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Research Paper

Longitudinal Differences of Phytoplankton Community during a Period of Small Water Level Fluctuations in a Subtropical Reservoir Bay (Xiangxi Bay, Three Gorges Reservoir, China)

key words: community change rate, temporal pattern, longitudinal differences

Abstract

The Three Gorges Reservoir (TGR) had a great inflow discharge with small water level fluctuations in the flood season of the year 2008, when a large-scale cyanobacterial bloom broke out in Xiangxi Bay (a tributary bay behaving like a lake) for the first time after the construction of the TGR impoundment. To compare spatiotemporal longitudinal differences of phytoplankton community structure during this period, weekly surveys were performed in Xiangxi Bay. The cyanobacterial bloom lasted from June 6 to July 18, 2008, with *Microcystis aeruginosa* as the dominant species. During this bloom the species diversity, evenness and community change rate was relatively low. The probable causes for the interruption of the bloom were precipitation and water temperature. In the non-cyanobacterial bloom period (July 25 to September 26, 2008) many other species dominated the community including *Stephanodiscus hantzschii* and *Cryptomonas ovata*, with higher values of species diversity, evenness and community change rate. As for the longitudinal differences, the community structure in the riverine zone was different from that in other zones, indicating the important effect of inflow from the upstream of Xiangxi Bay. The management actions in Xiangxi Bay should prevent blooms in the mainstream, lacustrine and transitional zone.

1. Introduction

Phytoplankton composition can be recognized as a natural bioindicator because of its complex and rapid responses to fluctuations of environmental conditions (LIVINGSTON, 2001). Phytoplankton community composition changes as a consequence of species succession, which occurs in response to new environmental conditions (ÁLVAREZ-GÓNGORA and HERRERA-SILVEIRA, 2006). Two important factors appear to control the phytoplankton community structure, as well as the species succession. The first one is related to physical processes such as mixing conditions, light, temperature, turbulence, and salinity; and the second one is associated with nutrients (YUSOFF *et al.*, 2002; NUCCIO *et al.*, 2003; DOMINGUES *et al.*, 2005; ÁLVAREZ-GÓNGORA and HERRERA-SILVEIRA, 2006; BROGUEIRA *et al.*, 2007; DOMINGUES *et al.*, 2007).

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The phytoplankton community structure can be characterized by species composition, biovolume and diversity (Côté and Platt, 1983; Jouenne *et al.*, 2007), influenced by environmental variability in space and time (Beisner, 2001). The mentioned characteristics of phytoplankton community structure have been studied for a large variety of aquatic ecosystems (Nuccio *et al.*, 2003; Zalocar, 2003; Jouenne *et al.*, 2007; Borges *et al.*, 2008; Bovo-Scomparin and Train, 2008).

The construction of a dam across a river and the consequent impoundment may induce cultural eutrophication, and cause profound changes in the hydrology and ecology of the waterbody (Ha *et al.*, 2003). For the Three Gorges Reservoir (TGR), the cultural eutrophication process has attracted broad concern since its impoundment in 2003 (Cai and Hu, 2006). Livingston (2001) pointed out that phytoplankton community structural changes are a good indicator of eutrophication effects. Unfortunately the relevant studies in the TGR are still lacking. Additionally, the operation pattern of TGR is to store clear water after the flood season and to release muddy water by lowering the reservoir water level during the flood season (Huang *et al.*, 2006; Shao *et al.*, 2006, 2008), with the water level fluctuating between 145 m a.s.l. and 175 m a.s.l. Under normal circumstances, the water level is kept at 145 m a.s.l. from June to September (also flood season in the TGR region); rises up to 175 m a.s.l. from October to January. The drastic water level fluctuations of the TGR are bound to significantly influence phytoplankton community structure and species succession process in its tributary bays.

Xiangxi Bay, as the largest tributary bay of the TGR in Hubei Province, behaves like a lake after the TGR impoundment (Cai and Hu, 2006; Ye *et al.*, 2007). Weekly dynamics of phytoplankton functional groups (Wang *et al.*, 2010a) and longitudinal patterns of phytoplankton distribution (Wang *et al.*, 2010b) are affected by the water level fluctuations of the TGR. However, the phytoplankton community structure in a relatively stable water level phase (with small water level fluctuations) has not been studied. Another concern is that during this period, in the year 2008, a large-scale cyanobacterial bloom broke out for the first time in Xiangxi Bay after the TGR impoundment. This period can be used as a case to study spatiotemporal longitudinal differences in phytoplankton community characteristics to enhance our understanding of phytoplankton distribution under the impact of many environmental variables, except water level.

The aim of the present study is to explore the spatial and temporal differences of the phytoplankton taxonomic composition, species diversity, evenness and community change rate along the longitudinal gradient of Xiangxi Bay, one of the largest tributary of the TGR.

2. Methods

2.1. Study Site and Sampling

The Three Gorges Reservoir (TGR) is located at 29°16′~31°25′ N, 106°~110°50′ E, with a normal water level of 175 m a.s.l., a surface area of 1080 km^2 and a capacity of 3.93×10^{10} m^3 (Huang *et al.*, 2006). A subtropical monsoon climate prevails (Jiang *et al.*, 2005; Jiang *et al.*, 2006), with an average annual rainfall of 1000~1300 mm. The Xiangxi River is the largest tributary of the TGR in Hubei Province, with a mainstream length of 94 km, a watershed area of 3099 km^2, a natural fall of 1540 m (mainly in the upstream of Xiangxi River), and an average annual discharge of 65.5 m^3/s (Wang *et al.*, 1997). Xiangxi Bay is the lower 20~40 km stretch of the Xiangxi River.

Weekly surveys were performed from June 6 to September 26 in 2008 (17 sampling occasions). This period is a warm flood season, with small water level fluctuations around 145 m a.s.l. The sampling sites were set up according to the longitudinal patterns of phytoplankton distribution in Xiangxi Bay (Wang *et al.*, 2010b). Wang *et al.* (2010b) identified longitudinal patterns in different water level fluctuations periods using chlorophyll *a*, transparency, and relative water column stability. In this study four sites were selected from the mouth to the end of Xiangxi bay, including the mainstream zone, the

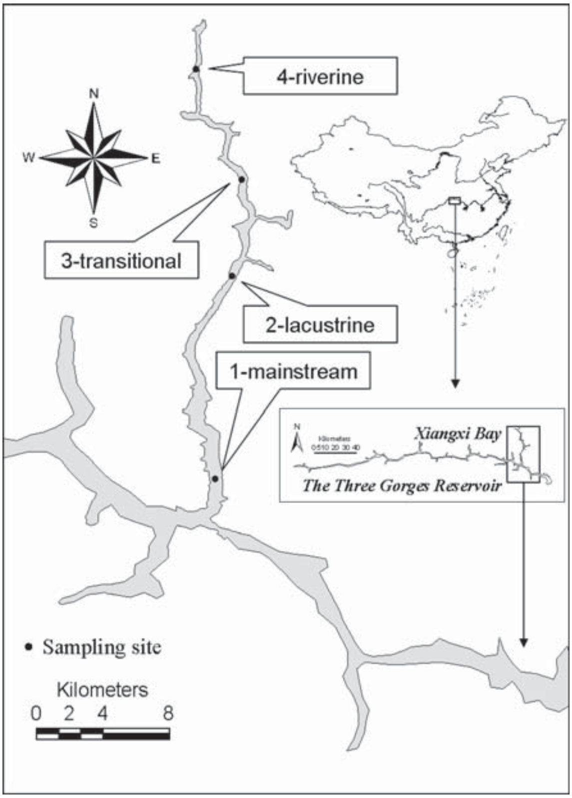


Figure 1. Locations of the sampling sites in Xiangxi Bay (the largest tributary bay of the Three Gorges Reservoir in Hubei Province).

lacustrine zone, the transitional zone and the riverine zone, respectively (Fig. 1). The sites are labeled as 1-mainstream, 2-lacustrine, 3-transitional and 4-riverine successively for clarity. The depths of the four sites are approximately 70 m, 20 m, 15 m and 5 m, respectively during the study period. Water is mostly used for landscape, and the population density is quite low along the whole bay.

Samples were collected with a 5 L Van Dorn sampler at a depth of 0.5 m below the water surface, because the water layer which has maximal chlorophyll through the water column is the water surface in general. Samples for analyses of nutrients were stored in a pre-cleaned plastic bottle and acidified with sulfuric acid for laboratory analysis. Samples for phytoplankton analyses were immediately fixed with neutral Lugol's solution.

2.2. Abiotic and Biotic Variable Measurements

Conductivity (Cond), pH, dissolved oxygen (DO), and turbidity of the water surface, as well as vertical profiles of water temperature (WT) were measured with Environmental Monitoring Systems (YSI 6600EDS, USA). The transparency (Sd) was determined with a 20 cm Secchi disc. The concentrations of ammonium nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), total nitrogen (TN), phosphate phosphorus (PO_4–P), total phosphorus (TP), and silicate silicon (SiO_2–Si) were measured with a segmented flow analyzer (Skalar San^{++}, Netherlands), according to Protocols for Standard Observation and Measurement in Aquatic Ecosystems of Chinese Ecosystem Research Network (CERN) (CAI, 2007; HUANG *et al.*, 2000).

Algae were identified and counted using a sedimentation method (CAI, 2007; HUANG *et al.*, 2000), in a Fuchs-Rosental slide, and with an Olympus CX21 microscope (Olympus Corporation, Japan) at 400 × magnification. Taxonomic identification of phytoplankton species was done according to HU and WEI (2006) and JOHN *et al.* (2002).

2.3. Data Analysis

Relative water column stability (RWCS) reflects the thermal stratification conditions of waterbody by the density differences in the water column (PADISÁK *et al.*, 2003). The higher score indicates the higher stability of the water column. The dimensionless parameter relative water column stability was calculated by comparing the density gradient of the whole water column to the density difference between 4 °C and 5 °C pure water using the following formula (PADISÁK *et al.*, 2003):

$$RWCS = \frac{D_b - D_S}{D_4 - D_5}$$

where D_b, D_s, D_4, and D_5 is the density of the bottom water, surface water, and water at 4 °C and 5 °C, respectively. In this study, the depth of 1 m was considered as "surface", the depth of 10 m was considered as "bottom" when the water depth of the sampling site was larger than 10 m, and the greatest depth was considered as "bottom" when the water depth of the sampling site was less than 10 m.

Algal biomass was calculated using the formulae for geometric shapes, and assuming the fresh weight unit as expressed in mass, where 1 $mm^3/L = 1$ mg/L (HUANG *et al.*, 2000; WETZEL and LIKENS, 2000).

In the present study, Shannon-Wiener's H, Simpson's D species diversity indices, evenness and community change rate were calculated for the biomass of phytoplankton, respectively.

Shannon-Wiener's H′ index (H) is given by:

$$H' = -\sum_{i=1}^{k} p_i \log_2 p_i$$

Simpson' D index (D) is given by:

$$D = 1 - \sum_{i=1}^{k} p_i^2$$

where k is the total number of phytoplankton taxa, and p_i is the proportion of phytoplankton taxon i in the total sample count over all k taxa.

Evenness (E) is calculated as:

$$E(\%) = 100 \times \frac{H'}{\log_2 k}$$

where H′ is Shannon-Wiener's H index, and k is the total number of phytoplankton taxa.

Community change rate (R) is estimated according to LEWIS (1978), with the formula:

$$R = \frac{\sum_{i=1}^{k} \left| p_{i,t1} - p_{i,t2} \right|}{t_2 - t_1}$$

where $p_{i,\,t1}$ is the proportion of the phytoplankton taxon i at time t_1, and $p_{i,\,t2}$ is the proportion of the phytoplankton taxon i at time t_2. The unit of R is day^{-1}. Increased R values imply increased changes in community composition.

The similarity index of the phytoplankton community assemblages (PSC) was applied to compare the structure difference between two communities, and calculated as follows:

$$PSC = 1 - 0.5 \sum_{i=1}^{k} \left| p_i - q_i \right|$$

where p_i is the proportion of the phytoplankton taxon i in community p, and q_i is the proportion of the phytoplankton taxon i in community q. The higher the value of PSC, the higher the similarity between the phytoplankton community p and q. In the present study, the similarity index between every two sampling sites was calculated in a same sampling occasion, and the means and ranges of the similarity index were obtained for every date and every two sites in pairs, respectively.

One-way ANOVA was employed to examine the differences of environmental conditions between the four sampling sites, and the differences of the relative water column stability between the two periods (cyanobacterial bloom period and non-cyanobacterial bloom period). Wilcoxon Signed Ranks Test was used to compare the characteristic variables of the phytoplankton community between the four sites. Abiotic variables were correlated with biotic variables using Spearman's correlation coefficients. All the statistical analyses were performed with the software SPSS 16.0.

3. Results

3.1. Physical and Chemical Conditions

The water level of TGR oscillated between 144.7 m (June 9) and 145.9 m (August 25), with a small range of 1.2 m (Fig. 2a). The maximal daily water level variation was 0.7 m (July 4). Rain occurred nearly every two weeks, with a maximal daily precipitation of 77.6 mm on August 29 (Fig. 2b). The estimated inflow charge of Xiangxi Bay in the study period was 63.22 m^3/s (Wang *et al.*, 2010b). Water temperature (Fig. 2c) increased from June 6 to August 1 at site 1-mainstream, 2-lacustrine and 3-transitional, while site 4-riverine had more fluctuations. From August 15 to September 26 the trend of water temperature was generally declining.

One-way ANOVA for physical and chemical variables (Table 1) indicated that, WT, conductivity, pH, transparency, RWCS, NO_3–N, PO_4–P, TP and TN/TP were significantly different between the four sites ($P < 0.05$). The site 3-transitional had the highest WT (26.6 °C), pH (8.1) and RWCS (96.8), while 4-riverine had the lowest values (21.8 °C, 7.4 and 29.6, respectively). Conductivity was relatively higher at site 1-mainstream (0.32 ms/cm) and 2-lacustrine (0.32 ms/cm) than 4-riverine (0.29 ms/cm). Transparency reached the highest value at 2-lacustrine (127 cm) and lowest one at 4-riverine (70 cm). Site 1-mainstream had a highest concentration of NO_3-N (1.14 mg/L) while 4-riverine had a lowest value (0.85 mg/L). The concentrations of PO_4-P and TP were highest at 4-riverine (0.14 and 0.16 mg/L), while TN/TP value at 4-riverine was the lowest (9.4). Moreover, the results showed that total P values were much lower than N values in the study period referred to Table 1.

3.2. Phytoplankton Biomass and Taxonomic Composition

3.2.1. Total Biomass

Temporal changes of total phytoplankton biomass are shown in Figure 3. The highest biomass values were from June 13 to July 11 and on September 12. The average values of total biomass were 2.11, 2.13, 4.24 and 3.07 mg/L for the sites 1-mainstream, 2-lacustrine, 3-transitional and 4-riverine, respectively. Generally, 3-transitional had a highest average value of total biomass. Site 4-riverine had relatively high values because it reached the highest total biomass on July 11.

Wilcoxon Signed Ranks Test (Table 2) showed that total biomass was significantly different between 1-mainstream and 3-transitional, as well as 2-lacustrine and 3-transitional ($P < 0.05$). The Spearman rank correlation analysis (Table 3) indicated that, total biomass was positively correlated to WT, DO, pH, RWCS, NH_4–N and TN/TP significantly ($P < 0.05$), and negatively correlated to PO_4–P, TP and SiO_2–Si ($P < 0.05$).

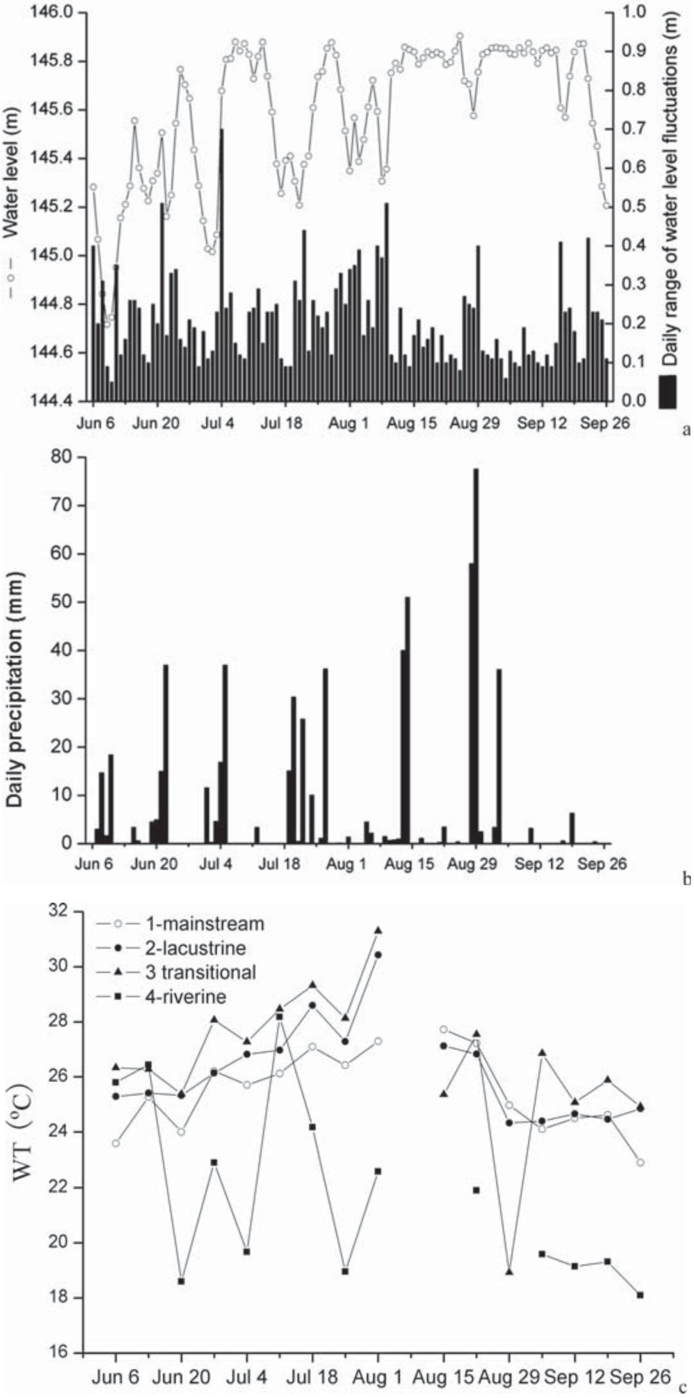


Figure 2. The water level of the TGR (a), precipitation (b) and water temperature (c) in Xiangxi Bay throughout the study period in 2008.

Table 1. Means and ranges of monitored environmental variables, significant levels (*P*), and values of *F* statistic and degrees of freedom from one-way ANOVA in Xiangxi Bay (bold: significant at the 0.05 level)

	1-mainstream	2-lacustrine	3-transitional	4-riverine	*P*	*F*	*df*
WT (ºC)	25.5 (22.9–27.7)	26.2 (24.3–30.4)	26.6 (18.9–31.3)	21.8 (18.1–28.2)	**<0.001**	12.42	61
Cond (ms/cm)	0.32 (0.28–0.37)	0.32 (0.28–0.35)	0.31 (0.24–0.35)	0.29 (0.24–0.32)	**0.007**	4.42	61
DO (mg/L)	11.4 (8.8–18.1)	13.2 (9.0–17.5)	15.0 (9.7–22.8)	13.4 (9.5–23.0)	0.137	1.93	49
pH	7.9 (7.5–8.5)	7.9 (6.7–8.6)	8.1 (7.4–8.7)	7.4 (6.6–8.8)	**<0.001**	6.94	61
turbidity	16.9 (8.5–30.4)	14.8 (8.8–29.7)	58.5 (9.1–478.5)	26.8 (11.3–63.6)	0.206	1.57	61
Sd (cm)	102 (50–220)	127 (50–300)	96 (10–210)	70 (25–130)	**0.030**	3.19	65
RWCS	38.8 (1.3–87.9)	63.9 (7.3–142.9)	96.8 (1.4–220.9)	29.6 (0–179.7)	**<0.001**	7.87	65
NH_4–N (mg/L)	0.07 (0.01–0.28)	0.06 (0.0001–0.15)	0.09 (0.01–0.34)	0.08 (0.01–0.47)	0.710	0.46	65
NO_3–N (mg/L)	1.14 (0.80–1.49)	1.10 (0.80–1.36)	1.00 (0.55–1.35)	0.85 (0.64–1.10)	**<0.001**	7.36	65
TN (mg/L)	1.34 (0.93–1.76)	1.30 (0.97–1.72)	1.24 (0.82–1.59)	1.15 (0.81–1.95)	0.187	1.65	65
PO_4–P (mg/L)	0.02 (0.01–0.06)	0.02 (0.01–0.05)	0.02 (0.01–0.14)	0.14 (0.04–0.39)	**<0.001**	21.65	65
TP (mg/L)	0.04 (0.01–0.10)	0.03 (0.01–0.07)	0.04 (0.01–0.20)	0.16 (0.07–0.41)	**<0.001**	19.97	65
TN/TP	58.6 (18.2–137.6)	84.7 (16.3–164.4)	57.7 (6.0–140.8)	9.4 (2.8–18.0)	**<0.001**	9.47	65
SiO_2–Si (mg/L)	3.95 (2.57–8.73)	3.72 (2.59–7.33)	3.74 (2.04–7.37)	3.38 (2.32–5.06)	0.735	0.43	65

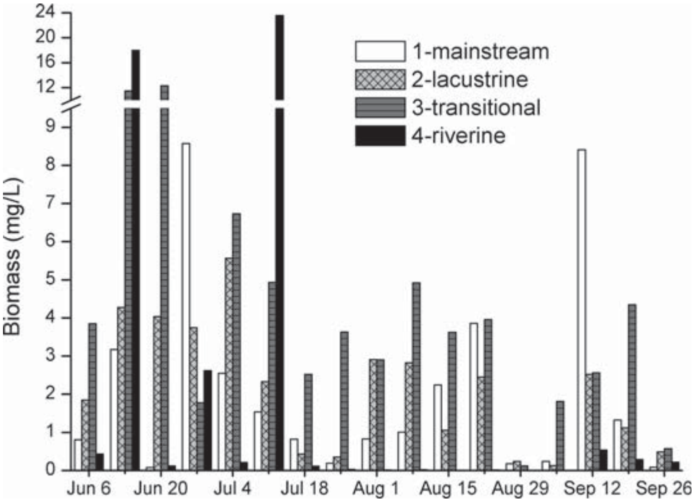


Figure 3. The total phytoplankton biomass during the study period in 2008.

3.2.2. Relative Biomass

A total of 88 phytoplankton species were identified, distributed in six major taxonomic categories: Cyanophyta (9, 10.2%), Cryptophyta (7, 8.0%), Bacillariophyta (19, 21.6%), Dinophyta (6, 6.8%), Chlorophyta (46, 52.3%) and Euglenophyta (1, 1.1%).

Figure 4 shows the temporal patterns of relative biomass for different taxonomic categories at each sampling site. Cyanophyta became the most important from June to July (*Microcystis aeruginosa*, colonial), coinciding with the highest biomass in the studied period. The highest cyanobacteria proportion occurred on June 27 for site 1-mainstream, from June 27 to July 4 for 2-lacustrine and 3-transitional, and on July 11 for 4-riverine, respectively. From

Table 2. Significant levels (*P*) from the Wilcoxon Signed Rank Test for studied characteristic variables of phytoplankton community in Xiangxi Bay (bold: significant at the 0.05 level)

	Cya	Cry	Bac	Din	Chl	Total	H′	D	E	R
Site 1–Site 2	0.227	0.266	0.196	0.499	0.381	0.586	0.906	0.981	0.687	0.918
Site 1–Site 3	**0.022**	**0.004**	0.756	**0.015**	0.586	**0.028**	0.435	0.407	**0.049**	0.569
Site 1–Site 4	0.433	0.650	0.112	0.273	**0.003**	0.112	0.334	0.394	0.363	0.433
Site 2–Site 3	0.109	**0.015**	0.278	**0.003**	0.619	**0.003**	0.687	0.287	0.068	0.796
Site 2–Site 4	0.177	0.394	0.069	0.398	**0.009**	0.078	0.394	0.776	0.125	0.272
Site 3–Site 4	0.096	**0.017**	**0.017**	**0.008**	**0.009**	0.078	0.609	0.955	0.069	0.470

Cya: Cyanophyta; Cry: Cryptophyta; Bac: Bacillariophyta; Din: Dinophyta; Chl: Chlorophyta; H′: Shannon-Wiener's H index; D: Simpson' D index; E: Evenness; R: Community change rate.

August to September, Bacillariophyta, Cryptophyta, Chlorophyta and Dinophyta were more important than Cyanophyta. At 1-mainstream and 2-lacustrine, Bacillariophyta, Cryptophyta and Chlorophyta were dominant categories, while 3-transitional had a highest proportion of Dinophyta, and Bacillariophyta dominated at 4-riverine.

No significant difference was found between 1-mainstream and 2-lacustrine for relative biomass of all the categories ($P > 0.05$), while significant differences existed between other two sampling sites (Table 2). Relative biomass for all the categories was correlated with many environmental variables except NO_3–N (Table 3). The environmental variables with significant, positive and high correlations to Cyanophyta dominance included WT (0.640), DO (0.645), pH (0.558), RWCS (0.555) and NH_4–N (0.408). Additionally, WT was positively and highly correlated to Cryptophyta and Chlorophyta dominance, Cond, pH, Sd and TN/TP were positively and highly correlated to Chlorophyta dominance, and RWCS was positively and highly correlated to Cryptophyta, Dinophyta and Chlorophyta dominance.

Table 3. The Spearman rank correlation coefficients between the attribute of phytoplankton, total phytoplankton, community variables and environmental variables (** correlation is significant at the 0.01 level (2-tailed); * correlation is significant at the 0.05 level (2-tailed).)

	Cya	Cry	Bac	Din	Chl	Total	H′	D	E	R
WT (ºC)	0.640**	0.576**	0.211	0.313*	0.512**	0.588**	0.193	0.144	–0.150	–0.303*
Cond (ms/cm)	0.299*	0.063	–0.391**	–0.293*	0.418**	0.155	–0.193	–0.201	–0.194	–0.155
DO (mg/L)	0.645**	0.284*	–0.069	0.005	0.399**	0.675**	–0.424**	–0.475**	–0.530**	–0.416**
pH	0.558**	0.396**	0.334**	0.292*	0.622**	0.781**	–0.066	–0.133	–0.404**	–0.332*
turbidity	–0.135	–0.374**	–0.109	–0.138	–0.387**	–0.243	–0.287*	–0.264*	–0.061	0.038
Sd (cm)	0.304*	0.223	–0.130	–0.086	0.448**	0.236	0.095	0.074	–0.056	–0.098
RWCS	0.555**	0.721**	0.328**	0.500**	0.568**	0.753**	0.152	0.110	–0.243*	–0.225
NH_4–N (mg/L)	0.408**	0.357**	0.176	0.180	0.383**	0.479**	0.127	0.124	–0.139	–0.200
NO_3–N (mg/L)	0.091	–0.018	–0.239	–0.111	0.163	–0.158	0.109	0.109	0.089	0.078
TN (mg/L)	0.368**	0.119	–0.236	–0.123	0.315*	0.124	–0.088	–0.085	–0.111	–0.195
PO_4–P (mg/L)	–0.309*	–0.457**	–0.334**	–0.317**	–0.493**	–0.528**	–0.204	–0.166	0.190	0.156
TP (mg/L)	–0.269*	–0.295*	–0.283*	–0.223	–0.397**	–0.395**	–0.255*	–0.232	0.105	0.191
TN/TP	0.336**	0.298*	0.206	0.188	0.443**	0.384**	0.248*	0.228	–0.093	–0.217
SiO_2–Si (mg/L)	–0.625**	–0.091	0.202	0.237	–0.446**	–0.281*	–0.018	–0.008	0.037	0.332**

Cya: Cyanophyta; Cry: Cryptophyta; Bac: Bacillariophyta; Din: Dinophyta; Chl: Chlorophyta; H′: Shannon-Wiener's H index; D: Simpson' D index; E: Evenness; R: Community change rate.

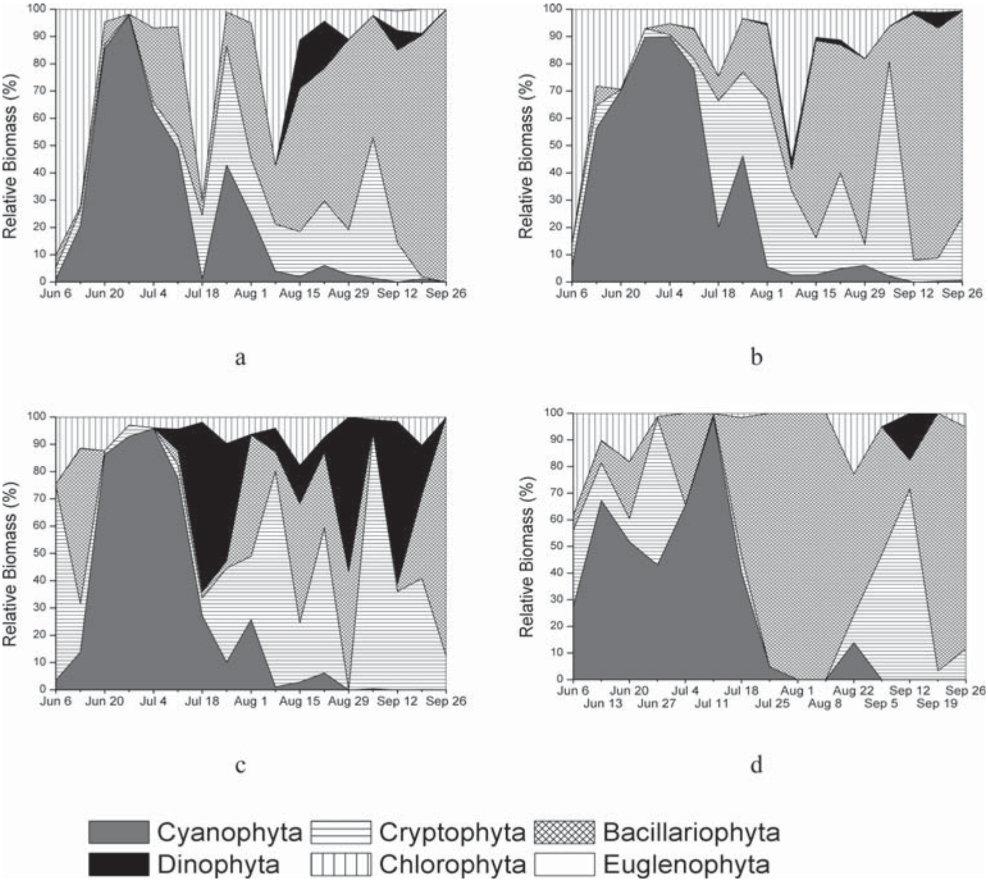
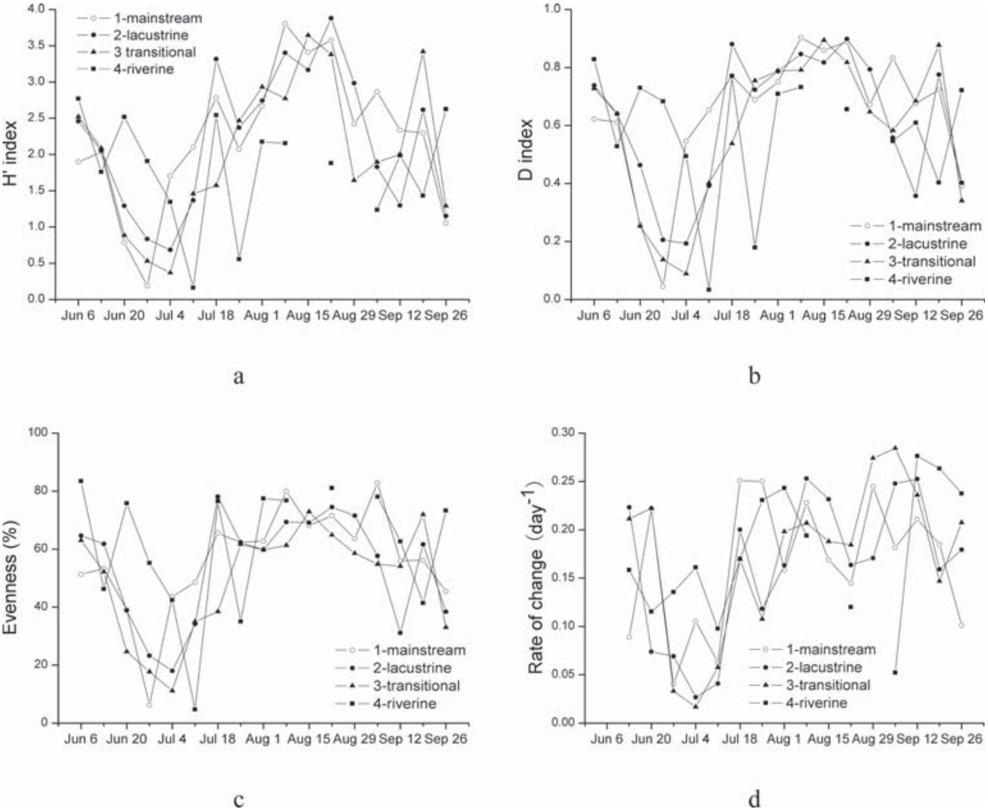


Figure 4. The relative biomass of phytoplankton during the study in 2008 (a: 1-mainstream; b: 2-lacustrine; c: 3-transitional; d: 4-riverine).

3.2.3. Species Diversity, Evenness and Community Change Rate

Similar temporal changes of species diversity, evenness and community change rate based on biomass are detected and exhibited in Figure 5. In general, species diversity, evenness and community change rate decreased from June 20 to July 11, corresponding to the period when the total phytoplankton biomass reached the highest values coinciding with the cyanobacterial bloom. In the non-bloom period these values increased. There was no significant difference ($P > 0.05$) between two sampling sites for all the variables of community characteristics (Wilcoxon Signed Ranks Test, see Table 2) beyond that the evenness was significantly different between site 1-mainstream and 3-transitional ($P = < 0.05$). These results suggested that the sampling sites along the longitudinal gradient of Xiangxi Bay had similar community characteristics when considering typical community variables such as species diversity, evenness and community change rate. Among these variables, species diversity based on H´ index was significantly correlated with DO, turbidity, TP and TN/TP, while species diversity based on D index was significantly correlated with DO and turbidity. Evenness was significantly cor-



a b

c d

Figure 5. The temporal changes of species diversity index (a: H´ index; b: D index; c: evenness and d: community change rate) based on biomass during the study period in 2008.

related with DO, pH and RWCS. The community change rate was significantly correlated with WT, DO, pH and SiO_2–Si (Table 3).

3.2.4. Similarity of the Phytoplankton Community Structure

The similarity of the phytoplankton community structure between every two sampling sites for each sampling date showed that (Table 4), the highest similarity occurred on June 20 (0.66), June 27 (0.69), July 4 (0.72) and July 11 (0.69), coinciding with the cyanobacterial bloom period. Moreover, the similarity results further confirmed that site 1-mainstream and site 2-lacustrine had the most similar community composition, with the average similarity index of 0.56, and the range from 0.20 to 0.91. In general, site 4-riverine seemed the most different from the other sites (with the average similarity of 0.28, 0.35 and 0.32 *vs*. 1-mainstream, 2-lacustrine and 3-transitional, respectively). This is probably related to the complex influences of inflow discharge and artificial activities from the upstream of Xiangxi Bay.

Table 4. The similarity index of phytoplankton community structure (means and ranges) based on biomass between every two sampling sites in the study period.

Sampling date	Similarity index	Sampling sites	Similarity index
June 6	0.32 (0.10–0.67)	Site 1 *vs*. Site 2	0.56 (0.20–0.91)
June 13	0.43 (0.30–0.74)	Site 1 *vs*. Site 3	0.42 (0.02–0.93)
June 20	0.66 (0.51–0.86)	Site 1 *vs*. Site 4	0.28 (0.01–0.67)
June 27	0.69 (0.44–0.93)	Site 2 *vs*. Site 3	0.52 (0.02–0.93)
July 4	0.72 (0.66–0.93)	Site 2 *vs*. Site 4	0.35 (0.01–0.79)
July 11	0.69 (0.48–0.89)	Site 3 *vs*. Site 4	0.32 (0.05–0.78)
July 18	0.24 (0.09–0.34)		
July 25	0.28 (0.05–0.73)		
August 1	0.41 (0.19–0.73)		
August 8	0.20 (0.01–0.50)		
August 15	0.61 (0.54–0.71)		
August 22	0.35 (0.06–0.67)		
August 29	0.11 (0.02–0.29)		
September 5	0.34 (0.09–0.58)		
September 12	0.33 (0.10–0.72)		
September 19	0.38 (0.19–0.56)		
September 26	0.25 (0.07–0.83)		

3.3. Temporal Patterns of Dominant Phytoplankton Species

22 species reached over 20% of the total biomass in one or more samples during the study, and their temporal patterns are exhibited in Figure 6. *Microcystis aeruginosa* was the dominant species in June and July. Some species including *Chroomonas acuta*, *Cryptomonas ovata*, *Cryptomonas erosa*, *Rhodomonas* sp., *Cyclotella stelligera*, *Stephanodiscus hantzschii* and *Pandorina morum* showed a long persistence during the investigation period, and *Stephanodiscus hantzschii* seemed more important. Other species showed a relative high biomass at a special site and special time, but persisted only for very short time periods.

4. Discussion

The risk of eutrophication in TGR has increased since its impoundment (Cai and Hu, 2006), and the cyanobacterial bloom investigated in the present study was the first large-scale cyanobacterial bloom in Xiangxi Bay (Wang *et al.*, 2009). Steinberg and Hartmann (1988) indicated that eutrophication of water bodies is often followed by significant shifts in the phytoplankton towards Cyanobacteria. So the relationship between bloom and eutrophication process is a noteworthy important issue in TGR. In a relative small time scale (for example, within a year), there are no remarkable changes in the eutrophication process and characteristics in Xiangxi Bay. The cyanobacterial bloom lasted at least a month, showing a high stability of cyanobacterial bloom, and after that the other species succeeded. The appearance and extinction of cyanobacterial bloom can not indicate an eutrophication process. In a larger time scale (many years), more data is needed to propose and support the relationship between the cyanobacterial bloom and eutrophication process in Xiangxi Bay. Many studies have considered the N and P limitations in aquatic ecosystems (Elser *et al.*, 2007; Gillor *et al.,* 2010). The relatively high N and low P concentrations in the study period indicated that phytoplankton seemed P limited but not N limited. Among the four sites, TN

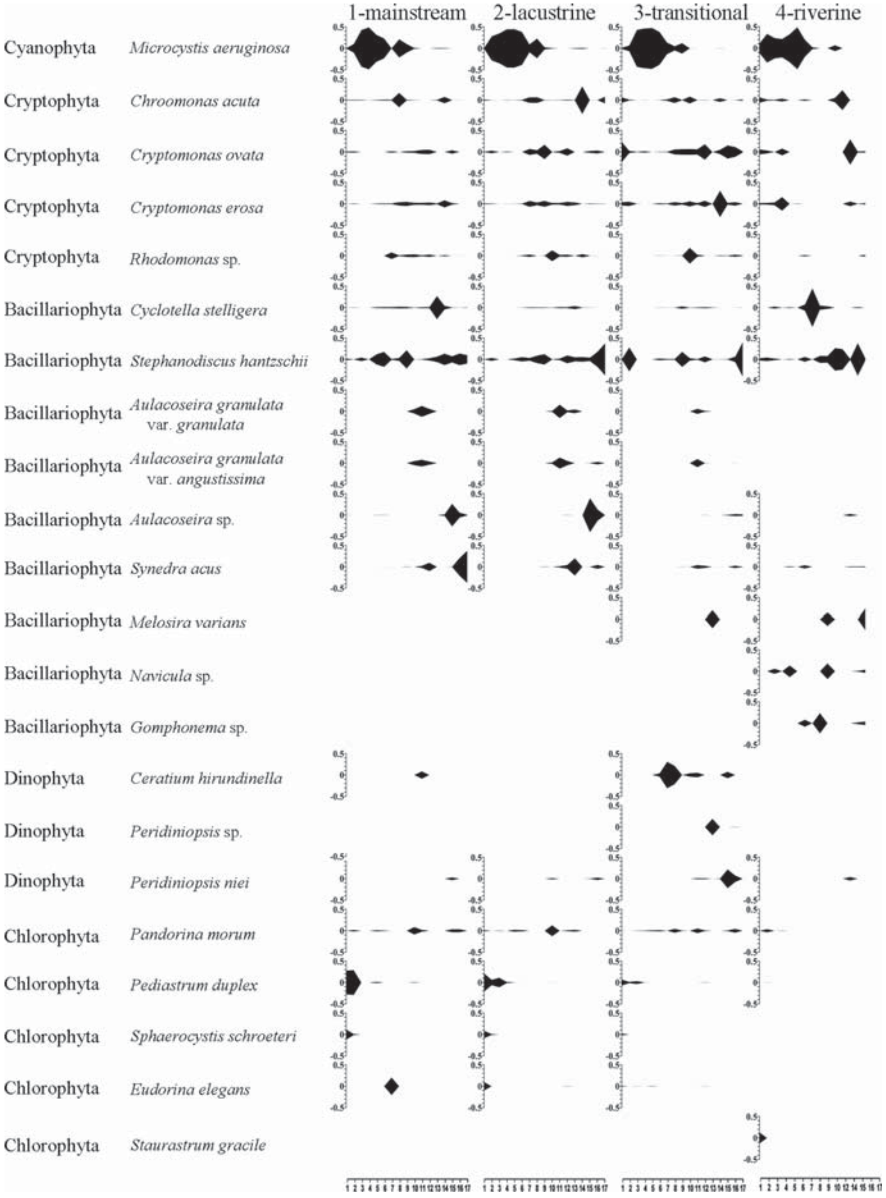


Figure 6. The temporal patterns of relative biomass for the main phytoplankton species during the study period in 2008 (the line with the numbers at the lowest part indicates the number of sampling dates, *i.e.*, the number of 1 to 17 means weekly sampling from June 6 to September 26 in year 2008.)

values are rather similar. However, site 4-riverine had higher TP (mean of 0.16 mg/L) than the other sites (range of 0.04 mg/L). This could further explain the differences among sites.

The present study showed significant differences of phytoplankton community structure along different zones except between in the mainstream and lacustrine zone of Xiangxi Bay.

The similarity in phytoplankton community structure indicated the important influence of the Yangtze River (mainstream of the TGR) on phytoplankton development in its tributary bays under small water level fluctuations. The Yangtze River influenced, probably, the first 9 km of Xiangxi Bay from the aspect of phytoplankton community structure. Nevertheless, in the middle and upper parts of Xiangxi Bay, the phytoplankton community structure seemed to be little affected by the Yangtze River. For instance, at 3-transitional, the total biomass was the highest, with Dinophyta accounting for a marked proportion, while Bacillariophyta accounted for a large proportion of the total biomass at 4-riverine. These mentioned characteristics of 3-transitional and 4-riverine agreed with the conclusions of their zonation (located in transitional zone and riverine zone, respectively) proposed by WANG *et al.* (2010b). The obvious difference of phytoplankton community structure at 4-riverine from the other sites showed the great impact of inflow from the upstream of Xiangxi Bay.

In this study, the results obtained by two different species diversity indices were almost the same. Shannon-Wiener's H index is strongly influenced by the number of taxa, while Simpson' D index is highly dependent on the few most abundant taxa, giving little weight to rare taxa (KOBAYASHI *et al.*, 2005). Furthermore, only when considering spatial difference in a same sampling occasion, there is no significant difference in species diversity, evenness and community change rate between the sites along the longitudinal gradient of Xiangxi Bay except evenness based on biomass between 1-mainstream and 3-transitional. It is accepted that many biotic and abiotic processes contribute to the variability of phytoplankton diversity in aquatic ecosystems, and these processes may act at different time and space scales (CHALAR, 2009). The present study suggests that the efficiency of traditional community variables like species diversity for discriminating the phytoplankton community structure along the longitudinal gradient of Xiangxi Bay under small water level fluctuations is quite low. Nevertheless, the community change rate is useful for indicating temporal changes of environmental stability (ZALOCAR, 2003). The low rate of community compositional change indicates a greater environmental stability, related to a higher complexity in the community organization; while a high value suggests environmental variability, possibly indicating a higher rate of biogeochemical processes (ZALOCAR, 2003). During the cyanobacterial bloom period, total phytoplankton biomass reached a highest value with a low community change rate (lower than 0.1 day^{-1}), while during the non-cyanobacterial bloom period the rate was relative high, indicating high environmental stability during the cyanobacterial bloom period and high environmental variability during the non-cyanobacterial bloom period. Meanwhile, the relative water column stability was not significantly different between the cyanobacterial bloom period and the other one ($P = 0.45$, $F = 0.58$, $df = 65$). We conclude that temporal fluctuation of phytoplankton community structure was more likely related to other physical variables such as precipitation and temperature.

The *Microcystis* blooms generally occur during the summer months due to increasing temperature in lake ecosystems, and *Microcystis aeruginosa* blooms were mainly related to the poor water quality (TAŞ *et al.*, 2006). In the previous studies, high values of WT, pH and Z_{eu}/Z_{mix} were detected when *Microcystis aeruginosa* dominated in Xiangxi Bay, indicating its good adaptability to the water column stratification conditions in summer influenced by weak water level fluctuations (WANG *et al.*, 2010a). Large-scale climatic conditions and the local weather pattern set the physic-chemical conditions which determine the cyanobacterial response (BORMANS *et al.*, 2005). LIPS and LIPS (2008) reported that the development of a cyanobacterial bloom in the Gulf of Finland (Baltic Sea) is highly dependent on weather conditions such as photosynthetically active radiation and water temperature. As an external disturbance, the precipitation process may promote the variations of other environmental variables, resulting in shifts towards other species in Xiangxi Bay. Water temperature was significantly positive correlated with Cyanophyta biomass during this study, indicating the water temperature could partly explain the disappearance of cyanobacterial bloom. Moreover, the disappearance of *Microcystis* bloom in the present period could be also associated to the decrease of photoperiod. *Chroomonas acuta*, *Cryptomonas ovata*, *Cryptomonas erosa* and *Rhodomonas* sp. were common species of Cryptophyta in Xiangxi Bay, showing a long persistence at nearly all the sampling sites. The long existence of *Cryptomonas ovata* and *Cryptomonas erosa* was in accordance with their opportunistic features (BOVO-SCOMPARIN and TRAIN, 2008; BORGES *et al.*, 2008), and the long existence of *Chroomonas acuta* and *Rhodomonas* sp. can be attributed to their sensibility to mixing and to light depletion, with a rapid reproduction rate and less susceptible to settling (REYNOLDS, 1997; DEVERCELLI, 2006). In the present study, *Cyclotella stelligera* and *Stephanodiscus hantzschii* were commonly found with a prominent dominance, especially at 1-mainstream and 4-riverine, probably associated with their good adaptation to the mixing conditions. Additionally, *Aulacoseira* sp., *Synedra acus*, *Pediastrum duplex*, *Sphaerocystis schroeteri* and *Eudorina elegans* appeared mainly at 1-mainstream and 2-lacustrine, *Ceratium hirundinella*, *Peridiniopsis* sp. and *Peridiniopsis niei* were mainly at 3-transitional, *Melosira varians* was mainly at 3-transitional and 4-riverine, while *Navicula* sp., *Gomphonema* sp. and *Staurastrum gracile* appeared only at 4-riverine. Among them, diatoms that form chains occurred at site 1-mainstream and 2-lacustrine, probably implying less water column stability at these two sites because filaments depend upon turbulence for suspension (HÖTZEL and CROOME, 1996; O'FARRELL *et al.*, 2001). *Ceratium hirundinella*, *Peridiniopsis* sp. and *Peridiniopsis niei* are large dinoflagellates, which can utilize segregated nutrients and are sensitive to deepening of mixing (REYNOLDS *et al.*, 2002; HUSZAR *et al.*, 2003). In Xiangxi Bay, 3-transitional had prevalence of mixotrophs, possibly light limitation favors mixotrophs success. The habitat template for *Melosira varians* and *Gomphonema* sp. is highly lotic environments (streams and rivulets) (PADISÁK *et al.*, 2009), and the water conditions at 4-riverine (or including 3-transitional) appeared to be more suitable for them. We conclude that there were notable differences between the composition and the temporal pattern of dominant phytoplankton species along the longitudinal gradient, in agreement with the longitudinal zonation of Xiangxi Bay.

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