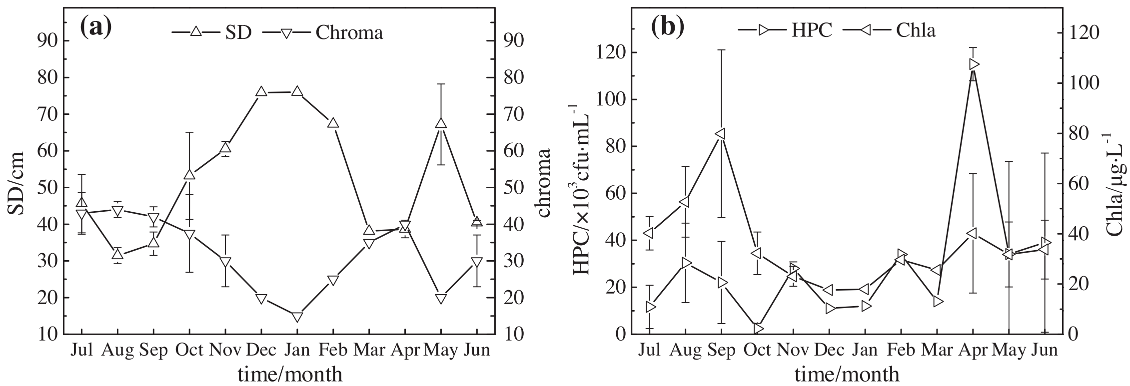

Fig. 3. Time course of sensory and biological indexes in water body of Feng-qing Lake. Biological indexes changed greatly for a whole year and the concentration of Chla reached the highest in September.

TN and NH_3–N both occurred during winter, with concentrations of 1.45 mg/L and 0.49 mg/L, respectively, as shown in Fig. 2(c), which were significantly lower than those in other seasons. These regular changes of nitrogen concentration may be caused by many reasons, but mainly by the supplement water source, which was from reclaimed wastewater with higher TN compared with fresh water. At the same time, the nitrobacterium conveyed from the upstream wastewater treatment plant may also be brought inevitably into Feng-qing Lake. In summer, the higher temperature will enhance the activity of nitrobacterium, which degrades NH_3–N in water biologically. Of course, other reasons such as biological utilization and evaporation can also influence nitrogen concentrations. In short, the above results indicate that the concentrations of TN and NH_3–N in Feng-qing Lake exhibited seasonal variation.

The concentration difference between TP and PO_4^{3-}–P was significant; however, the variation trends of both parameters were similar. The monthly mean concentrations of TP and PO_4^{3-}–P reached 0.102 ± 0.013 mg/L in autumn (September 2013) and 0.036 ± 0.021 mg/L in summer (July 2013). However, the lowest concentrations of TP and PO_4^{3-}–P were 0.035 mg/L in winter (December 2013) and 0.002 mg/L in spring (March 2014), respectively. TP concentration increased from December to September and then decreased, which may be related to the phosphorus sediment in Feng-qing Lake. Beginning in March, the aquatic organism in the lake and sediment began to grow with the increase of temperature. Then, the growth and proliferation of aquatic organism consumed much oxygen (O_2), which brought the sediment and water bottom under anoxic condition in April. At this time, large amounts of P were released quickly from the sediment to water, which led to the increase of TP in water. When TN and TP concentrations of each measurement were combined, the N:P ratio in Feng-qing Lake was always above 16, which indicated that Feng-qing Lake is P-limited, according to Redfield's (1958) quantification.

The pH value of Feng-qing Lake varied at a range of 8.30–9.18. The highest pH value was recorded in summer (July 2013), and the lowest pH value was observed in winter (December 2013), as shown in Fig. 2(d). In general, the pH value in the lake maintained a high level throughout the year, which may be attributed to two aspects. First, the base saturation in soils of north China is much higher. Second, the photosynthesis of aquatic plant absorbs CO_2 in the water, which leads to the higher pH value.

3.1.2. Sensory and biological indices

Sensory indices are frequently influenced by other factors, e.g., algae density and Chla concentration. Chroma, an important index for evaluating the eutrophication of a lake, is also influenced by phytoplankton algae and suspended solids. A high chroma indicates that the water is seriously polluted, which has a negative influence on the landscape function and esthetics of the surface water (Van Houtven et al., 2014). Some investigators have reported that the quantity of algae mostly influences the chroma of the water body (Kolada, 2014). The sensory and biological indices of Feng-qing Lake during the study period are shown in Fig. 3, in which Fig. 3(a) presents the time course of SD and chroma, and Fig. 3(b) shows the change in HPC and Chla concentration.

Transparency strongly influences the light available for phytoplankton photosynthesis, and light was directly related to phytoplankton growth. Thus, transparency is one of the factors affecting phytoplankton growth. The transparency of water in Feng-qing Lake reached up to 76.0 cm in winter (January 2014) and as low as 31.4 ± 2.2 cm in summer (August 2013), which was respectively attributed to the limited algal growth in winter and overgrowth in summer. The chroma value fluctuated at a large range, with the highest value of 44 in summer (August 2013) and the lowest value of 15 in winter (January 2014).

Biological indices changed significantly during the study period. For example, HPC varied from 790 cfu/mL in December to 120,000 cfu/mL, when the peak value was gained in April. Meanwhile, Chla concentration varied from 17.59 μg/L to 120.56 μg/L; the top value was observed in September (Fig. 3).

In summary, the water quality of Feng-qing Lake supplemented with reclaimed water presented a significant seasonal variation. The water quality of Feng-qing Lake was better in winter than in other seasons, and its condition worsened from March to September, particularly in August and September.

3.2. Variations of phytoplankton communities

3.2.1. Phytoplankton structure and variations

A total of 39 genera of phytoplankton belonging to 6 phyla and 22 families were identified in the 29 samples collected from Feng-qing Lake during the year. Among these genera, 15 belong to Cyanophyta, 12 belong to Chlorophyta, and 7 belong to Bacillariophyta, which represent approximately 38.46%, 30.77%, and 17.95% of the total genera, respectively. In addition, the samples included two genera in Euglenophyta (5.13%), two genera in Dinophyta (5.13%), and one genus in Cryptophyta (2.56%). The monthly variation of genera is shown in Fig. 4.

In terms of monthly average community composition, Cyanophyta was dominant and Chlorophyta ranked as second, which shows that Feng-qing Lake supplemented with reclaimed water is a Cyanophyta–Chlorophyta type lake (Recknagel et al., 2014). The total genera number was high in autumn, e.g., 23 genera in September, 26 in October, and 25 in November. The total genera number was low in December, with only 8 genera. The number of genera belonging to Dinophyta and Euglenophyta remained

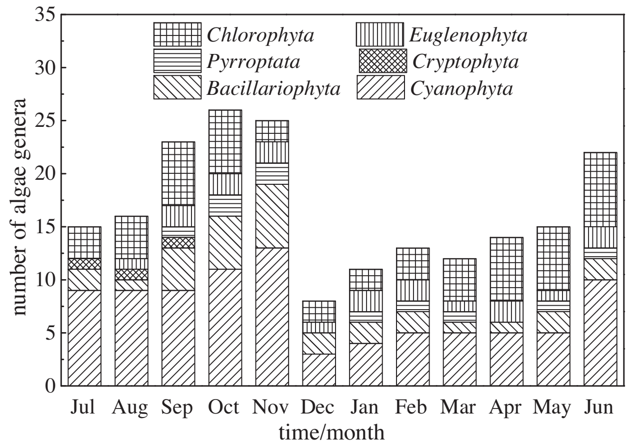

Fig. 4. Time course of algae species in water body of Feng-qing Lake. *Cyanophyta* was absolutely dominant and *Chlorophyta* ranked the second, showing that Feng-qing Lake supplemented with reclaimed water belonged to *Cyanophyta–Chlorophytatype* lake.

stable (i.e., 1–2 genera). Only one genus belonging to Cryptophyta was initially found in July, August, and September, and then it disappeared after October. However, the number of genera in Bacillariophyta increased after October, which indicates that the growth and reproduction of Cryptophyta are weak and may easily be inhibited by Bacillariophyta. Moreover, phytoplankton that belonged to Bacillariophyta existed all year, with the richest in September, October, and November (Fig. 4), which is consistent with the distribution rule of the total genera. These findings suggest that Feng-qing Lake will become a eutrophic lake with cyanobacterial blooms.

3.2.2. Dominant species and cell density

The dominant species of phytoplankton were determined based on the Berger–Parker dominance index formula, as shown in Eq. (1):

$$d = \frac{n_i}{N}, \tag{1}$$

where n_i is the number of individuals of species i within a given area in one month, and N is the total number of individuals of all species within the given area in one month (Pan et al., 2014). Then, the total number of individuals per month accounting for over 10% of the species was determined as the dominant species, and that over 40% was determined as the strong dominant species. The total number of individuals per month between 1% and 10% was slated for common species (Mai, 2003). The relative richness of dominant species and algal cell density in Feng-qing Lake supplemented with reclaimed water are shown in Fig. 5.

The most dominant specie in Feng-qing Lake was *Pseudanabaena limnetica* (Cyanophyta) for the entire year, except when *Chlorella vulgaris* exhibited a relative richness of 50.00% and 58.88% in May and June, respectively. Moreover, *Raphidiopsis curvata* (Cyanophyta) and *Cosmarium* sp. (Chlorophyta) were the secondary dominant species in July and September when the highest atmospheric temperature occurred in Xi'an, which indicates that a high temperature is suitable for the growth of a wide variety of algae, as shown in Fig. 5(a). *P. limnetica* is frequently a dominant species in freshwater lakes; it is a filamentous, non-heterocystous (Kolada, 2014), and non-toxic (Mischke, 2003) freshwater cyanobacterium (Raphaël et al., 2006), with a certain degree of halotolerance (Stal, 2008). Lu et al. (2013) found that *P. limnetica* was the dominant species in Dong-ping Lake with a low concentration of phosphorus. Meanwhile, Rojo and Alvarez Cobelas (1994) also showed that the dominant algae species was *P. limnetica* in a Spanish lake during an entire year. *C. vulgaris* is also the dominant species in several eutrophicated lakes, particularly in a landscape lake supplemented with reclaimed water. In addition, previous authors reported that *C. vulgaris* frequently became the dominant species in landscape water (Li et al., 2005; Fan et al., 2012). The present study found that *P. limnetica* and *C. vulgaris* are the most dominant species in Feng-qing Lake according to the result of monitoring for an entire year, as shown in Fig. 5(a). Simultaneously, the competition between *P. limnetica* and *C. vulgaris* was overt. According to the analysis of the parameters of water quality and dominant species, the concentrations of DO and COD were low in May and June when the dominant species was *C. vulgaris.* However, whether *P. limnetica* and *C. vulgaris* compete for DO and COD remained unanswered. Meanwhile, some results reported that *P. limnetica* rapidly grew in a collaborative environment (Bano and Siddiqui, 2004), and this species could initially outperform other microalgal species and consequently dominate in culture (von Alvensleben et al., 2013).

Algal cell density and the relative richness of dominant species are shown in Fig. 5(b). The figure shows that the highest algal cell density occurred in April. In particular, the cell density of *P. limnetica* rapidly increased from February to April (up to 2.61×10^8 cells/L), which is consistent with the results of Mounir et al. (2013) and Li et al. (2013). However, this type of algae is mostly abundant in August, September, and October. Meanwhile, the concentration of Chla also reached the highest in September, as shown in Fig. 3(b). These results appeared to contradict some common views that high algal cell density indicates a high concentration of Chla.

In fact, Chla concentration, which is a composite indicator of phytoplankton quantity, was influenced by several factors, such as the cell size of algae and the concentration of different algae. On one hand, although algal cell density was highest in April, the cell size of *P. limnetica* in April was significantly smaller than that in September (Fig. 6). On the other hand, the Chla concentration of Chlorophyta was considerably more than that of Cyanophyta when Cyanophyta was the most dominant algae (>90% of the total genera) in April, as shown in Fig. 5. However, a large number of algae belonging to Chlorophyta were observed in September, e.g., *C. vulgaris*, which can explain why the cell density of algae was the highest in April. Meanwhile, Chla concentration was lower during the same period. The results also show that Chla concentration was more suitable for evaluating the eutrophication of a lake than algal cell density.

In summary, *P. limnetica*, which belongs to Cyanophyta, and *C. vulgaris*, which belongs to Chlorophyta, were the most dominant algae species in Feng-qing Lake when the lake was supplemented with reclaimed water. The richness of these two species was high from August to October, and the highest density of the aforementioned alga cells occurred in April, which is similar to the result of Chla concentration.

3.3. Relation between dominant species and environmental factors

3.3.1. PCA on environmental factors

PCA, which is one of the multivariate analysis methods, was used to obtain several independent variables that can explain most of the variances from the original variables (Liu et al., 2014a). The method was also used to determine spatial and temporal changes in physical and chemical conditions (Becker et al., 2009). PCA was performed using Canoco for Windows 4.5.

T, DO, SD, salinity, TN, TP, Chla, chroma, turbidity, NH_3–N, $PO_4{}^{3-}$–P, HPC, COD, pH value, and algal cell density were selected as the independent variables for PCA. The PCA ordination triplot is shown in Fig. 7, and the summary statistics for PCA is shown in Table 2. In Fig. 7, the lines with arrows represent the environmental factors, and the length of the arrow indicates the weight of the environmental factors. The angles between arrows indicate the sign of

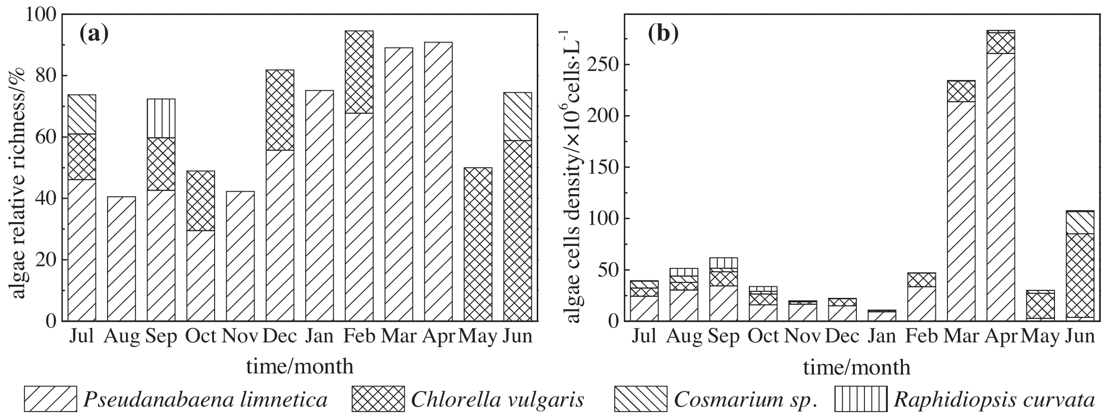

Fig. 5. Time course of species richness and cells density of dominant algae in Feng-qing Lake. The mostly strongly dominant species in Feng-qing Lake was *Pseudanabaena limnetica* (Cyanophyta) in a whole year except May and June, when *Chlorella vulgaris* had the relative richness of 50.00% and 58.88%, respectively. The highest algae cells density occurred in April.

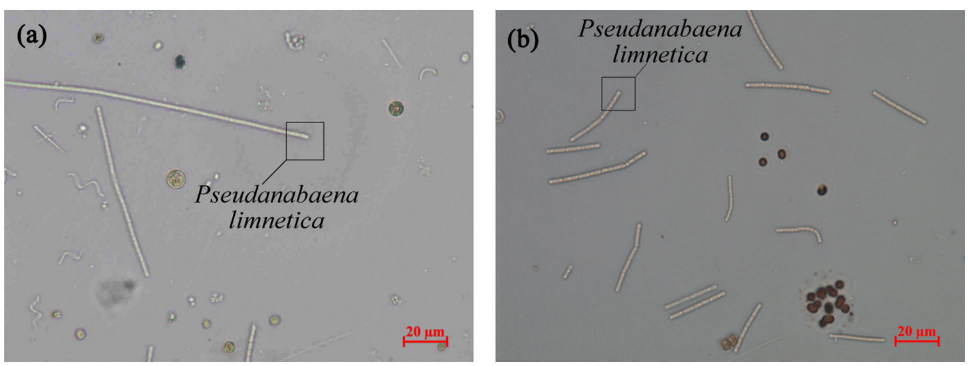

Fig. 6. Cell size of *Pseudanabaena limnetica* in water body of Feng-qing Lake. *Pseudanabaena limnetica* of Sep and Apr in Feng-qing Lake showed an obvious difference in size even for the same algae.

correlation among environmental factors. The approximated correlation was positive when the angle was sharp and negative when the angle was larger than 90°.

PCA using 15 environmental variables revealed two main axes that can explain most of the variations (Fig. 7 and Table 2). The first principal component (Axis 1) accounted for 51% of the variation and increased to 69% (Table 2) when taken together with the second principal component. The most important variables for Axis 1 ordination were T (−0.89), TP (−0.90), SD (0.91), Chla (−0.81), chroma (−0.88), and turbidity (−0.87). Regarding Axis 2, TN (−0.66), NH_3–N (0.65), PO_4^{3-}–P (0.79), and DO (0.50) were the most important variables for ordination (Fig. 7 and Table 2). The PCA results indicate that the first principal component reflected the eutrophication levels and the second principal component reflected the pollution levels (Fig. 7). In general, the lengths of the environmental factors of T, TP, TN, SD, and DO were longer than those of the others, which indicate that these five variables are the basic environmental factors in landscape water supplemented with reclaimed water.

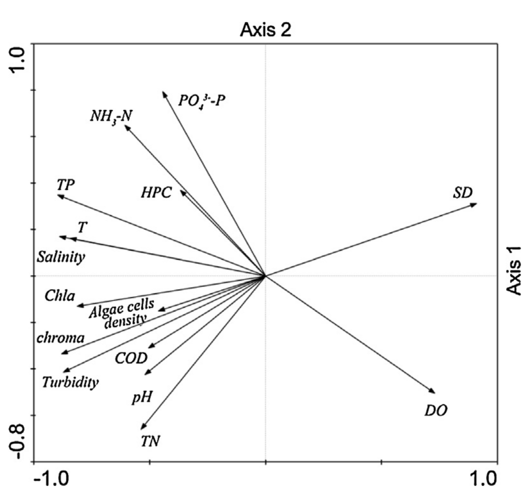

Fig. 7. Ordination diagram of PCA exhibits environmental variables (arrows) in water body of Feng-qing Lake. The first principal component reflected the eutrophication levels and the second principal component reflected the pollution levels. T, TP, TN, SD, and DO were the basic environmental factors for estimating the eutrophication degree of a landscape lake supplemented with reclaimed water.

Table 2
Summary statistics for PCA analysis on the environmental variables.

	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.51	0.18	0.15	0.07
T	−0.89	0.17	−0.31	0.19
COD	−0.51	−0.31	−0.36	−0.64
TN	−0.54	−0.66	0.29	−0.15
TP	−0.90	0.35	−0.10	−0.01
NH_3–N	−0.61	0.65	0.39	−0.02
PO_4^{3-}–P	−0.44	0.79	−0.33	0.17
pH	−0.52	−0.43	−0.30	0.60
Salinity	−0.84	0.16	0.30	−0.12
SD	0.91	0.31	−0.13	−0.17
HPC	−0.37	0.37	0.74	−0.15
Chla	−0.81	−0.13	−0.18	−0.36
Algal density	−0.46	−0.15	0.83	0.20
Chroma	−0.88	−0.34	−0.07	0.04
Turbidity	−0.87	−0.41	−0.10	0.09
DO	0.73	−0.50	0.38	0.05

Chla is the most important index for estimating the eutrophication degree of a lake. For example, the values of trophic level index were determined annually from annual mean surface water concentrations of Chla, TN, TP, and SD (Özkundakci et al., 2014; Wang et al., 2002). The PCA results of the environmental factors showed that Chla concentration was closely related to TP ($r = 0.583$, $p < 0.01$), TN ($r = 0.449$, $p < 0.05$), and COD ($r = 0.415$, $p < 0.05$) because of their small angles, and thus, Chla concentration was negatively correlated with SD ($r = -0.567$, $p < 0.01$) because of their obtuse angle (Fig. 7). This result was consistent with the correlation mentioned by Wang et al. (2002). In addition, Chla concentration was negatively correlated with DO and positively correlated with salinity, algal cell density, and pH value. However, the aforementioned correlations were insignificant ($p > 0.05$).

With regard to sensory indices, SD was negatively correlated with chroma ($r = -0.904$, $p < 0.01$), T ($r = -0.639$, $p < 0.01$), pH ($r = -0.481$, $p < 0.01$), Chla ($r = -0.567$, $p < 0.01$), COD ($r = -0.486$, $p < 0.01$), TN ($r = -0.543$, $p < 0.01$), and TP ($r = -0.592$, $p < 0.01$). In particular, the correlation between SD and turbidity was highly significant ($r = -0.904$, $p < 0.01$), which indicates that eutrophication levels could be estimated approximately by sensory indices (Fig. 7). Because the transparency is mostly governed by the amount of total suspended solids, algal and organic detritus particles derived from bloom decay together with co-occurring bacteria can cause further increase in water turbidity (Cai et al., 1997).

DO has a decisive significance in the growth and reproduction of various aquatic organisms. The PCA results show that DO was negatively correlated with T ($r = -0.744$, $p < 0.01$), TP ($r = -0.744$, $p < 0.01$), PO_4^{3-}–P ($r = -0.516$, $p < 0.01$), salinity ($r = -0.432$, $p < 0.05$), and chroma ($r = -0.487$, $p < 0.01$). Bacterioplankton also exhibited a certain relationship with algal cell density, and some researchers indicated that studies on bacterioplankton helped increase understanding on eutrophication levels, which may provide the evaluation basis for overall water governance (Silva et al., 2014). Bacterioplankton can be attached to phytoplankton, which can significantly influence bacterioplankton diversity. This finding indicates that bacterioplankton abundance can reflect phytoplankton richness to a certain extent (Eiler and Bertilsson, 2004). In the present study, HPC was positively related to algal cell density ($r = 0.613$, $p < 0.01$), which is consistent with the aforementioned literature (Fig. 7).

3.3.2. CCA on dominant species and environmental factors

CCA was performed to analyze the relationship between phytoplankton and environmental variables, as well as to further understand the driving factors that control phytoplankton community structure (Li et al., 2013). The results of the CCA were visualized in the form of ordination diagrams based on Axes 1 and 2 produced using CanoDraw for Windows program. Quantitative environmental variables were represented by lines with arrows, and species scores were represented by symbols (Lepš and Šmilauer, 2003). The directions of the arrows in the quadrant indicate the correlations between environmental factors and the axis; the lengths of the environmental variable arrows represent the relative explanatory power of phytoplankton species within the ordination (Li et al., 2013). A total of 4 dominant species and 10 environmental factors were chosen for CCA according to the frequencies and abundance of phytoplankton. The CCA ordination triplot of Feng-qing Lake is shown in Fig. 8, and the summary statistics for the first two axes of CCA is shown in Table 3.

The eigenvalues of Axes 1 and 2 were 0.454 and 0.120, respectively. Together, these axes explained 57.4% of the total variance (Table 3). Species–environment correlations for species Axes 1 and 2 were 0.999 and 0.995, respectively (Table 3). The first two species axes were approximately vertical, with a correlation of 0.004. Moreover, the correlation between the first two environmental axes

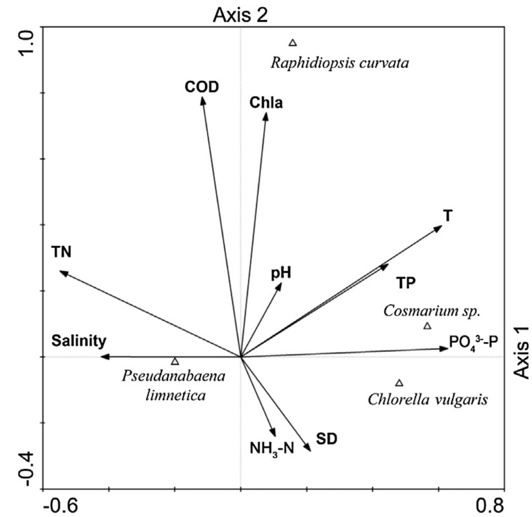

Fig. 8. Ordination diagram of CCA exhibits dominant species and environmental variables (arrows) in water body of Feng-qing Lake. T, PO_4^{3-}–P, TN and COD are the most important factors that influence dominant algae in the artificial lake supplemented with reclaimed water. *P. limnetica* and *C. vulgaris* are the most dominant species throughout the year in landscape water supplied with reclaimed water.

Table 3
Summary statistics for the first two axes of CCA on the dominant species and environmental variables.

	Axis 1	Axis 2
Eigenvalues	0.454	0.120
Species–environment correlations	0.999	0.995
Cumulative percentage variance		
of species data%	75.80	95.70
of species–environment relation%	76.10	96.10
Test of significance of first canonical axis	$F = 3.127$	$P = 0.018$
Test of significance of all canonical axes	$F = 23.420$	$P = 0.002$

was 0. These results show that the ordination result was credible because the linear combinations of the ordination axes and the environmental factors provide a good representation of the relationship between species and environmental factors (ter Braak, 1986; Jiang et al., 2014).

Axis 1 was mostly correlated to T, PO_4^{3}–P, and TN, with the correlation coefficients of 0.609, 0.628, and −0.548, respectively, whereas Chla and COD were mostly correlated to Axis 2, with the correlation coefficients of 0.736 and 0.783, respectively, (Fig. 8), which shows that these five environmental factors are closely related to the dominant species. The development of Cyanophyta populations is dependent upon the concentration of nutrients and other ecological factors such as light, temperature, composition and quantity of organic matter, and so on. There will be an outbreak of Cyanophyta bloom when eutrophic water bodies are exposed to appropriate water temperature, air temperature, flow rate, radiation, and other external conditions (Heisler et al., 2008). In our research, environmental factors such as temperature (T) and nutrient substrate were connected with the dominant species (Cyanophyta and Chlorophyta) in the ordination diagram.

P. limnetica was closer to the center of CCA ordination, which indicates that it has a wide tolerance to changes in the ecological condition of landscape water supplemented with reclaimed water. Moreover, *P. limnetica* was found to be closer to the arrows of TN and salinity, which shows that TN and salinity have a significant effect on the species. *P. limnetica* can grow well even under low temperature and low phosphorus concentration. It has low light requirement and can adapt to environmental changes even in low-transparency (SD) environments. In addition, this species is frequently the dominant species in shallow lakes (Mischke, 2003; Casé et al., 2008; Chomérat et al., 2007). *P. limnetica* has been found in a wide range of salinities (from 180 mg/L to 2350 mg/L), but it reached highest abundances (>10^8 cells/L) between 330 mg/L and 940 mg/L (median 650 mg/L) (Chomérat et al., 2007). *R. curvata* is located in the first quadrant of the bioplot (Fig. 8) that is related to T and COD and is suitable for survival in environments with high temperature, which can explain why the second dominant alga is *R. curvata* only in September. However, high COD has a negative influence on the growth of *R. curvata*. *C. vulgaris* and *Cosmarium* sp. both belong to Chlorophyta and are located in the first and fourth quadrants, respectively. The two species are very close, which indicates that their living environments are similar. T, TP, PO_4^{3-}–P, SD, NH_3–N, and pH value have significant positive correlations with *C. vulgaris*, which indicates that these environmental factors have the strongest influence on *C. vulgaris* in Feng-qing Lake. Furthermore, *C. vulgaris* can grow better in environments with high T, TP, PO_4^{3-}–P, SD, and NH_3–N concentrations and pH value, but low salinity and COD, which is consistent with the conclusion of Liu et al. (2014b). *C. vulgaris* can remove NH_3–N from wastewater. It can also be the dominant species in water with high concentrations of NH_3–N (Kim et al., 2013; Lananan et al., 2014), which can explain why *C. vulgaris* occurs alternately in Feng-qing Lake as the second dominant species, as stated in Section 2.2. *Cosmarium* sp. and *C. vulgaris* can survive in a similar environment, but *Cosmarium* sp. grows slowly in water with a high pH value. Thus, the population of *Cosmarium* sp. decreases with rising pH value.

In general, T, PO_4^{3-}–P, TN, and COD are the most important factors that influence dominant algae in the artificial lake supplemented with reclaimed water. Given that *P. limnetica* has a certain degree of halotolerance (Stal, 2008) and less demand for T and phosphorus, it can adapt to the environment of landscape water supplemented with reclaimed water and frequently survive as the strong dominant species. The other dominant species include *C. vulgaris*, *Cosmarium* sp., and *R. curvata*. *C. vulgaris*, which is influenced by T, TP, PO_4^{3-}–P, NH_3–N, and pH, frequently becomes the second dominant species. *P. limnetica* and *C. vulgaris* are the most dominant species throughout the year in landscape water supplied with reclaimed water.

4. Conclusion

The water quality of Feng-qing Lake supplemented with reclaimed water exhibited a significant seasonal variation. According to data for the entire year, the highest quality of the lake was observed during winter. The water quality of the lake gradually worsened from March to September, and the worst water quality was recorded in summer.

The eutrophication of Feng-qing Lake supplied with reclaimed water occurred rather quickly in summer and autumn. A total of 39 genera of phytoplankton, which belonged to 6 phyla and 22 families, were identified in Feng-qing Lake. Among these genera, 15 belong to Cyanophyta, which represents approximately 38.46% of the total genera, 12 belong to Chlorophyta (30.77%), and 7 belong to Bacillariophyta (17.95%) The number of genera was highest in autumn (October) and lowest in winter (December) when algal cell density was at the lowest. The dominant species were *P. limnetica* and *C. vulgaris*, which belonged to Cyanophyta and Chlorophyta, respectively. *P. limnetica* cell density was highest in April (up to 2.61×10^8 cells/L), whereas the cell density of *C. vulgaris* was highest in June (up to 8.15×10^7 cells/L). *P. limnetica* exhibited a strong competitive advantage over other species, which resulted in its dominance nearly throughout the year. *C. vulgaris* was the strong dominant species in May and June, as well as the second dominant species in other months.

PCA showed that T, TP, TN, SD, and DO were the main environmental factors that influenced water quality. CCA showed that TN, PO_4^{3-}–P, COD, and T were the environmental factors with the strongest influence on the dominant species in Feng-qing Lake. In addition, TN and salinity had considerable influence on *P. limnetica*. T and COD were the main environmental factors that influenced *R. curvata*. *Cosmarium* sp. and *C. vulgaris* were mostly influenced by T, TP, PO_4^{3-}–P, SD, NH_3–N, and pH. These findings imply that the biomass of *P. limnetica* and *Cosmarium* sp. can be used as biological quality indicators in landscape water supplemented with reclaimed water.

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