Spatial and temporal variations of two cyanobacteria in the mesotrophic Miyun reservoir, China

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ABSTRACT
Spatial variations in phytoplankton community within a large mesotrophic reservoir (Miyun reservoir, North China) were investigated in relation to variations in physico-chemical properties, nutrient concentrations, temperature and light conditions over a 5 month period in 2009. The dynamics of phytoplankton community was represented by the dominance of cyanobacteria through summer and fall, following with a short term dominance of chlorophyta in late fall, and a relatively high abundance of diatom in October; on the other hand, maximum phytoplankton biomass was recorded in the north shallow region of Miyun reservoir with a higher nutrients level. Particular attention was paid to the impacts of environmental conditions on the growth of two cyanobacteria genera, the toxin-producing Microcystis and the taste & odor-producing Oscillatoria. Microcystis biomass was in general greatly affected by water temperature and mixing depth/local water depth ratio in this reservoir, while the Oscillatoria biomass in the surface and middle layers was greatly affected by total dissolved phosphorus, and that in the bottom layer was related with the Secchi depth/local water depth ratio. Abundant Oscillatoria biomass was observed only in late September when Microcystis biomass decreased and allowed sufficient light go through.

Introduction

Construction of reservoirs has become the main way in securing drinking water source in the world (Kwak and Russell, 1994). However, deterioration of water quality characterized with the abnormal growth of algae frequently occurs once the river-type source water is replaced by the reservoir-type water (Codd, 2000; Šimek et al., 2011; Zhao et al., 2011). Cyanobacterial blooms associated with the taste & odor (T&O) problems and algal toxins (cyanotoxins) have become one of the major issues for reservoir management and attracted intensive research concerns (Graham et al., 2010; Li et al., 2012a; Zamyadi et al., 2012). Until today, most of the previous studies have mainly focused on the occurrence of harmful algae blooms (HAB) in the eutrophic reservoirs (Naselli-Flores, 2011; Paerl et al., 2011; O’Neil et al., 2012). Regional algal blooms occurring in oligotrophic and mesotrophic drinking water reservoirs, which could become a threat to drinking water supply, has often been ignored.

Miyun Reservoir, a large reservoir with an average depth of approximately 20 m, is the major surface-source of drinking water for Beijing City, and has been kept in the mesotrophic state through a set of strict environmental protection measures. However, two well-known cyanobacterial metabolites, 2-methylisoborneol (MIB) and microcystin-LR (MC-LR), have been detected in the source water taken from this reservoir in recent years, with the concentrations up to 150 ng/L (Yu et al., 2007) and 41 ng/L (Zheng et al., 2007), respectively. Two-methylisoborneol, a notorious T&O compound, is mainly produced by filamentous and coccoid cyanobacteria including Oscillatoria sp. (Izaguirre et al., 1999; Izaguirre
et al., 2007), Phormidium sp. (Izaguirre et al., 2007), Pseudanabaena sp. (Izaguirre et al., 1999) and Synechococcus sp. (Izaguirre et al., 2007) etc. Although no evidence has shown that MIB is toxic to human health, occurrence of odor can make customers to suspect the safety of drinking water. So the complaints from customers could significantly increase when a T&O episode occurs (Smith, 2002), which could not be neglected by water supply industries. The microcystin-producing genera that are of major importance in phytoplankton have been identified as Microcystis sp. (Tillett et al., 2000), Anabaena sp. (Rapala et al., 1997) and Planktothrix sp. (Christiansen et al., 2003). Among the suspected species, Oscillatoria sp. and Microcystis sp. account for the majority of T&O and microcystin events in Miyun Reservoir respectively, according to previous phytoplankton surveys (data not shown). Therefore, the occurrence and distributions of both genera in Miyun Reservoir could significantly impact the drinking water quality. As a benthic cyanobacteria, Oscillatoria sp. is commonly present on the shallow shore with a good transparency, while the bloom forming Microcystis sp. tends to occur at the surface of eutrophic water bodies (Wilhelm et al., 2011; Acuña et al., 2012). Thus, it is interesting why the two cyanobacteria with contradictory habitats grow in the deep Miyun Reservoir with a low nutrient level, and it is important to reveal the temporal and spatial variations of nutrients and phytoplankton community for establishing a strategy on controlling their growth.

In the present work, continuous survey covering different regions of Miyun Reservoir was performed over a period from June to October in 2009, shows that the temporal and spatial variations of phytoplankton community and physico-chemical properties of the reservoir including water temperature, dissolved oxygen (DO), pH, water transparency and nutrient concentrations. This work attempted to identify the impacts of environmental conditions in Miyun Reservoir on the potential MIB and MC-LR producers; the result of the study could assist decision makers in managing water quality related issues in drinking water reservoirs.

1. Materials and methods

1.1 Study site

Miyun Reservoir, located 100 km northeast of Beijing (40°30'N, 116°55'E), is the main drinking water storage for Beijing. The water level of the reservoir dropped from the highest record of 153.98 m (above sea level) in 1994 to 137 m (above sea level) in 2012, which is mainly due to continuous drought from 1999 to 2004 and overuse (Ma et al., 2010). The reservoir is characterized with a large area (total volume: 4,375 km³; surface area: 188 km²; maximum depth: 60 m) and complex bathymetry (a mountain valley reservoir). A bathymetry map was obtained from the interpolated depth data collected from an Acoustic Doppler Current Profiler instrument (ADCP, LAUREL, USA), as shown in Fig. S1. The reservoir can be divided into four parts according to the bathymetry characteristics: the west deep region and south deep region are relatively deep (maximum water depth, \( z_{\text{max}} \): 36 m; mean water depth, \( z_{\text{ave}} > 20 \) m) compared to the north shallow region (\( z_{\text{max}} \): 10 m; \( z_{\text{ave}} \): 6 m) and northeast shallow region (\( z_{\text{max}} \): 14 m; \( z_{\text{ave}} < 5 \) m). The northeast shallow region is characterized with a relatively high turbidity due to the inflow. As shown in Fig. 1, two main inflows, Bai River and Chao River, enter the reservoir via two large inlets and maintain the reservoir’s water capacity; the main outflow is a channel located in south deep region flowing to drinking water plants, while the Bai Release Channel is normally closed.

1.2 Sampling

Water survey was performed once a month during June 2 to October 26 in 2009, except in September when 3 campaigns were conducted because of the occurrence of high Oscillatoria density. According to the bathymetry, hydrological and geochemical characteristics of the reservoir, a total of 8 sampling sites (MY01–MY08) (Fig. 1). MY01, MY07 and MY08 are located in the deep region, close to Bai Dam and Chao Dam, respectively; MY02 and MY03 are close to the largest upstream – Bai River; MY05 is in the north shallow region; MY04 is in the ship channel with frequent disturbance from boats; MY06 is in the edge of north shallow region with a depth around 10 m. Eleven extra sampling sites MY09–MY19 were used

![Map of Miyun Reservoir and the sampling sites. MY01–MY08 are routine field sampling sites, while MY09–MY19 were used in September to get more information for Oscillatoria sp., where the detection of physico-chemical parameters and nutrients, as well as algal enumeration were performed. Bai River and Chao River are the two main inflow rivers, and Bai Release Channel is a manual controlled outflow for agriculture etc.; MY07 is water intake position to drinking water supply. WDR: west deep region; NSR: north shallow region; NESR: northeast shallow region; SDR: south deep region.](image_url)
during the 3 campaigns in September because the Oscil-
latoria sp. occurs mainly during this period according to
previous investigation. Each sampling position (including
extra sampling sites) was located with a GPS navigator
(Garmin, Olathe, KS, USA). Water samples were collected
from different depth at each site, the surface water samples
were collected from the water column at 0.5 m depth in the
mixed layer, the bottom samples were collected just above
the sediment for the shallow sites or 15 m depth for the
deep ones, and the middle layer samples were collected from
5 m depth for the shallow sites, and 8 m depth for the
deep regions. Samples were initially stored in colored
glass bottles and kept cool until processing, within 12 hr
after collection.

1.3 Limnological characteristics
Water temperature, DO, pH, conductivity, salinity and
Chlorophyll-a profiles were measured in situ using a multi-
parameter probe (YSI-6600, USA). Water transparency
was measured with a Secchi disk (diameter: 20 cm, black
and white).

Water samples were collected using a 5-L bottle
 sampler. Subsamples were filtered through a 0.45 μm play-
carbon filter (Millipore, USA) for the analyses of dissolved
substances including nitrate-nitrogen (NO$_3^-$-N), nitrite-
nitrogen (NO$_2^-$-N), ammonium-nitrogen (NH$_4^+$-N), soluble
reactive phosphorus (SRP), total dissolved nitrogen (TDN)
and total dissolved phosphorus (TDP). The analyses were
performed according to standard methods (Apha, 1995).

1.4 Algal identification and enumeration
Phytoplankton samples for cell enumeration were pre-
served with Lugol’s iodine at the final concentration of
5% (Sherr and Sherr, 1993) in settling chambers (100 mL),
then kept at standstill for at least 48 hr and concentrated
10 fold by removing the top water. Species identification
was carried out following previously introduced methods
(Prescott, 1951; Bellinger, 1974; Ling and Tyler, 2000).
The algal cell density was determined by the counting
chamber method using Sedgewick-Rafter cell (50 mm ×
20 mm × 1 mm) under a Olympus BX51 microscope with
phase contrast and bright field illumination. A magnifica-
tion of 400× and 200× was used to identify and enumerate
the cells, respectively. For each sample, triplicate of 1
mL each concentrated solution (from the same bottle) was
collected and counted separately (at least 400 algal cells or
10 rows of squares in counting chamber were counted).

1.5 Data analysis
The water density was estimated from the profiles of
water temperature according to the water density and
temperature curve. The mixing depth ($z_{mix}$) was defined
as the depth at which the potential density in the up-
ner layer changes by 0.03 kg/m$^3$ relative to the surface
density. Phytoplankton biomass were log transferred with
the formula $Y = \log(X+1)$ when seasonal variation of
biomass was considered. Spatial and seasonal variations of
physico-chemical parameters were tested with $t$-test. Lin-
ear regression was performed to evaluate the correlations
between phytoplankton biomass with physico-chemical
parameters. All statistic analyses were carried out with R
2.15 and corresponding packages (R Core Team, 2012).

2 Results

2.1 Physico-chemical conditions
The physico-chemical characteristics varied in different
regions of Miyun Reservoir due to its complex bathymetry
(Fig. S1). The comparison of some physico-chemical
parameters measured by YSI6600 including water temper-
ure, DO and pH was performed between MY08 (deep
region) and MY05 (shallow region). The surface water
temperature varied between 10°C (in winter) and 26°C (in
summer), whereas the temperature in shallow region was
higher than in deep region for approximately 2 weeks in
July (Fig. 2a and b). From June to August, a very thick
hoilmnion zone (10–15 m, Fig. 2b) was observed in MY08,
while a very thin hoilmnion zone (1–3 m, Fig. 2a) was
observed in MY05. The thermal stratification disappeared
in MY05 in September, but lasted till the end of October in
MY08.

Surface pH increased from 7.3 in June to near 10 in
July, which should be attributed to the high photosynthetic
activity of the Microcystis sp., and decreased slowly to less
than 8 from August (Fig. S2). During the period between
July and September, when the Microcystis biomass was
high, the DO concentration in the water column varied
between 1.0 mg/L in the bottom and 10 mg/L in the surface
water in both shallow and deep regions (Fig. S2).

The TDP concentration varied in the range of 5 and
50 μg/L in the reservoir, with the surface TDP level in
the shallow region being 10–20 μg/L and that in the deep
region being below 10 μg/L. The highest TDP concentra-
tion of 50 μg/L was detected in the bottom of the shallow
region between September and October, while the highest
concentration of 30 μg/L was detected in the deep region in
a short period in the end of August. The relatively low TDP
levels and the high mean N:P ratio of 73 ± 71 (by weight)
suggest that phosphorus should be limiting nutrient and
of vital importance in this reservoir.

No significant spatial variations of TDN and NO$_3^-$-N
were observed during the study period. TDN and NO$_3^-$-N
showed similar seasonal distribution pattern: the values of
(865 ± 140) μg/L for TDN and (317 ± 95) μg/L for NO$_3^-$-N
observed in July decreased to the minimum concentrations
of (567 ± 61) μg/L and (258 ± 85) μg/L in September,
respectively. In addition, the concentrations of TDN and
NO$_3^-$-N in the bottom water were significantly higher than
in surface water with a difference of 118 and 132 μg/L, respectively (Fig. S3). \( \text{NH}_4^+ \) in surface water decreased from (245 ± 13) μg/L in July to (202 ± 54) μg/L in September when \textit{Microcystis} was abundant and thermal stratification occurred, and increased to (306 ± 53) μg/L at the end of the study; furthermore, the mean \( \text{NH}_4^+ \) concentration in the deep region was approximately 21 μg/L higher than in the shallow region (Fig. S3).

During the study period, water transparency measured as Secchi depth (SD) varied between 1.0 and 3.0 m in shallow region (mean: 1.48 m) and between 1.5 and 4.0 m in deep region (mean: 2.29 m) (Fig. S4). Water transparency was significantly lower in the shallow region than in the deep region \((p < 0.001)\). In both shallow and deep regions water transparency followed the same seasonal trend. The highest water transparency was recorded in the end of October (mean: 1.60 m for north and northeast shallow regions and 2.43 m for west and south deep regions), the lowest in September (mean: 1.34 m for north and northeast shallow regions and 2.04 m for west and south deep regions).

2.2 Mixing depth \((Z_{\text{mix}})\) was estimated by water temperature profile.
Mixing depth varied from 1.6 to 20.8 m in south deep regions and 3 to 11.2 m in north shallow regions. Mixing depth decreased from July to August, when the thermal stratification was formed in the deep regions and \textit{Microcystis} was abundant. As the thermal stratification break down in September, the vertical mixing process in the water column was enhanced.

2.3 Phytoplankton community distribution and succession
A total of 46 phytoplankton genera belonging to 6 phylum were identified (Table 1) in the reservoir from June to October 2009. The main taxonomic groups included Chlorophyta (16), Cyanophyta (13) and Bacillariophyta (12) followed by the less diverse Pyrrophyta (2), Chrysophyta (1) and Euglenophyta (1). Phytoplankton in the reservoir was dominated by cyanobacteria in cell number from June to September, whereas Chlorophyta was dominant for a very short time in the end of September when the thermal stratification of water column started to break down, and diatoms gained the dominant position in October when the thermal stratification disappeared. The total cell number increased from 1750 cells/mL (average concentration of all sampling sites and layers) in June to the maximum concentration of 10,215 cells/mL (average concentration of all sampling sites and layers) in September and remained high concentration in October (Fig. S5).

\textit{Microcystis} sp. was the dominant species during most
| Table 1 | List of phytoplankton genera identified in water samples collected during the study period (June-October 2009) from Miyun Reservoir |
|-----------------------------------------------|
| Phytoplankton | Jun 02 | Jul 14 | Aug 04 | Sep 08 | Sep 22 | Sep 28 | Oct 26 |
| Bacillariophyta (12) |  |  |  |  |  |  |  |
| Cyclotella sp. | ++ | ++ | + | +++ |  |
| Cymbella sp. | + |  |  |  |  |  |  |
| Diatom sp. |  |  |  |  | + |  |  |
| Diplonensis sp. | ++ | ++ | + | + |  |  |  |
| Eunotia sp. |  |  |  |  | ++ |  |  |
| Fragilaria sp. | +++ | ++ | ++ | +++ | +++ |  |  |
| Frustulia sp. | + |  |  |  |  |  |  |
| Melosira sp. | +++ | +++ | +++ | ++ | +++ | ++ |  |
| Navicula sp. | ++ | + |  |  |  |  |  |
| Pinnularia sp. |  | + |  |  |  |  |  |
| Rhizosolenia sp. | ++ |  |  |  |  |  |  |
| Synedra sp. | ++ | ++ | +++ | +++ | +++ | +++ | +++ |
| Chlorophyta (16) |  |  |  |  |  |  |  |
| Ankistrodesmus sp. | ++ | +++ | ++ | +++ | ++ | + |  |
| Chlorella sp. | +++ | ++ | +++ | +++ | +++ | +++ | ++ |
| Closterium sp. | + |  |  |  |  |  |  |
| Crucigenia sp. | + |  |  |  |  |  |  |
| Golenkinia sp. | ++ |  |  |  |  |  |  |
| Micractinium sp. | ++ | + |  |  |  |  |  |
| Oocystis sp. | ++ |  |  |  |  |  |  |
| Pedostrum sp. | +++ | +++ | +++ | +++ | +++ | +++ | +++ |
| Scenedesmus sp. | +++ | ++ | +++ | +++ | +++ | +++ | +++ |
| Selenastrum sp. | ++ | + | ++ | ++ | +++ | +++ | +++ |
| Staurastrum sp. | ++ | ++ | + | + | ++ | + | + |
| Tetraedron sp. | ++ | ++ | + | ++ | ++ | + | + |
| Treubaria sp. | ++ | + | ++ | + |  |  |  |
| Trochiscia sp. | + |  |  |  |  |  |  |
| Volvox sp. |  |  |  |  |  |  | +++ |
| Chrysophyta (1) |  |  |  |  |  |  |  |
| Dinobryon sp. | +++ | +++ | ++ | + | ++ |  |  |
| Cyanophyta (13) |  |  |  |  |  |  |  |
| Anabaena sp. | +++ | ++ | +++ | +++ | +++ | +++ | +++ |
| Aphanizomenon sp. | +++ | ++ | +++ | +++ | +++ | +++ | +++ |
| Aphanocapsa sp. | ++ |  |  |  |  |  |  |
| Chroococcus sp. | ++ | ++ | ++ | ++ | ++ |  |  |
| Cylindropermum sp. | ++ | ++ | ++ | ++ | ++ |  |  |
| Jaaginema sp. | ++ |  |  |  |  |  |  |
| Limnothrix sp. |  |  |  |  |  |  |  |
| Merismopedia sp. | ++ | +++ | +++ | +++ | +++ | +++ | +++ |
| Microcystis sp. | +++ | +++ | +++ | +++ | +++ | +++ | +++ |
| Oscillatoria sp. | + | +++ | +++ | +++ | +++ | +++ | +++ |
| Phormidium sp. | + | ++ | + |  |  |  |  |
| Pseudanabaena sp. |  |  |  |  |  |  |  |
| Synechocystis sp. | +++ | ++ | +++ | ++ | ++ |  |  |
| Euglenophyta (1) |  |  |  |  |  |  |  |
| Euglena sp. |  | + |  |  |  |  |  |
| Pyrrhophyta (2) |  |  |  |  |  |  |  |
| Ceratium sp. | ++ | ++ | ++ | + | ++ |  |  |
| Peridinium sp. | ++ | ++ | ++ | ++ | ++ | ++ | ++ |

+: [1-10), ++: [10, 100), +++: [100, 1000), ++++: [1000, 10000); unit: cells/mL.
of the time in this study. Several other species were present with considerable concentrations: *Syedna* sp. was present in low numbers (< 100 cells/mL) in June and July, and started increasing in September and was quite abundant (1000–2000 cells/mL) throughout the fall and winter. Besides, *Chlorella* sp., *Pediastrum* sp., *Selenastrum* sp., *Fragilaria* sp., and *Melosira* sp., exhibited relatively high concentrations (100–1000 cells/mL) during September and October; filamentous *Oscillatoria* sp., which could produce earthy-smelly MIB, exhibited relatively high concentration (100–1000 cells/mL) in September. *Anabaena* sp., which could produce earthy-smelly odorous compound geosmin, and *Aphanizomenon* sp. were present from July to September (100–700 cells/mL). However, odor event caused by geosmin in this reservoir has never been reported perhaps due to the limited *Anabaena* density. The *Merismopedia* sp. showed high numbers in cells, but with less importance considering the fact that the cell volume is small. The other species recorded in the reservoir, many of which were observed only once, did not form substantial amounts of biomass, including *Cymbella* sp., *Diatoma* sp., *Eunotia* sp., *Frustulia* sp., *Pinnularia* sp., *Crucigenia* sp., *Echinosphaerella* sp., *Oocystis* sp., *Trochiscia* sp., *Aphanocapsa* sp. and *Pseudanabaena* sp.

The phytoplankton community was not evenly distributed in the reservoir, as shown in Fig. S6; generally, there was an increasing gradient of algal cell number from west and south deep regions to north and northeast shallow regions in the reservoir, ranging from the minimum 2500 cells/mL (average cell concentration of three layers) observed in west deep region (MY02) to the maximum 8700 cells/mL observed in north shallow region (MY10); Significant difference was shown between west and south deep regions and north shallow region ($p < 0.05$).

2.4 *Microcystis* sp. and *Oscillatoria* sp.

The two cyanobacteria genera of *Microcystis* sp. and *Oscillatoria* sp. were notorious as they can produce algal toxin microcystin and odorous compound MIB, respectively (Sabart et al., 2010; Li et al., 2012b). As shown in Fig. 3, the dominance of *Microcystis* sp. started before the first sampling in the beginning of June with a high concentration (1012 ± 582 cells/mL), increased till August with the maximum concentration (7610 ± 5460 cells/mL) being observed, and then decreased in the following months. *Oscillatoria* exhibited a different seasonal distribution pattern: it was initially observed in 5 out of 20 samples with very low concentrations (1.9 ± 3.5 cells/mL) in July, and continuously increased as the density of *Microcystis* cells declined during September with the maximum concentration (662 ± 370 cells/mL) recorded in September 22, subsequently decreased till the last campaign in the end of October.

Both *Microcystis* and *Oscillatoria* showed great spatial variations due to the large area and complex bathymetry of Miyun Reservoir, as shown in Fig. 4 (data from September). Generally, the west deep region and northeast shallow region showed much lower concentration than that in north shallow region and south deep region for both species. Besides, higher spatial variations of *Oscillatoria* biomass both in vertical and horizontal directions were observed than that of *Microcystis* biomass: relatively higher proportion of *Oscillatoria* biomass distributed in north shallow region than other regions, while considerable *Microcystis* biomass distributed in south deep region as well. On the other hand, higher proportion of *Microcystis* biomass was distributed in the surface layer for most sampling sites; however, the benthic *Oscillatoria* biomass in the bottom layer was not significant higher than in the surface and middle layer. It should be noted that the bottom layer samples did not include sediments, which could be the reason for the relatively low *Oscillatoria* biomass in the bottom samples.

2.5 Correlations between biomass and environmental factors

The *Microcystis* biomass did not show significant correlation with phosphorus concentration in surface waters ($r^2 = 0.228$, $p > 0.05$), although phosphorus is critical to algal growth in such a P-limiting reservoir; the buoyant *Microcystis* absorb nutrient in the bottom layer by adjusting its vertical position, thus its growth was not limited by the low phosphorus concentration in surface waters. However, the biomass was significantly correlated to mixing depth/local water depth ($z_{mix}/z_{max}$), as shown in Fig. 5.

*Oscillatoria* sp. was one of the successful benthic cyanobacteria in Miyun Reservoir (Table 1). Phosphorus was of the same importance for *Oscillatoria* sp. as for *Microcystis* sp. in the P-limiting reservoir; besides, light availability was also of vital importance for benthic algae. Different traits were observed for *Oscillatoria* sp. in different layers. The *Oscillatoria* biomass showed significant correlation with TDP in the surface ($r^2 = 0.640$, $p < 0.001$, $k = 0.1306$, Fig. 6a) and middle water layers ($r^2 = 0.505$, Fig. 6b).
Fig. 4 Spatial of *Microcystis* sp. (a) and *Oscillatoria* sp. (b) in Miyun Reservoir; the size of each pie chart represents the mean algal cell number of the reservoir in the sampling date, and the color represents the sampling vertical locations. Data are average value of three observations in September.

Fig. 5 Significant correlations between *Microcystis* biomass (log transferred logρm) and mixing depth/local water depth (z\text{mix}/z\text{max}) ratio. The data are from the surface sample a: in north zone during the study period, and b: in whole reservoir in September 08; the thick solid lines are the linear regressions, and the thin dashed lines are 95% confidence interval (CI) of corresponding regressions.

\[ p < 0.005, k = 0.0227, \text{Fig. 6a} \], but not in the bottom layer. However, *Oscillatoria* biomass was significantly correlated with SD/z\text{max} ratio in bottom layer (\( r^2 = 0.575, p < 0.005, \text{Fig. 6b} \)). The different characteristics in three layers suggested that the limiting resource for *Oscillatoria* sp. was phosphorus in both the surface and middle layer, while the limiting resource in the bottom layer was light availability, which was affected by the water transparency (SD) and the local depth (z\text{max}).

3 Discussion

During most of the sampling period, the reservoir was dominated with cyanobacteria. Some members of the cyanobacteria are able to make vertical movements by regulating their buoyancy within the water column through intracellular gas vacuoles (Walsby, 1969). This mechanism gives this group the advantage of relocating themselves at the optimal depth within a stable water column to obtain solar radiation in surface water in daytime and absorb sufficient nutrients in bottom layer at night (Walsby and Booker, 1980; Reynolds et al., 1987; Xiao et al., 2012).

*Microcystis* occurred throughout the Miyun Reservoir during the study period from June to the end of October in 2009. *Microcystis* dominance generally occurs at higher water column temperature (McQueen and Lean, 1987), and has been shown to succeed at temperatures in the range of 15–25°C (Robarts and Zohary, 1987). Water temperature can be regarded as a good indicator of light accumulation (Šolić and Krstulović, 1992); besides, temperature is not considered to be the primary cause for phytoplankton succession but may work in combination with other factors (Jacoby et al., 2000). The *Microcystis* biomass was significantly correlated with the water temperature in the range of 16–26°C (\( r^2 = 0.656, p < 0.001, \text{Fig. S7} \)), which was in accordance with an 11-year study of *Microcystis* in Lake Taihu (Liu et al., 2011). Although most of *Microcystis* blooms have been reported to occur at low N:P ratios (Nalewajko and Murphy, 2001; Ståhl-Delbanco et al., 2003), *Microcystis* dominance occurred in the reservoir with a very low phosphorus content (TDP, 5–50 μg/L) and high N:P ratio (73 ± 71, by weight). The absolute *Microcystis* biomass showed positive correlation with mixing depth, as shown in Fig. 5. It is well known that the thermal stratification is conducive to the dominance of buoyant population of *Microcystis* (Visser, 1996). When *Microcystis* became dominant on Sep 08, however, larger mixing depth could allow a better nutrient transportation from the bottom layer to the whole water body. At the same time, larger mixing depth will facilitate the *Microcystis* sp. to absorb nutrients in the bottom layer. So the *Microcystis*
sp. could also benefit from the increase of mixing depth.

Significant correlation was observed between the increases in pH and *Microcystis* biomass in Miyun Reservoir ($r^2 = 0.320$, $p < 0.05$; Fig. S8a). At high rates of photosynthesis in summer, *Microcystis* depletes CO$_2$, which causes an increase in pH (Jacoby et al., 2000). At the same time, *Microcystis* biomass showed significant correlation with water transparency ($r^2 = 0.574$, $p < 0.001$; Fig. S8b). The presence of *Microcystis* cells in surface water could decrease the water transparency, which may inhibit the growth of benthic algae because of the decreasing light irradiation. Thereby like pH, low water transparency (SD) is an environmental condition that is partially caused by *Microcystis* to enhance their dominance. However, the continuous consumption of nutrients (Figs. 2c, 2d, S3) in the surface water associated with decreased light availability in September was unable to sustain more *Microcystis* biomass, hence, the *Microcystis* population started to decrease as a consequence of increased water transparency, which created the condition for the growth of benthic algae.

Significant seasonal variation of *Microcystis* biomass, which was mainly determined by water temperature (or light availability accumulation) (Fig. S7), was observed with an obvious increase from June to August, and then a continuous decrease till the end of this study. On the other hand, the spatial variation of *Microcystis* biomass could be partially explained by the $z_{\text{mix}}/z_{\text{max}}$ ratio (Fig. 5). According to the investigation of recent years, the thermal stratification occurred every summer and autumn in Miyun Reservoir, which was conducive to the dominance of *Microcystis* in the reservoir (Visser, 1996). With regard to *Microcystis* biomass distribution in the reservoir, the north shallow region with a relatively high $z_{\text{mix}}/z_{\text{max}}$ ratio as well as the nutrient concentration had probably the highest risk for causing severe *Microcystis* blooms, while the other regions (west and south deep regions) were relatively safe due to high depth and low nutrient level. There is also a possibility of *Microcystis* occurrence in the south deep region due to the water flow along with *Microcystis* cells from the north shallow region.

*Oscillatoria* showed different seasonal distribution compared to *Microcystis*: maximum concentration of *Oscillatoria* biomass was observed in September, when the decreasing *Microcystis* biomass in the surface layer allowed more light going through. At the same time, the nutrient in the water column enhanced by mixing process. Moreover, significant spatial variation of *Oscillatoria* was observed (Fig. 4b). Similar with the distribution of *Microcystis*, the north shallow region was also the favorable habitat for *Oscillatoria* owing to high nutrients (Fig. 2c) as well as low water depth.

4 Conclusions

In conclusion, phytoplankton dynamics during June to October in Miyun Reservoir was characterized by shifts among Cyanophyta, Bacillariophyta and Chlorophyta. Two harmful cyanobacterial of *Microcystis* sp. and *Oscillatoria* sp. were observed in the mesotrophic reservoir with different temporal and spatial distribution patterns. *Microcystis* dominance occurred during most of the study period, with the maximum biomass observed in August; subsequently the *Oscillatoria* population increased due to the high water transparency as well as sufficient nutrient compensated by enhanced mixing process in September. *Microcystis* biomass was significantly correlated with water temperature as well as $z_{\text{mix}}/z_{\text{max}}$ ratio; on the other hand, the *Oscillatoria* biomass in the surface and middle layers was significantly related with TDP, and that in the bottom layer with SD/$z_{\text{max}}$ ratio.

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Supporting materials

Supplementary data associated with this article can be found in online version.

REFERENCES


