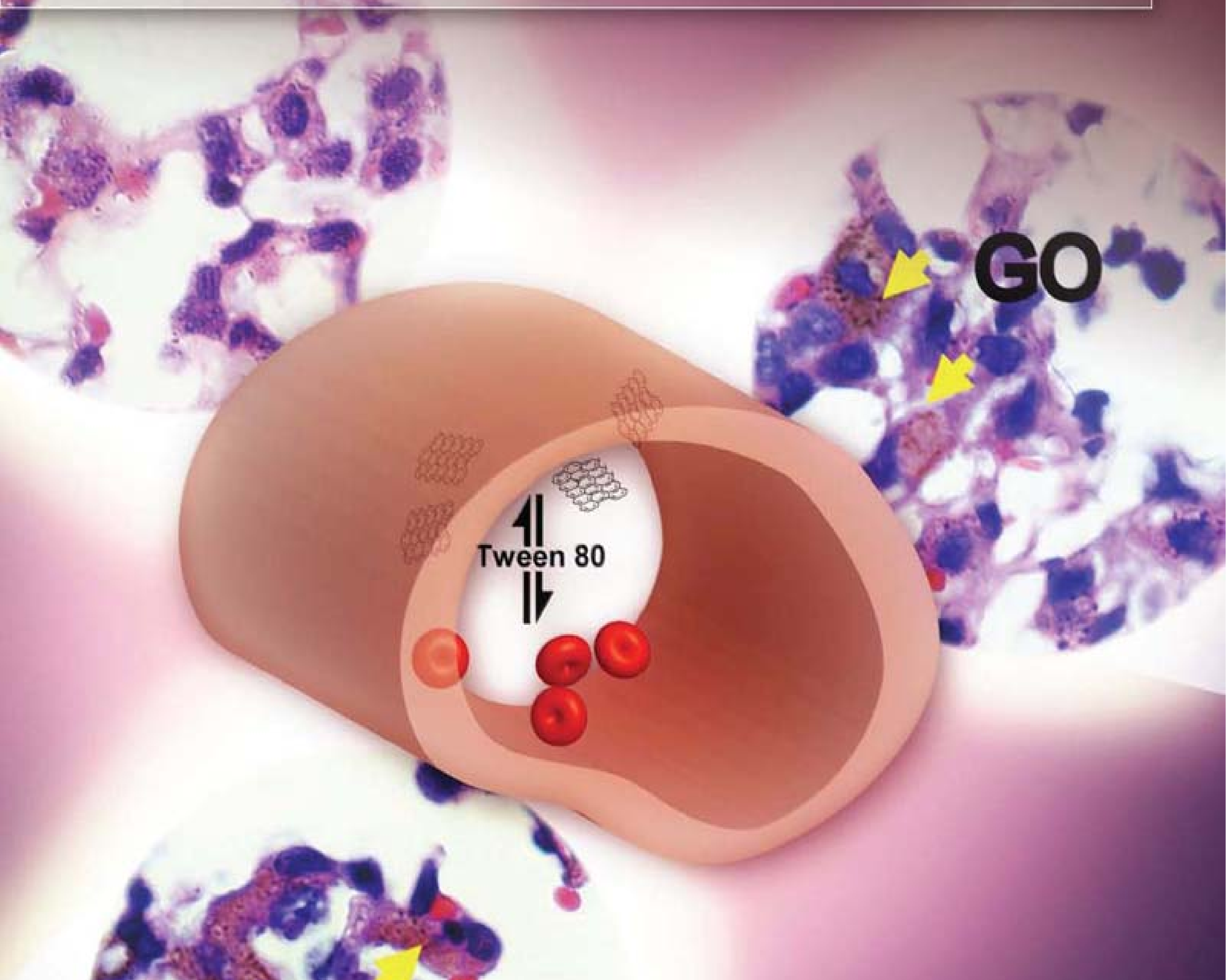
JES
JOURNAL OF ENVIRONMENTAL SCIENCES

ISSN 1001-0742
CN 11-2629/X

May 1, 2013 Volume 25 Number 5
www.jesc.ac.cn



ELSEVIER
Science Press

Sponsored by
Research Center for Eco-Environmental Sciences
Chinese Academy of Sciences

ISSN 1001–0742 **Journal of Environmental Sciences** Vol. 25 No. 5 2013

CONTENTS

Environmental biology

Environmental health and toxicology

Atmospheric environment

Aquatic environment

Environmental catalysis and materials

Serial parameter: CN 11-2629/X*1989*m*205*en*P*24*2013-5

Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 2013, 25(5) 962–970

JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Eutrophication development and its key regulating factors in a water-supply reservoir in North China

Liping Wang*, Lusan Liu, Binghui Zheng

State Environmental Protection Key Laboratory of Estuary and Coastal Environment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China

Received 13 July 2012; revised 08 November 2012; accepted 12 November 2012

Abstract

Yanghe Reservoir is an important source of drinking water for Qinhuangdao City, North China; however, in recent decades this water source has been eutrophic with recurrent summer cyanobacterial blooms. The trophic grade of the system in summer was mesotrophic-eutrophic in 1990 and became hypertrophic in 2011. The nutrient availability is extremely high during the entire year, and the water temperature should be the primary driver of the summer blooms. In May–October of 2010 and 2011, abrupt variations were observed in the Secchi depth (SD) and chlorophyll *a* (Chl-*a*), and both the correlated analysis of Chl-*a*-SD and trophic status indices (TSI) deviation ($TSI_{Chl\text{-}a}$-TSI_{SD}) showed that algal cell density dominated light attenuation. During the algal bloom outbreak, the microcystin concentration was found to vary between 0.35–2.12 μg/L in 2010 and 0.11–1.86 μg/L in 2011. The maximum microcystin content was more than two times the safety limit required for drinking water. Inflow discharges were most concentrated in the summer, with periods of lower residence time and the largest water level fluctuation over the entire year. When a high availability of nutrients promoted a high Chl-*a* concentration in the whole system, it appeared that the instability caused by the decrease in residence time could not produce effective changes in the cyanobacterial abundance. The results indicated that nutrient enrichment in the aquatic systems of Yanghe Reservoir is the most serious problem and that the status would not been modified effectively by increasing hydrological fluctuations (e.g., decreasing the residence time). Therefore, decreasing the nutrient concentrations is the only route to improve the water quality of this reservoir.

Key words: eutrophication; trophic state; cyanobacterial bloom; limiting factors; water-supply reservoir

DOI: 10.1016/S1001-0742(12)60120-X

Introduction

The anthropogenic (human-induced) eutrophication of water-supply reservoirs is one of the most prevalent environmental problems responsible for the degradation of water quality worldwide (Genkai-Kato and Carpenter, 2005; Kagalou et al., 2008; Nyenje et al., 2010). The causes of eutrophication are closely related to the nutrient (mainly phosphorus and nitrogen compounds) input from point sources (usually sewage discharge) and from diffuse sources (agriculture and other anthropogenic activities) in the drainage basin. The potential consequences of eutrophication range from nuisance to serious human health threats; in addition, water treatment and recreational activities are physically impeded by eutrophication-driven algal blooms. The eutrophication process and its outbreak mechanisms in lakes or reservoirs have been extensively studied, and the need to reduce the anthropogenic nutrient inputs to aquatic ecosystems has been widely recognized (Conley et al., 2009). Additionally, the importance of the hydrological conditions is being gradually recognized (Ferris and Lehman, 2007) since nutrients are not the only driver of algal growth (Burford et al., 2007). In spite of many advances, eutrophication is often a combined-effect problem, and the mechanisms might be entirely different for different water systems. For a reservoir and its watershed, the elucidation of the algal bloom characteristics and the key factors regulating the trophic states have important theoretical and practical significance in the development of a management strategy (Wetzel, 2001; Poor, 2010).

Cyanobacteria are ancient microalgae that inhabit quite diverse environments, and have long been recognized as a water-quality problem in lakes and reservoirs due to their potential toxicity and their capacity to cause off-flavor in drinking water (Hitzfeld et al., 2000). Consequently, water utility management is concerned about controlling the input of cyanobacteria into treatment plants. Cyanobacteria

---

* Corresponding author. E-mail: wanglp@craes.org.cn

present a range of characteristics that provide them with a clear competitive growth advantage over planktonic algae under certain environmental conditions; furthermore, these cells are not a preferred food for zooplankton and are not grazed by this aquatic community (Chorus and Bartram, 1994). Due to the scarcity of water resources and concerns for public health, the frequent monitoring of water sources is fundamental to follow the spatial and temporal changes in the water quality; and is useful for the development of protection and preservation measures.

Yanghe Reservoir is located in North China (119°3′–119°18′E and 39°56′–40°18′N). In recent decades the water body has been undergoing intense eutrophication, resulting in the loss of water quality and increases in the occurrence of cyanobacterial blooms (Li and Tang, 2001; Li et al., 2007; Yang et al., 2009). The purpose of this study is to analyze the eutrophication evolution of Yanghe Reservoir and thereby elucidate the mechanisms that regulate cyanobacterial growth. Through this study, a deeper knowledge of the necessary management strategies can be achieved.

1 Materials and methods

1.1 Sampling and data measurements

Yanghe Reservoir is an important source of drinking water for Qinhuangdao City, China, it has a capacity of 3.53×10^8 m^3, with a watershed of 755 km^2 and an average depth of 5.7 m. The West River and East River are the main inflow discharges into Yanghe Reservoir (**Fig. 1**). The climate in this area is a typical warm temperate continental monsoon climate, with four distinct seasons and an ice-cover period of 2–3 months every year (from Dec to Feb). The water temperature is 10–29°C during May–Oct, which is suitable for algal growth. To clarify the mechanisms of algal bloom development and extinction, an intensive 6-month (May–Oct) investigation was performed concerning the water quality and chlorophyll a (Chl-*a*) level during two consecutive years (2010–2011). **Figure 1** shows the four sampling stations: Y1 (near the dam), Y2 (in the center of the reservoir), Y3 (the West River estuary) and Y4 (the East River estuary).

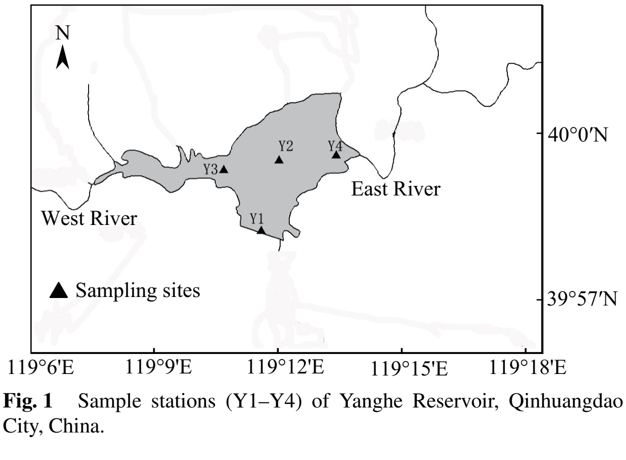


Fig. 1 Sample stations (Y1–Y4) of Yanghe Reservoir, Qinhuangdao City, China.

Semimonthly during May–Oct in 2010 and 2011, we monitored the water temperature, pH, dissolved oxygen (DO), Secchi depth (SD), total phosphorus (TP), phosphate phosphorus (PO_3-P), total nitrogen (TN), nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_4-N), chemical oxygen demand (COD_{Mn}), total organic carbon (TOC) and Chl-*a*. The temperature, pH and DO of the surface water (< 0.5 m depth) were measured using a Multi-parameter Water Quality Meter (YSI, USA), and SD was measured using a 20-cm Secchi disk *in situ*. Replicate subsamples from the surface water (600 mL) were collected in sulfuric acid-washed (pH < 2) plastic sample bottles and transported to the laboratory for the TP, PO_3-P, TN, NO_3-N, NH_4-N, COD_{Mn} and TOC analyses using standard methods (Huang et al., 1999; SEPB, 2002). Additional replicate subsamples for the Chl-*a* analysis were collected by filtering known volumes of water into GF/F glass fiber filters; the filters were stored on ice until being frozen in the laboratory. The Chl-*a* concentration was measured using a spectrophotometric method (SEPB, 2002).

During algal bloom outbreaks, the samples for the phytoplankton analysis were collected by sweeping with a plankton net (net frame 25 cm ø, mesh net e.g., 22 μm); all of the samples were preserved immediately in a 4% solution of formaldehyde. The taxonomic identifications were performed according to the main morphological and morphometric characteristics of the vegetative and reproductive phases using a microscope (Zeiss Axioskop 2 Mot Plus, Germany). The phytoplankton samples for quantitative analysis were collected using plastic bottles (1 L) and were immediately preserved in a 4% solution of formaldehyde. The phytoplankton population densities (cells/mL) were estimated using the sedimentation technique (Utermöhl, 1958) under an inverted microscope (400 × magnification). The samples were dominated mainly by several species of microcystis. The cell number of the microcystis species, consisting of colonial aggregations of individual cells, was estimated by assessing the individual colony volume and dividing by the average single-cell volume for the different species (Hötzel and Croome, 1999).

Replicate subsamples were collected for microcystin (MC) determination. The samples were protected in coolers with ice packs and immediately transported to the laboratory. The MCs were extracted from the cells by ultrasonicating the samples to release the intracellular toxins. The total MC concentrations (extracellular and intracellular) were measured using a polyclonal enzyme-linked immunosorbent assay (ELISA; An and Carmichael, 1994; Metcalf et al., 2000) with a commercial ELISA kit (Beacon Analytical Systems Inc., USA). The assays of standards or samples were performed following the kit instructions. For each assay, the negative control, calibrators and samples were tested at least in duplicate. Standard calibration curves were drawn using commercial microcystin-LR.

The average volume of the reservoir, inflow discharge, water level and rainfall during the investigation period were kindly provided by the local hydrological station.

1.2 Data analysis

The trophic state indices (TSIs) of the reservoir were calculated using the methods described by Carlson (1977) and Kratzer and Brezonik (1981). The equations are as follows:

$$\mathrm{TSI}_{\mathrm{TN}} = 54.45 + 14.43\ln(\mathrm{TN}) \tag{1}$$

$$\mathrm{TSI}_{\mathrm{TP}} = 14.42\ln(\mathrm{TP}) + 4.15 \tag{2}$$

$$\mathrm{TSI}_{\mathrm{SD}} = 60 - 14.42\ln(\mathrm{SD}) \tag{3}$$

$$\mathrm{TSI}_{\mathrm{Chl}\text{-}a} = 9.81\ln(\mathrm{Chl}\text{-}a) + 30.6 \tag{4}$$

The water with TSIs less than 40 are grouped into an oligotrophic state, and TSIs ranging from 40 to 50 are distinguished into a mesotrophic state. If the TSI values range from 50 to 70, the waters belong to a eutrophic state, whereas for TSI values higher than 70, the waters belong to a hypertrophic state (Kratzer and Brezonik, 1981).

The estimated residence time is generally calculated by relating the annual amount of water passing through the reservoir to the volume of the entire basin. In this study, the residence time for each month during May–Oct was calculated as follows (modified from George and Hurley, 2003):

$$\tau = \frac{V_{\mathrm{T}}}{Q_{\mathrm{T}}} \tag{5}$$

where, τ (day) is the water residence time for each period, V_{T} (m^3) is the average volume of the reservoir and Q_{T} (m^3) is the average inflow discharge for each period. A nonparametric correlation analysis was performed using SPSS 20.0 software.

2 Results

2.1 Assessment of trophic status from 1990 to 2011

August was the most concentrated period of algal blooms, thus we collected the monitoring data in August of several years since 1990 (Li, 2001; Li and Tang, 2001; Cui and Li, 2005; Cai et al., 2007; Li et al., 2007; Yang et al., 2009; Zhang et al., 2009). Episodic data can provide some information on the long-term eutrophication dynamics in this reservoir. The results showed that TN, TP and Chl-*a* increased significantly since 1990 (**Fig. 2**), with their mean concentrations increasing from 0.72 mg/L, 0.029 mg/L and 3.35 μg/L in 1990 to 4.25 mg/L, 0.103 mg/L and 88.5 μg/L

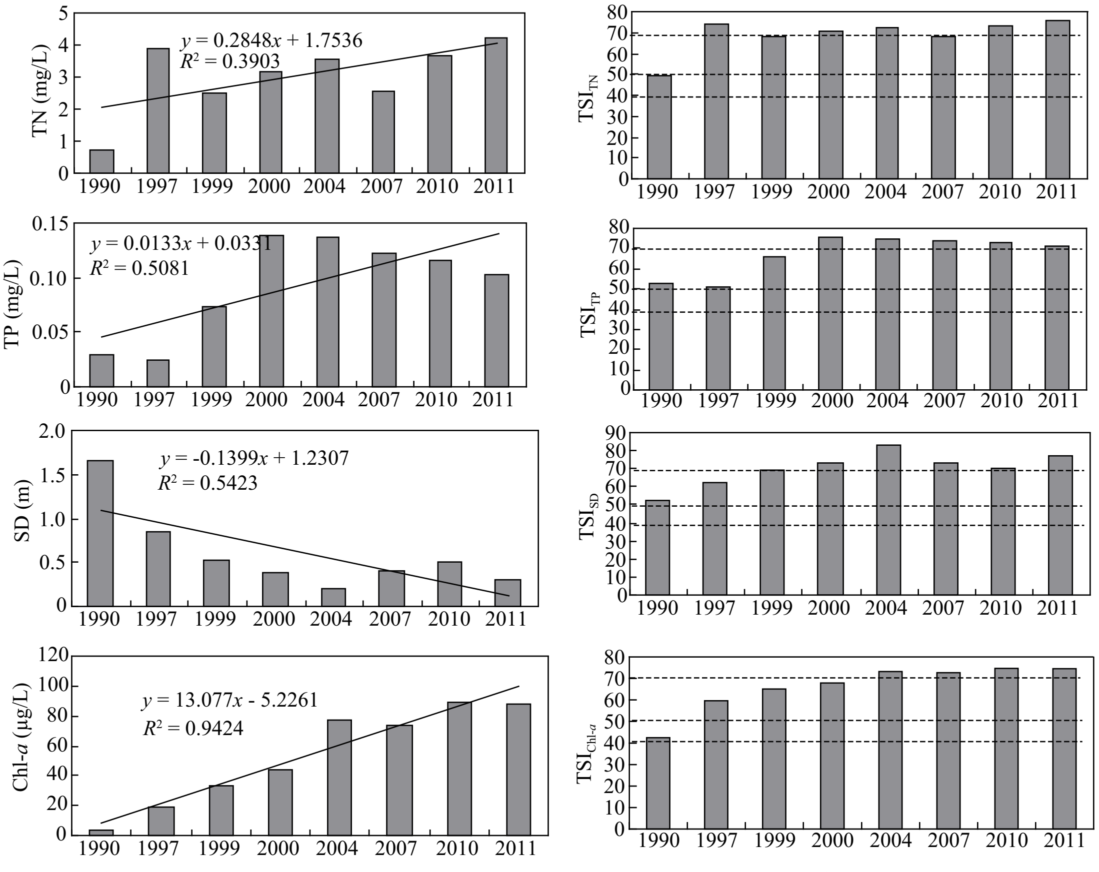


Fig. 2 Mean values of TN, TP, secchi depth (SD), Chl-*a* and $\mathrm{TSI}_{\mathrm{TN}}$, $\mathrm{TSI}_{\mathrm{TP}}$, $\mathrm{TSI}_{\mathrm{SD}}$, $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ in August of each year during 1990–2011. The dashed lines indicate the threshold value of the mesotrophic (40), eutrophic (50) and hypertrophic (70) states, repectively. TSI: trophic state index.

in 2011, respectively. The SD decreased significantly (**Fig. 2**): it was 1.65 m in 1990, and it decreased to 0.3 m in 2011. The TSI values based on TN (TSI_{TN}), TP (TSI_{TP}), SD (TSI_{SD}) and Chl-*a* ($TSI_{Chl\text{-}a}$) also increased rapidly, from 49.71, 52.71, 52.78 and 42.46 in 1990 to 75.33, 70.98, 77.36 and 74.58 in 2011, respectively. According to the Carlson-type TSI, the trophic states of the system were mesotrophic (TSI_{TN}, $TSI_{Chl\text{-}a}$) or eutrophic (TSI_{TN}, TSI_{TP}) in 1990 and became hypertrophic in 2011. For TN, TP, SD, a good relationship was observed only between SD and Chl-*a*, as shown in **Fig. 3** ($R^2 = 0.9186$), indicating that the concentration of algal cells has been responsible for the observed SD.

2.2 Developing status of water quality from May to Oct.

Figure 4 presents the developing trend of 12 water quality parameters during May–Oct in 2010 and 2011, and **Table 1** shows the mean values and their range of water quality parameters. There were no significant differences in the developing status of the 12 parameters between 2010 and 2011: algal blooms were observed in the summer of both years. This period is marked in **Fig. 4** using two dashed lines. Significant seasonal variations were observed in temperature, DO, SD and Chl-*a*. The temperature and Chl-*a* concentrations were higher in summer, whereas the DO and SD had lower values in the same period. The concentrations of TN, NO_3-N and NH_4-N increased notably from May to Oct.

The relationship between the water quality factors and Chl-*a* in 2010 and 2011 are provided in **Table 2**, with temperature, SD, DO, pH, TP, PO_3-P and COD_{Mn} showing clear correlations with Chl-*a* for both 2010 and 2011. The SD, DO and pH results were induced by water eutrophication but were not the driving factors; therefore, the SD, DO and pH parameters were the major symptoms of water quality deterioration induced by the algal bloom outbreak. Because Yanghe Reservoir is situated in the northern temperate zone and most cyanobacteria are favored by higher temperatures, temperature should be a driving factor of summer blooms. COD_{Mn} might also be an important factor. The relationship between temperature and Chl-*a* is shown in **Fig. 5**.

The calculated residence time showed a remarkable variation during the study period, with the mean values in May, June, July, August, September and October being 120, 27, 12, 18, 63 and 37 days respectively. According to the classification of Straškraba and Tundisi (1999), a reservoir with $\tau \le 20$ days can be distinguished into class A, i.e., a fully mixed system, and a reservoir with $20 < \tau < 300$ days should be grouped into class B, i.e., an intermediate stratified system. If $\tau \ge 300$ days, the reservoir will be characterized by well-developed stratification and belongs to class C. According to these criteria, class A was the most common in summer, whereas class B was often observed in the other seasons.

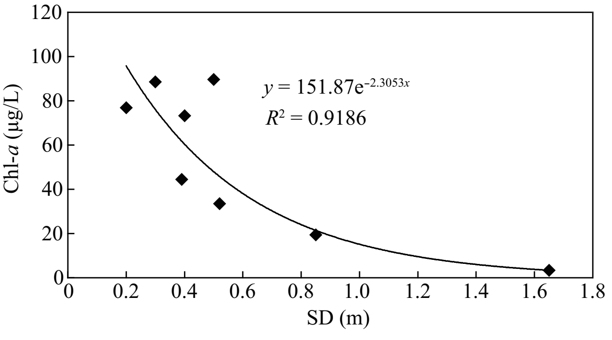


Fig. 3 Power regression between SD and Chl-*a* during 1990–2011.

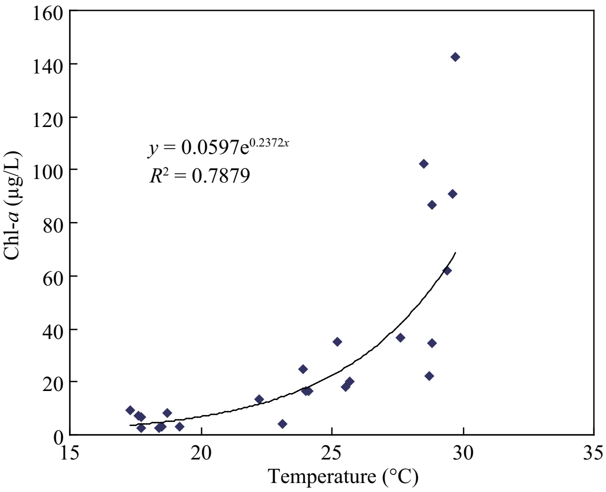


Fig. 5 Power regression between temperature and Chl-*a* concentration.

2.3 Algal bloom outbreak

Cyanobacterial blooms occurred from Jul 16 to Sep 13 in 2010 and from Jul 13 to Sep 2 in 2011. The two bloom events covered the entire water area of Yanghe Reservoir with a dark green color and a strong abnormal odor. The Chl-*a* concentration in the surface water varied from 34.36 to 142.53 μg/L in 2010 and 31.98 to 136.97 μg/L in 2011, exceeding the threshold of algal bloom occurrence (Chl-*a* > 30 μg/L; Jin et al., 1995; Chen and Mynett, 2004). **Figure 6** displays the water level and its fluctuation, and the temperature and rainfall from May to Oct in 2010 and 2011. There was a similar developing trend between 2010 and 2011. As shown in **Fig. 6**, a larger daily range of water level occurred in the summer, and the rainfall was mainly concentrated in the latter parts of July and August. No heavy rainfall was observed, with a smaller water level variation prior to the occurrence of the algal bloom. In contrast, several heavy rainfalls with a larger water level variation during the algal bloom occurred, but the Chl-*a* concentration remained high, i.e., the algal bloom did not disappear.

The cyanobacterial population consisted mainly of several *Microcystis* species. In 2010, the predominant species included *M. aeruginosa*, *M. incerta* and *M. pallida (Farlow) lemm*, with cell densities varying between

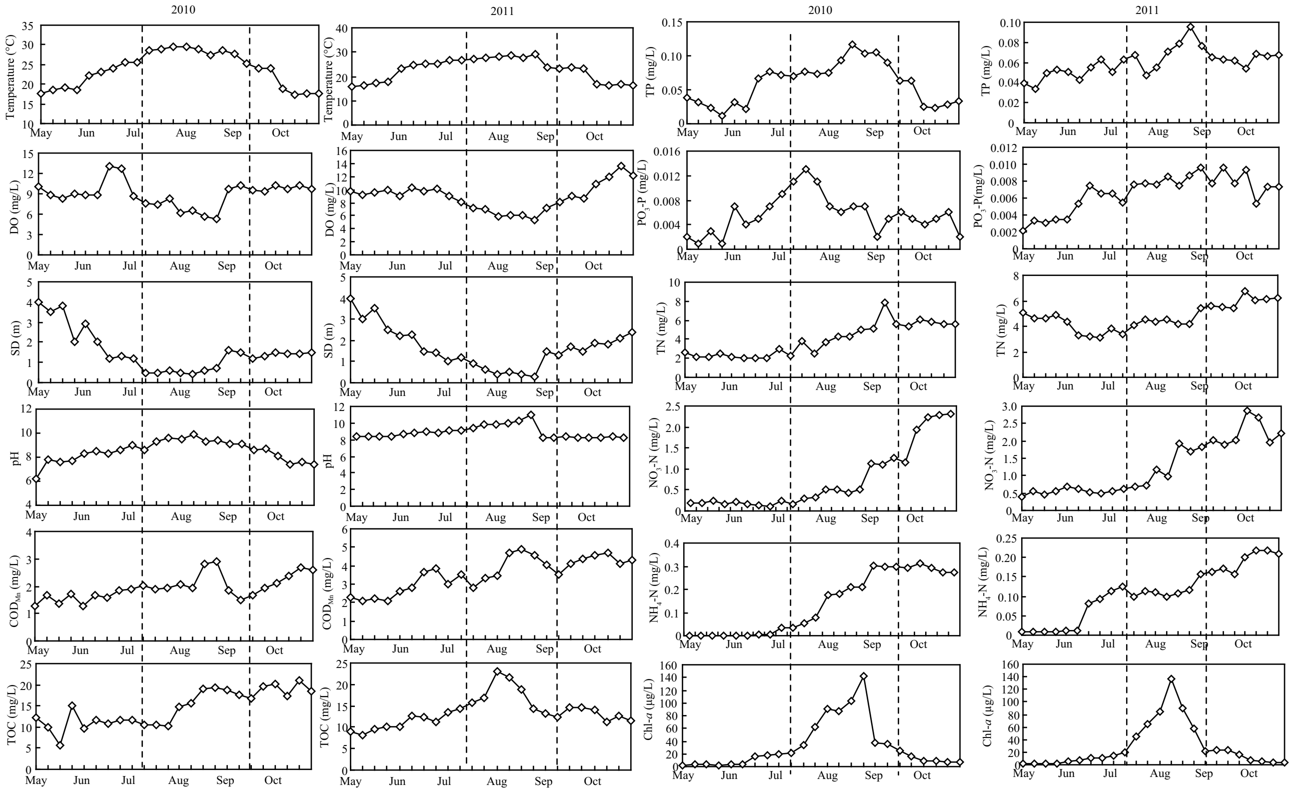


Fig. 4 Developing trends of temperature, DO, SD, pH, COD_{Mn}, TOC, nutrient and Chl-*a* concentrations from May to October in 2010 and 2011. All of the data were the mean values of each station, and the period between the two dashed lines indicates the period of algal bloom outbreak.

Table 1 Mean values and ranges of environmental and biotic variables during May–Oct of 2010 and 2011

	May–Oct 2010		May–Oct 2011	
	Mean ± S.D.	Range	Mean ± S.D.	Range
SD (m)	1.56 ± 1.08	0.20–4.20	1.66 ± 0.98	0.30–4.00
DO (mg/L)	8.87 ± 1.85	5.38–13.07	8.91 ± 2.09	5.38–13.58
pH	8.62 ± 0.54	7.12–9.56	8.87 ± 0.78	8.17–10.92
COD_{Mn}(mg/L)	1.97 ± 0.46	1.23–2.92	3.23 ± 0.86	2.06–4.68
TOC (mg/L)	15.46 ± 4.82	5.71–27.79	13.57 ± 3.66	8.26–23.16
TP (mg/L)	0.062 ± 0.030	0.011–0.115	0.060 ± 0.014	0.0336–0.095
TN (mg/L)	3.880 ± 1.872	1.670–7.625	4.713 ± 1.014	3.078–6.752
NO_3-N (mg/L)	0.890 ± 0.853	0.1003–2.5260	1.252 ± 0.788	0.393–2.856
NH_4-N (mg/L)	0.151 ± 0.131	0.0002–0.3312	0.109 ± 0.070	0.0077–0.2191
PO_3-P (mg/L)	0.0056± 0.0037	0.001–0.019	0.0066 ± 0.0022	0.0022–0.0096
Chl-*a* (μg/L)	31.74± 39.61	2.39–162.26	27.31 ± 34.99	1.46–136.97

Table 2 Relationship between water quality factors in 2010 (lower triangle) and 2011 (upper triangle)

	Chl-*a*	Temperature	SD	DO	pH	TN	NO_3-N	NH_4-N	TP	PO_3-P	COD_{Mn}	TOC
Chl-*a*	**1.000**	0.682**	–0.724**	–0.761**	0.795**	–0.197	0.019	0.059	0.426*	0.452*	0.407*	0.884**
Temperature	0.715**	**1.000**	–0.846**	–0.790**	0.766**	–0.643**	–0.229	–0.038	0.402*	0.469*	0.251	0.695**
SD	–0.592**	–0.696**	**1.000**	0.645**	–0.724**	0.266	-0.203	-0.393*	-0.616**	–0.713**	-0.582**	–0.799**
DO	–0.704**	–0.468*	0.291	**1.000**	–0.744**	0.415*	0.193	0.220	–0.339	–0.299	–0.091*	–0.640**
pH	0.711**	0.907**	–0.737**	–0.476**	**1.000**	–0.500**	–0.179	–0.114	0.445*	0.280	0.259	0.669**
TN	0.188	–0.068	–0.319	–0.012	0.111	**1.000**	0.783**	0.601**	0.114	0.223	0.321	–0.124
NO_3-N	–0.170	–0.443*	–0.146	0.215	–0.268	0.798**	**1.000**	0.838**	0.524**	0.584**	0.763**	0.165
NH_4-N	0.253	–0.008	–0.392*	–0.056	0.164	0.942**	0.828**	**1.000**	0.549**	0.719**	0.792**	0.281
TP	0.766**	0.850**	–0.610**	–0.356*	0.766**	0.208	–0.234	0.246	**1.000**	0.632**	0.753**	0.381*
PO_3-P	0.368*	0.687**	–0.646**	–0.315	0.594**	–0.106	–0.238	–0.118	0.447*	**1.000**	0.772**	0.614**
COD_{Mn}	0.535**	0.121	–0.578**	–0.386*	0.204	0.439*	0.495**	0.538**	0.283	0.181	**1.000**	–0.041
TOC	0.290	–0.076	–0.392*	–0.058	0.080	0.824**	0.729**	0.879**	0.212	–0.220	0.664**	**1.000**

**$p < 0.01$; *$p < 0.05$.

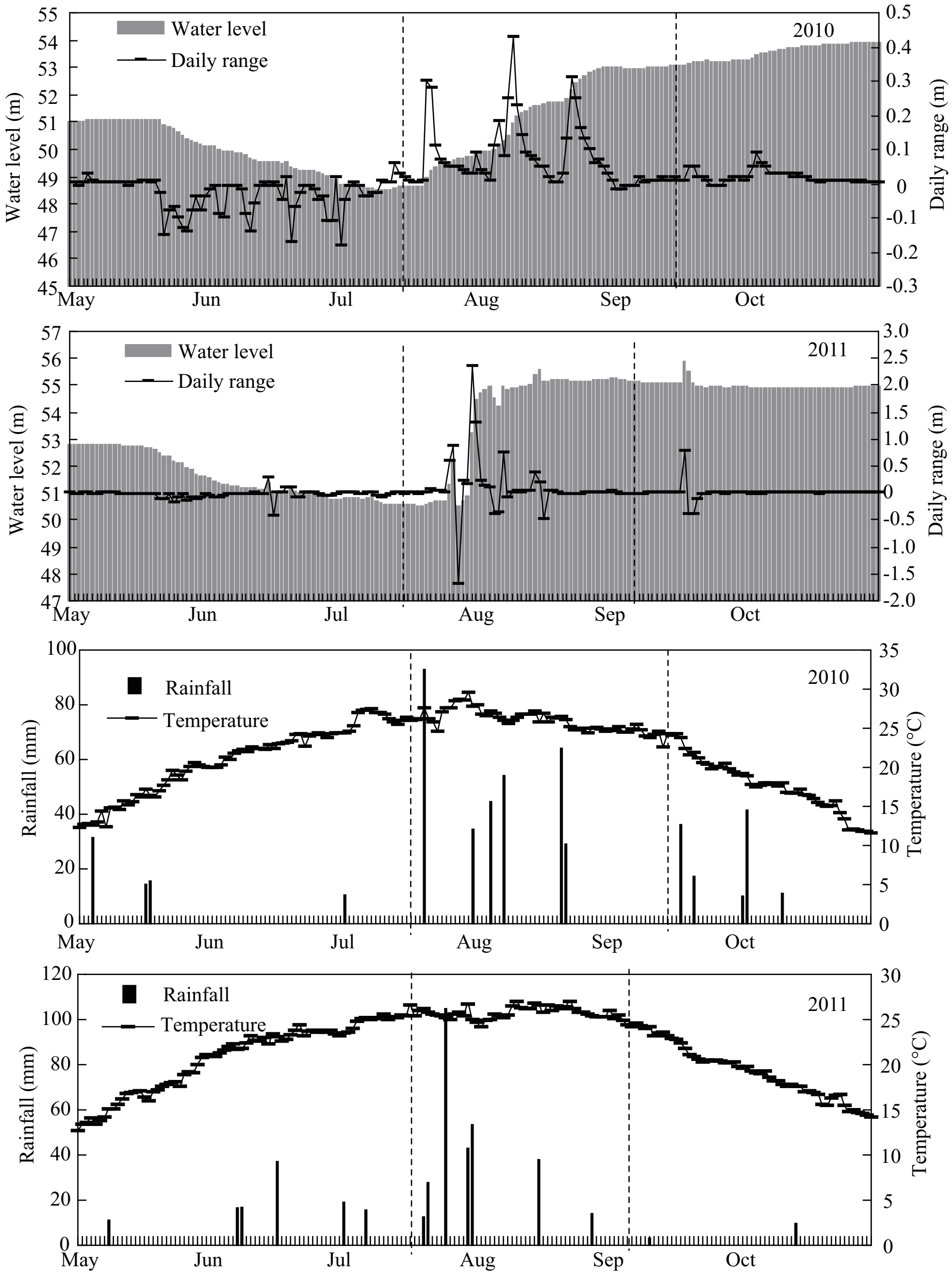


Fig. 6 Developing trend of the water level and its daily range, water temperature, and rainfall during May–Oct in 2010 and 2011. The period between the two dashed lines indicates the period of algal bloom outbreak.

1.92×10^5–41×10^5 cells/mL, 0.08×10^5–8×10^5 cells/mL and 0.13×10^5–0.92×10^5 cells/mL, respectively. In 2011, *M. aeruginosa*, *M. ichthyoblabe* and *M. wesenbergii* were dominant, and the cell densities varied between 1.80×10^5–35×10^5 cells/mL, 0.16×10^5–14×10^5 cells/mL and 0.21×10^5–1.05×10^5 cells/mL, respectively. During the bloom outbreak, the MC concentration varied between 0.35–2.12 μg/L in 2010 and 0.11–1.86 μg/L in 2011. The detection limit of the ELISA kit applied in the present study is 0.05 μg/L, and the amount of MCs in the control was not detectable.

3 Discussion

3.1 Nutrient situation and its effect on eutrophication

In recent decades, the nutrient concentrations in Yanghe Reservoir have been higher than the critical values for eutrophication (TN > 0.2 mg/L and TP > 0.02 mg/L in the reservoir, Jin et al., 1995) due to the increasing anthropogenic inputs of nitrogen and phosphorus to the system. Because of the effect of historical conditions in the Yanghe basin, in the autumn, the local farmers produced starch using simple equipment upstream of its tributary.

Amylaceous wastewater with high nitrogen and phosphorus concentrations converged in the reservoir (Liu, 2005; Li et al., 2007), indicating that the agricultural activities upstream were responsible for the exogenous pollution of nutrients. The data showed that sediment accumulation is approximately 3.5×10^7 m^3, with a mean thickness of 0.96 m, accounting for approximately 10% of the volume of the system and becoming a large place for nutrient storage. Nitrogen and phosphorous are deposited in the sediment in the winter and could be released by various means with increasing temperature, thus generating endogenous pollution (Liu, 2005). Liu (2005) studied the release variations of nitrogen and phosphorous under different conditions, and the results showed that internal pollution is an important factor limiting the trophic grade of Yanghe Reservoir. **Figure 4** suggests that the concentration of nutrients increased sharply in the autumn and decreased early in the following year, thus being recycled year after year. Our results confirmed that the exogenous and endogenous pollution were responsible for the high level of nutrients, indicating that the upstream agriculture is a serious threat to the reservoir. Without control, the eutrophication in this system will increase in severity.

Based on the Carlson-type trophic state index $\mathrm{TSI_{TN}}$, the trophic state of the system was hypertrophic (TSI > 70) over the study period (**Fig. 7**), and $\mathrm{TSI_{TP}}$ varied from 40–50, with several values being higher than 50. This result suggested that there is an adequate nutrient level for algal growth in the system. Significant changes were observed in $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ and $\mathrm{TSI_{SD}}$. $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ was lower than 50 in most months, whereas $\mathrm{TSI_{SD}}$ was higher than 50 from Jul to Sep and was lower than 50 in the other period . Carlson (1991) expanded on the concept of TSI differences by providing a two-dimensional graphical approach to assess the type and degree of limitation in lake/reservoir ecosystems. When $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ is equal to or greater than $\mathrm{TSI_{SD}}$, one may infer that algae dominate light attenuation. When $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ is lower than $\mathrm{TSI_{SD}}$, the nonalgal seston is responsible for light attenuation. When $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ is equal to or greater than $\mathrm{TSI_{TP}}$, phosphorus generally is limiting to algal growth. The deviation between $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ and $\mathrm{TSI_{TN}}$ can be used to infer whether nitrogen limitation occurs,

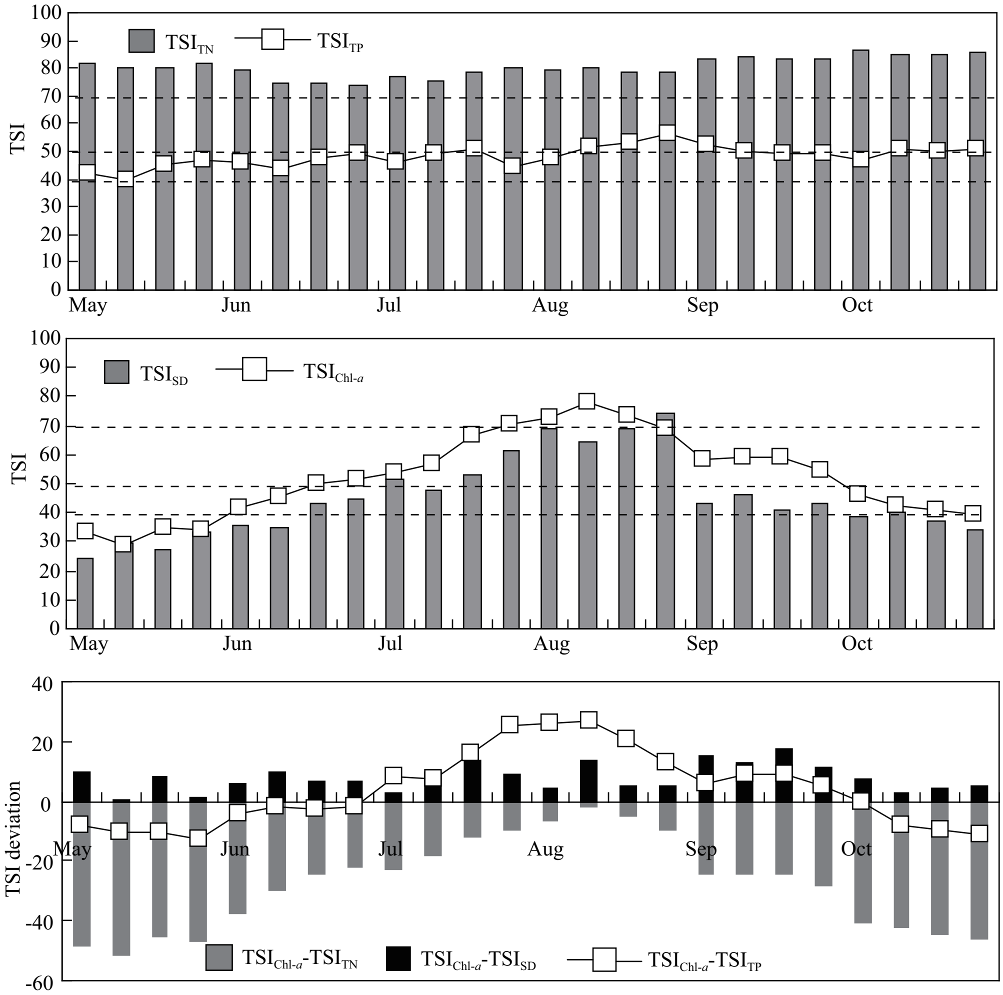


Fig. 7 Mean values of $\mathrm{TSI_{TN}}$, $\mathrm{TSI_{TP}}$, $\mathrm{TSI_{SD}}$, $\mathrm{TSI}_{\mathrm{Chl}\text{-}a}$ and TSI deviation at each site during May–Oct in 2011. The dashed lines indicate the threshold values of the mesotrophic (40), eutrophic (50) and hypertrophic (70) state, respectively.

and these correlations have been confirmed and used successfully in previous studies (e.g., An and Park, 2003; Lee et al., 2010). In the present study, $TSI_{Chl\text{-}a}$ was greater than TSI_{SD}, suggesting that the algae dominate the light attenuation (**Fig. 7**), and $TSI_{Chl\text{-}a}$ was lower than TSI_{TN}, suggesting that the nitrogen concentration was sufficient for phytoplankton growth. In contrast, $TSI_{Chl\text{-}a}$ was greater than TSI_{TP} from July to September, whereas $TSI_{Chl\text{-}a}$ was lower than TSI_{TP} in the other months over the study period, indicating that phosphorus was the limiting nutrient during July–September and was not a limiting factor in the other period. Since the phosphorus availability in the system is extremely high, it never became a limiting factor (TP > 0.02 mg/L, **Fig. 4**), suggesting that phosphorus might affect the algal biomass by regulating the N/P ratio (Chiaudani and Vighi, 1974). The results of the TSI deviation were consistent with the results of the correlation analysis between the nutrients and SD or Chl-*a* (**Table 2**).

3.2 Hydrodynamic effect and microcystin risk during the bloom

For Yanghe Reservoir, the inflow discharges were most concentrated in the summer (July to August) and accounted for approximately 60% of the annual total (**Fig. 6**). In general, a long residence time promotes algal bloom outbreaks (Kimmel et al., 1990). However, the situation in Yanghe Reservoir may be different to some extent. Before the algal bloom outbreak, the system was grouped into class B ($\tau > 20$ days, an intermediate stratified system, Straškraba and Tundisi, 1999), whereas during the algal bloom occurrence (e.g., August), the residence time was decreased ($\tau < 20$ days) due to the increased inflow discharge. At this time, the system would be characterized as a fully mixed system, yet the algal bloom continued during this period. Additionally, both the inflow discharge and water level fluctuations were the largest in this period over the whole year. These results suggest that, when the input of nutrients is high and continuous throughout the year, the instability caused by the decrease in the residence time is not able to produce negative effective changes in the cyanobacterial abundance.

In this study, we detected temporal variations in the concentrations of MC in the surface water collected at the Y1 station. The maximum MC content during the bloom period reached 2.12 ± 0.29 μg/L on Sep 2, 2010 and 1.86 ± 0.37 μg/L on Aug 25, 2011. Reports have shown that the quantification of MCs using ELISA may cause an underestimation of the MC concentration in comparison with a determination by high-performance liquid chromatography (Mathys and Surholt, 2004). However, the maximum concentration is more than two times the safety limit of 1 μg/L MC required for drinking water (WHO, 1998). The results of this survey indicated that there was an MC risk in Yanghe Reservoir and that attention should be paid to the period of cyanobacterial bloom in the summer. Routine monitoring of the MC concentration in the summer and autumn is necessary because MCs are chemically very stable (Dawson, 1998) and can enter the food chain, ultimately being present in human food. A very effective way to deal with high microcystin concentrations is to remove the cells, intact and without damage (Drikas et al., 2001; Hart et al., 1998). Any damage may lead to cell leakage and, consequently, to an increase in the dissolved toxin concentration. Therefore, water utilities should be concerned about controlling the cyanobacterial cell input to water treatment plants. For example, filtration and flotation could be performed.

4 Conclusions

Yanghe Reservoir has undergone drastic eutrophication, and the nutrient availability in this system is extremely high throughout the year. The Chl-*a* concentration was elevated, even during periods of low residence time in the summer. The cyanobacterial blooms were mainly concentrated during July–Sep, concomitant with suitable temperatures (23.5–29.5°C). The cyanobacterial blooms produced harmful cyanotoxins for which the largest value was approximately two times higher than the safety limit for drinking water. An effective treatment for removing the cells is very important for the water supply from this reservoir. To prevent the outbreak of algal blooms and improve the water quality as a source of drinking water, the nutrient concentrations must be decreased by simultaneously reducing the exogenous pollution and controlling the endogenous pollution.

Acknowledgments

This work was supported by the Plan of the National Sci-Tech Major Special Item for Water Pollution Control and Management (No. 2009ZX07528-003).

References

An J S, Carmichael W W, 1994. Use of a colorimetric protein phosphatase inhibition assay and enzyme linked immunosorbent assay for the study of microcystins and nodularins. *Toxicon*, 32(12): 1495–1507.

An K G, Park S S, 2003. Influence of seasonal monsoon on the trophic state deviation in an Asian reservoir. *Water Air and Soil Pollution*, 145(1): 267–287.

Burford M A, Johnson S A, Cook A J, Packer T V, Taylor B M, Townsley E R, 2007. Correlations between watershed and reservoir characteristics, and algal blooms in subtropical reservoirs. *Water Research*, 41(18): 4105–4114.

Cai J B, Li W Q, Pang Y, Sun Y, 2007. Limiting factors of eutrophication in Yanghe Reservoir. *Water Resources Protection*, 23(3): 52–55.

Carlson R E, 1977. A trophic state index for lakes. *Limnology and Oceanography*, 22(2): 361–369.

Carlson R E, 1991. Expanding the trophic state concept to identify non-nutrient limited lakes and reservoirs. In: Enhancing the States's Lake Management Programs (Carpenter L, ed.). 59–71.

Chen Q W, Mynett A E, 2004. Predicting *phaeocystis globosa* bloom in Dutch coastal waters by decision trees and nonlinear piecewise regression. *Ecological Modeling*, 17(3-4): 277–290.

Chiaudani G, Vighi M, 1974. The N:P ratio and tests with *Selenastrum* to predict eutrophication in lakes. *Water Research*, 8(12): 1063–1069.

Chorus I, Bartram J, 1994. Toxic Cyanobacteria in Water: A Guide to Public Health Consequences, Monitoring and Management. World Health Organisation, London.

Conley D J, Paerl H W, Howarth R W, Boesch D F, Steizinger S P, Havens K E et al., 2009. Controlling eutrophication: Nitrogen and phosphorus. *Science*, 323(5917): 1014–1015.

Cui L T, Li Z W, 2005. Study on phosphorus as a critical limiting factor in algae bloom occurrence in Yanghe Reservoir. *Journal of Agro-Environment Science*, 24(Z1): 141–143.

Dawson R M, 1998. The toxicology of microcystins. *Toxicon*, 36(7): 953–962.

Drikas M, Chow C W K, House J, Burch M D, 2001. Using coagulation, flocculation and settling to remove toxic cyanobacteria. *Journal of American Water Works Association*, 93(2): 100–111.

Ferris J A, Lehman J T, 2007. Interannual variation in diatom bloom dynamics: Roles of hydrology, nutrient limitation, sinking, and whole lake manipulation. *Water Research*, 41(12): 2551–2562.

Genkai-Kato M, Carpenter S R, 2005. Eutrophication due to phosphorus recycling in relation to lake morphometry, temperature, and macrophytes. *Ecology*, 86(1): 210–219.

George D G, Hurley M A, 2003. Using a continuous function for residence time to quantify the impact of climate change on the dynamics of thermally stratified lakes. *Journal of Limnology*, 62(S1): 21–26.

Hart J, Fawell J K, Croll B, 1998. The fate of both intro- and extracellular toxins during drinking water treatment. *Water Supply*, 16(5): 611–617.

Hitzfeld B C, Höger S J, Dietrich D R, 2000. Cyanobacterial toxins: Removal during drinking water treatment and human risk assessment. *Environmental Health Perspectives*, 108(S1): 113–122.

Hötzel G, Croome R, 1999. A Phytoplankton Methods Manual for Australian Freshwaters. Land and Water Resources Research and Development Corporation, Australian.

Huang X F, Chen W M, Cai Q M, 1999. Survey, Observation and Analysis of Lake Ecology. Chinese Standardization Press, Beijing.

Jin X C, Liu S K, Zhang Z S, 1995. China Lake Environment. Ocean Press, Beijing.

Kagalou I, Papastergiadoub E, Leonardosa I, 2008. Long term changes in the eutrophication process in a shallow Mediterranean lake ecosystem of W. Greece: Response after the reduction of external load. *Journal of Environmental Management*, 87(3): 497–506.

Kimmel B L, Lind O T, Paulson L J, 1990. Reservoir primary production. In: Reservoir Limnology: Ecological Perspectives (Thorton K W, Kimmel B L, Payne E E, eds.). John Wiley & Sons, New York. 133–193.

Kratzer C R, Brezonik P L, 1981. A carlson-type trophic state index for nitrogen in florida lakes. *JAWRA Journal of the American Water Resources Association*, 17(4): 713–715.

Lee J, Kim J M, Kim D S, Hwang S J, An K G, 2010. Nutrients and chlorophyll a dynamics in a temperate reservoir influenced by Asian monsoon along with *in situ* nutrient enrichment bioassays. *Limnology*, 11(1): 49–62.

Li F B, 2001. Eutrophication of Yanghe Reservoir and its fishery utilization. *Water and Wastewater Engineering*, 27(10): 30–33.

Li F B, Tang J Y, 2001. Eutrophication countermeasurs for Yanghe Reservoir. *Liaoning Urban and Rural Environmental Science and Technology*, 21(3): 12–14.

Li W Q, Cai J B, Pang Y, Xiao X F, 2007. Eutrophication assessment of Yanghe Reservoir and its control measures. *Water Resources Protection*, 23(2): 16–19.

Liu N, 2005. Study on rule of nitrogen and phosphor release from sediments in Yanghe Reservoir. Ph.D Thesis. Taiyuan University of Technology, Taiyuan.

Mathys W, Surholt B, 2004. Analysis of microcystins in freshwater samples using high performance liquid chromatography and an enzyme-linked immunosorbent assay. *International Journal of Hygiene and Environmental Health*, 207(6): 601–605.

Metcalf J S, Bell S G, Codd G A, 2000. Production of novel polyclonal antibodies against the cyanobacterial toxin microcystin-LR and their application for the detection and quantification of microcystins and nodularin. *Water Research*, 34(10): 2761–2769.

Nyenje P M, Foppen J W, Uhlenbrook S, Kulabako R, Muwanga A, 2010. Eutrophication and nutrient release in urban areas of sub-Saharan Africa – a review. *Science of the Total Environment*, 408(3): 447–455.

Poor N D, 2010. Effect of lake management efforts on the trophic state of a subtropical shallow lake in Lakeland, Florida, USA. *Water Air and Soil Pollution*, 207(1-4): 333–347.

State Environmental Protection Bureau (SEPB), 2002. Water and Wastewater Monitoring and Analysis Methods (4th ed.). China Environmental Science Press, Beijing.

Straškraba M, Tundisi J G, 1999. Reservoir Water Quality Management. International Lake Environment Committee, Shiga.

Utermöhl H, 1958. Zur Vervolkommung der quantitativen phytoplankton-Methodik. *Mitteilungen Internationale Vereiningung fuer Theoretische und Angewandte Limnologie*, 9: 1–38.

Wetzel R G, 2001. Limnology, Lake and River Ecosystems (3rd ed). Academic Press, London.

WHO, 1998. Cyanobacterial toxins: microcystin-LR. In: Guidelines for Drinking-Water Quality (World Health Organization, eds.). Addendum to Volume, Geneva. 95–110.

Yang X C, Wang S F, E X L, Yang K X, 2009. Correlation between microcystin and water pollution indexes of Yanghe Reservoir, Qinhuangdao. *Journal of Environmental Health*, 26(2): 137–138.

Zhang Y, Wang X L, Luo Y, 2009. Discussion on reason analysis and prevention methods of Yanghe Reservoir Eutrophication. *Haihe Water Resources*, (5): 26–28.

JOURNAL OF ENVIRONMENTAL SCIENCES

环境科学学报(英文版)

(http://www.jesc.ac.cn)

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.

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. 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.

Journal of Environmental Sciences (Established in 1989)
Vol. 25 No. 5 2013

Supervised by	Chinese Academy of Sciences	**Published by**	Science Press, Beijing, China
Sponsored by	Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences		Elsevier Limited, The Netherlands
		Distributed by	
Edited by	Editorial Office of Journal of Environmental Sciences P. O. Box 2871, Beijing 100085, China Tel: 86-10-62920553; http://www.jesc.ac.cn E-mail: jesc@263.net, jesc@rcees.ac.cn	Domestic	Science Press, 16 Donghuangchenggen North Street, Beijing 100717, China Local Post Offices through China
		Foreign	Elsevier Limited http://www.elsevier.com/locate/jes
Editor-in-chief	Hongxiao Tang	**Printed by**	Beijing Beilin Printing House, 100083, China

CN 11-2629/X **Domestic postcode: 2-580** **Domestic price per issue RMB ¥ 110.00**

ISSN 1001-0742

9 771001 074130 05>