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PRIMARY RESEARCH PAPER

Daily and vertical dynamics of rotifers under the impact of diatom blooms in the Three Gorges Reservoir, China

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Abstract The Three Gorges Dam was built in 2005 with a storage capacity of 39.3 billion m^3, ranking 22nd in the world. However, since the impoundment of the reservoir, serious blooms of phytoplankton have occurred. Rotifers, having a key role in the freshwater aquatic food web, are important grazers of phytoplankton and an essential food resource to higher trophic consumers. To explore the impacts of phytoplankton blooms on the rotifer community, daily and vertical surveys of rotifers were conducted in a bay of the Three Gorges Reservoir (Xiangxi Bay). Altogether 46 rotifer species were registered, and *Synchaeta tremula*, *Polyarthra vulgaris*, and *Brachionus calyciflorus* were the most abundant species accounting for 36, 26, and 16% of the mean rotifer densities, respectively. Although these dominant species always prevailed in the rotifer community, their proportions changed significantly from non-bloom phase to bloom phase, e.g., the significance of *S. tremula* deceased from 46.8 to 33.2%, while *P. vulgaris* and *B. calyciflorus* increased from 23.9 and 13.9% to 26.2 and 16.2%, respectively. In the vertical water column, all the rotifer following phytoplankton displayed an aggregated distribution, concentrating at the upper layers (0.5–5 m), especially during the bloom phase. From the non-bloom phase to the bloom phase, rotifer densities, the dominant rotifers, Shannon–Wiener and Margalef's diversity increased significantly, while the evenness displayed the opposite trend. Non-metric multidimensional scaling analysis (NMDS) revealed that the samples in the non-bloom phase were well separated from those in the bloom phase. This means that the outbreak of the diatom bloom in the Xiangxi Bay had significant impacts on the rotifer community. Further investigations are needed to address the impacts of the changes of rotifer community on higher trophic levels.

Keywords Rotifers · Short-term dynamic · Vertical distribution · Diatom bloom · The Three Gorges Reservoir · The Xiangxi Bay

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Introduction

Algal blooms are defined as sudden spurts of algal growth, causing quick increase of biomass (densities) of phytoplankton in the water column, which persist for days or weeks and affect water quality adversely (Pinckney et al., 1997). Phytoplankton blooms can cause the loss of aquatic biodiversity, reduced yields of desirable fish, threats to endangered aquatic species and decreases in the perceived aesthetic value of the water body (Holst et al., 2002; Simth, 2003). Freshwater rotifers within the zooplankton community play an important role as grazers of phytoplankton (Herzig, 1987). They are an essential component in the freshwater plankton food web and exist in high density in lakes, reservoirs and rivers, outnumbering other groups of mesozooplankton (Rodríguez & Matsumura-Tundisi, 2000; Molinero et al., 2006). The outbreak of phytoplankton can have impacts on rotifer community. It has been reported that the intense grazing activity of rotifers caused by abundant food was an important factor inducing the seasonal succession of rotifer communities (Lair & Ali, 1990).

Although there is solid knowledge on many aspects of zooplankton ecology, such as life history variation, reproductive ecology and feeding preferences, we still have little ability to predict zooplankton population dynamics in nature (Hampton, 2005). The dynamic prediction of ecological system following perturbation is a major goal of ecology (Cottingham et al., 2004). Nowadays, a main perturbation of freshwaters is eutrophication, which can strongly affect numbers, standing crops, population dynamics, production, as well as community structure of zooplankton all or which have serious impacts on aquatic ecosystems (Cajander, 1983). Many large rivers in Europe, North America and East Asia are endangered by eutrophication (Ha et al., 2003). The Yangtze River, China, is no exception, where a world famous project—the Three Gorges Dam—was constructed. Since the impoundment of the Three Gorges Reservoir, some sections of the river underwent the process of eutrophication, and strong diatom blooms were recorded. The outbreak of diatom blooms drew much attention and surveys about sedimentation, physical–chemical variables, phytoplankton and benthic macro-invertebrates, while studies on zooplankton are scarce, especially on a short-time scale (Cao et al., 2006; Shao et al., 2008a, b; Xu et al., 2009). Among zooplankton, rotifers represent the major fraction in the Three Gorges Reservior (Zhou et al., 2006b, 2007, 2009). The temporal dynamic of rotifers in a new impoundment is very complex and exhibits a strong variation over a short period of time (Keppeler & Hardy, 2004). Until now, the vertical distribution of rotifers on short-time scale is missing (Andersen et al., 2001). Thus, the intentions of this research were: (1) to describe the daily and vertical dynamic of rotifers at the initial stages of the Three Gorges Reservoir and (2) to test the hypotheses that diatom blooms in the Xiangxi Bay can have important impact on the rotifer community.

Materials and methods

Study site description

The Three Gorges Reservoir has a capacity of 39.3 billion m^3, a water level of 175 m, a surface area of 1080 km^2 and includes 40 large reservoir bays, each of which has a watershed area >100 km^2 (Xu et al., 2010). Xiangxi Bay is the biggest tributary near the dam of the Three Gorges Reservoir in Hubei province, China. It is a highly eutrophic bay with a mean TP of 0.153 mg l^{-1} and TN of 1.29 mg l^{-1} (Cao et al., 2006). In this bay, strong diatom blooms have been recorded. The dominant algae species were *Asterionella formosa*, *Peridiniopsis* sp., *Stephanodiscus neoastraea* and *Cyclotella caspia*, which can reach 10^8 cells l^{-1} (Zhou et al., 2006a; Xu et al., 2009). Wasmund et al. (1998) defined the beginning of a phytoplankton bloom by a doubling of the biomass relative to the winter level; Iriarte & Purdie (2004) defined the persistence of phytoplankton bloom as chlorophyll *a* concentration exceeding 10 μg l^{-1}. In this study, we defined the diatom bloom by chlorophyll *a* concentration exceeded the annual mean value of 11.7 μg l^{-1}.

Field sampling

Field samples were collected daily in a fixed site-Guanzhuangping (31.004°N, 110.763°E), from 23 February to 28 April, 2005. In the vertical water column, six layers were considered, including 0.5 m (sur), 2 m, 5 m, 10 m, 15 m and 20 m (near the bottom). For rotifer species identification and enumeration, 1.5 l water was taken using a 5-l Van Dorn sampler at each layer, and samples were fixed with standard Lugol's solution. Subsequently, the rotifer samples were concentrated by sedimentation and preserved with 4% formalin. Rotifers were counted in two Sedgewick-Rafter subsamples, and densities were determined for discrete species. Simultaneously, 600 ml of water was taken for chlorophyll *a* (Chl *a*)

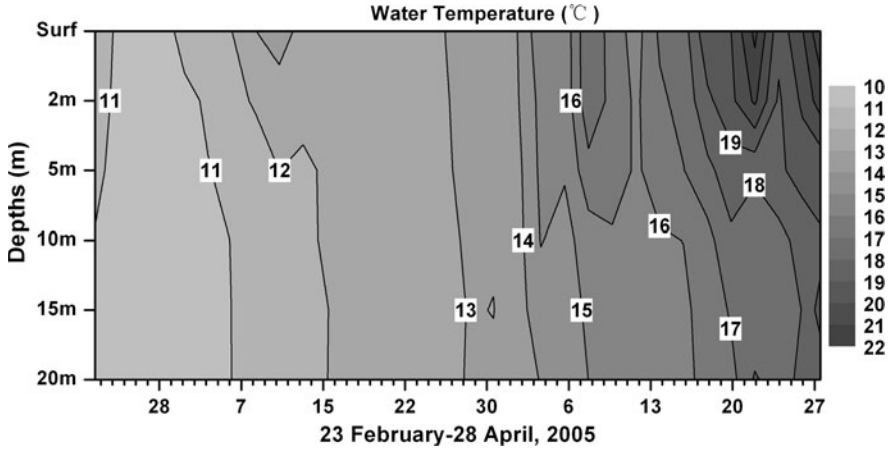

Fig. 1 Daily and vertical water temperatures in the Xiangxi Bay between 23 February and 28 April, 2005

concentration determinations, which were filtered on a WHATMAN GF/C glass-fibre filter and determined spectrophotometrically after 95% acetone extraction. Water temperature was measured using a Horiba multimeter (W-23XD), and water transparency was measured by Secchi disk transparency. Sampling was not possible on 11 March and 24 March because of strong winds or other climatic factors.

Statistical analysis

There are several methods used to observe the spatial variance of plankton (Jone & Francis, 1982) such as variance s^2 of a quantity x, Morisita's index and Tayloris Power Law (Horne & Schneider, 1995). Considering Morisita's index was independent of population density and sample size, we used it to detect the spatial dispersion in the vertical water column (Martin-Smith & Vincent, 2005; Thackeray et al., 2006). The index was calculated as:

$$I_{\S} = n\left(\sum(X^2) - \sum X\right) \Big/ \left(\left(\sum X\right)^2 - \sum X\right),$$

where X is the number of individuals in a given sampling unit and n is the number of sampling units. All the Morisita's index was tested with the critical value of 1 by one sample t test. When the index is equal to 1, it is a random distribution, less than 1 for a regular distribution and greater than 1 for an aggregated distribution.

Based on the threshold of Chl *a* concentration (11.7 μg l^{-1}), all the samples were divided into two categories: non-bloom and bloom phases. There were 196 samples belonging to the non-bloom phase and 168 in the bloom phase. Since our data did not meet the criteria of normality, we used Mann–Whitney U test to compare the differences in Chl *a* concentration, densities of total rotifers and dominant rotifers, Shannon–Wienner, Margalef's and evenness between the non-bloom and bloom phases. Non-metric multidimensional scaling (NMDS), performed with PRIMER (Version 5), was used to evaluate among-sites separation, which is an ordination method and well suited to the data that are non-normal or are on arbitrary, discontinuous, or otherwise questionable scales (Wu et al., 2009). Bray–Curtis similarity was used as the distance measure in the analyses. Spearman rank correlation analysis was used to detect the relationships between Chl *a* concentration and densities of total rotifers and dominant species, respectively. The level of significance was set at $P < 0.05$.

Results

Water temperature ranged from 9.77 to 23.50°C, with an average of 14.10°C. From February to April, it increased significantly and regularly (Friedman test, $P < 0.05$) (Fig. 1), but in the vertical water column all the Morisita's index was significantly lower than 1 (one sample t test, $P < 0.001$), which indicated that water temperature was evenly distributed in the water column (Table 1). From Fig. 1, it was also obvious that water temperature changed little from the surface to the bottom, although in April water temperature at the upper layer increased more than that in the deeper layers.

Table 1 Values of Morisita's indices for water temperature, Chl *a* concentration, dominant species and total rotifer density in the Xiangxi Bay

	WT	Chl *a*	*S. tremula*	*P. vulgaris*	*B. calyciflorus*	Total density
23-Feb	0.92	0.95	3.69			3.69
24-Feb	0.92	0.87	3.29	6.00		3.02
25-Feb	0.93	1.21	1.38	2.84		1.06
26-Feb	0.92	0.74	2.27	6.00		1.39
27-Feb	0.92	0.86	1.46			1.48
28-Feb	0.92	1.04	1.22	6.00		1.17
1-Mar	0.92	1.10	1.33	2.84		1.31
2-Mar	0.92	1.12	1.47	1.38		1.45
3-Mar	0.93	0.94	1.61	2.15		1.58
4-Mar	0.92	0.87	1.14	1.38		1.13
5-Mar	0.92	0.74	1.03	2.27	6.00	1.03
6-Mar	0.93	0.91	1.17	1.27	1.17	1.14
7-Mar	0.93	0.50	1.24	1.76	2.84	1.20
8-Mar	0.93	0.84	1.06	1.68	1.81	1.08
9-Mar	0.93	1.41	1.01	1.53	3.06	1.03
10-Mar	0.93	1.22	1.05	1.38	1.38	1.04
12-Mar	0.93	1.23	1.15	1.46	1.63	1.22
13-Mar	0.93	1.17	1.04	1.17	1.59	1.07
14-Mar	0.93	1.05	1.21	1.52	1.38	1.25
15-Mar	0.93	1.36	1.15	1.37	2.84	1.32
16-Mar	0.93	0.96	1.16	1.10	1.23	1.06
17-Mar	0.93	1.11	1.01	1.05	1.13	1.03
18-Mar	0.93	0.86	1.18	1.21	1.55	1.05
19-Mar	0.93	0.99	1.31	1.16	1.44	1.24
20-Mar	0.93	1.11	1.22	1.24	1.29	1.13
21-Mar	0.93	1.01	1.27	2.23	1.48	1.53
22-Mar	0.93	0.95	1.21	1.12	1.19	1.14
23-Mar	0.93	0.82	1.25	1.43	1.62	1.37
25-Mar	0.93	0.79	1.43	1.71	1.62	1.48
26-Mar	0.93	0.90	1.14	1.54	1.53	1.41
27-Mar	0.93	0.93	1.15	1.05	1.20	1.03
28-Mar	0.94	0.99	1.20	1.17	1.39	1.10
29-Mar	0.94	1.23	1.07	1.52	1.64	1.20
30-Mar	0.94	1.29	1.37	1.61	2.05	1.40
31-Mar	0.94	1.16	1.46	1.90		1.63
1-Apr	0.94	1.00	1.22	1.45		1.12
2-Apr	0.94	1.36	1.49	1.72		1.36
3-Apr	0.95	1.43	1.76	1.42		1.43
4-Apr	0.94	1.40	1.45	1.60	6.00	1.47
5-Apr	0.94	1.61	1.52	2.02		1.67
6-Apr	0.95	1.50	1.17	1.10		1.12
7-Apr	0.95	1.37	1.42	1.45	6.00	1.42
8-Apr	0.95	1.39	1.40	1.73	3.69	1.53
9-Apr	0.95	1.22	1.29	1.51	1.79	1.38

Table 1 continued

	WT	Chl *a*	*S. tremula*	*P. vulgaris*	*B. calyciflorus*	Total density
10-Apr	0.95	1.18	1.27	1.57	1.52	1.43
11-Apr	0.95	1.26	1.60	1.51	1.65	1.50
12-Apr	0.95	1.19	1.96	1.39	1.56	1.52
13-Apr	0.95	1.11	1.72	1.77	1.23	1.26
14-Apr	0.95	1.15	1.40	1.32	1.39	1.38
15-Apr	0.95	1.22	1.59	1.66	1.75	1.57
16-Apr	0.95	1.11	1.18	1.90	1.50	1.51
17-Apr	0.96	1.15	1.05	1.70	1.68	1.61
18-Apr	0.95	1.30	1.48	2.29	1.38	1.58
19-Apr	0.96	1.50	1.54	1.78	2.21	1.95
20-Apr	0.95	1.49	1.63	1.79	1.86	1.90
21-Apr	0.97	1.24	1.99	1.99	2.08	1.70
22-Apr	0.96	1.49	2.14	2.15	1.57	2.07
23-Apr	0.96	1.18	1.64	2.43	3.24	1.80
24-Apr	0.96	1.12	1.67	1.83	2.84	1.62
25-Apr	0.96	1.19	1.49	1.47		1.52
26-Apr	0.96	1.38	2.35	1.93	6.00	2.15
27-Apr	0.97	1.10	1.66	1.67	6.00	1.64
28-Apr	0.96	1.35	1.58	2.38	6.00	2.05

Note: Blank entry means it was absent in the quantitative samples

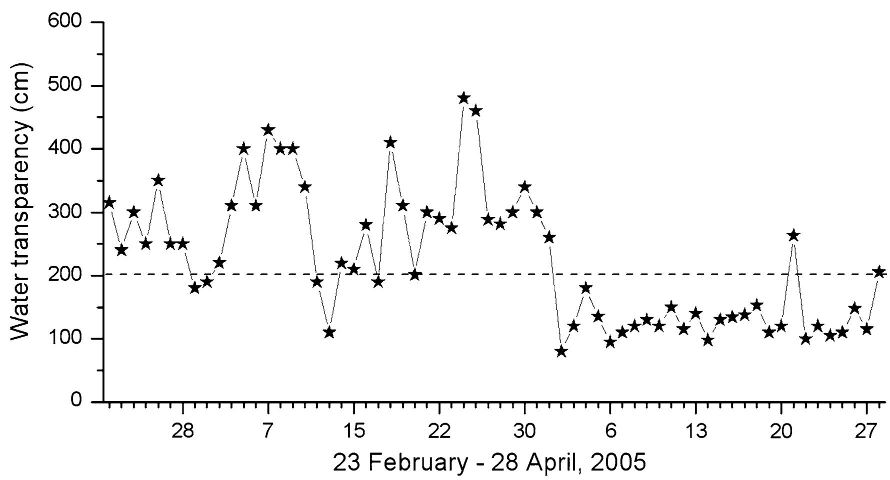

Fig. 2 Daily changes of water transparency in the Xiangxi Bay between 23 February and 28 April, 2005

During the sampling period, water transparency ranged from 80 to 480 cm, with an average of 234 cm. It decreased significantly (less then 200 cm) when diatoms bloomed (Fig. 2).

During the investigation, phytoplankton changed significantly with time, and three blooms were recorded: the first bloom lasted 2 days (1 March and 2 March); the second bloom was observed from 12th March to 22nd March and the third bloom began on 29 March and lasted until to the end of the study (Fig. 3). From Fig. 3, it was apparent that the bloom in April (dominated by *A. formosa*) was stronger than that in March (mainly *Cyclotella* sp). One sample *t* test revealed that all Morisita's indices were significantly higher than 1, which proved that phytoplankton showed a surface aggregated distribution

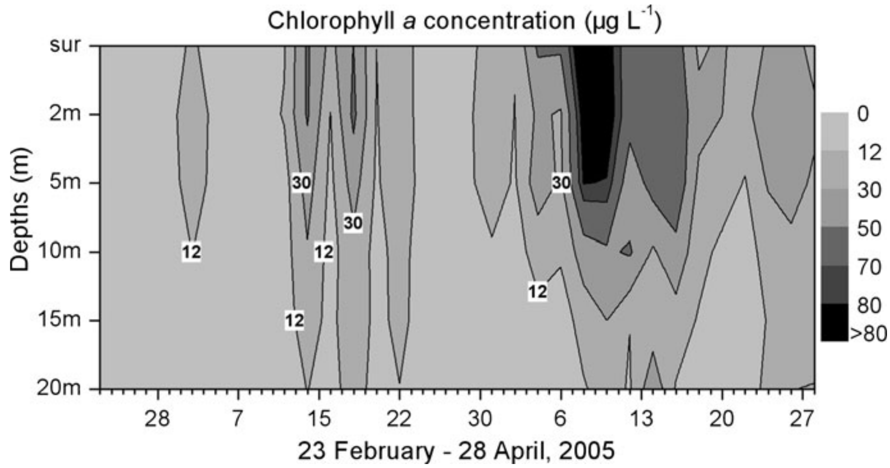

Fig. 3 Daily changes of Chl *a* concentrations in the Xiangxi Bay between 23 February and 28 April, 2005

(Fig. 3; Table 1). In our study, water transparency was a good signal of the blooms, which decreased to less than 200 cm during the bloom (Fig. 2).

A total of 46 rotifer species were registered, belonging to 17 families and 21 genera, with 36 and 40 species in the non-bloom and bloom phase, respectively. *Synchaeta tremula* (Müller, 1786), *Polyarthra vulgaris* (Carlin, 1934) and *B. calyciflorus* (Pallas, 1766) were the predominant species, accounting for 36, 26 and 16% of the mean rotifer densities, respectively. Although these dominant species prevailed both in the non-bloom and bloom phases (Table 2), their proportions changed significantly from non-bloom to bloom phase. For instance, the significance of *S. tremula* deceased from 46.8 to 33.2% but *P. vulgaris* and *B. calyciflorus* increased from 23.9 and 13.9% to 26.2 and 16.2%, respectively.

Total rotifer densities showed significant temporal variation and spatial heterogeneity in the vertical water column (Fig. 4). During the diatom bloom, total rotifer densities exceeded 1000 ind l^{-1}. This increase was initiated by the diatom bloom in the Xiangxi Bay, although with several days lag.

Densities of *S. tremula* ranged from 0 to 3645 ind l^{-1} with an average of 386 ind l^{-1}. It increased with a several days lag after the diatom bloom and displayed an aggregated distribution in the vertical water column with Morisita's indices significantly higher than 1 (Table 1; Fig. 5). In the first bloom, rotifers reached higher densities in deep layers but in the latter blooms they concentrated in the upper layers (Fig. 5).

Polyarthra vulgaris with a mean of 277 ind l^{-1} was the second most abundant species in the Xiangxi Bay. Before 13 March, its density was less than 200 ind l^{-1}; afterwards its densities in the water column rose sharply, and density peaks were recorded after the second bloom (from 15 March to 13 April) (Fig. 5). They also displayed an aggregated distribution with the Morisita's indices significantly higher than 1 and concentrated in the upper layers (Table 1; Fig. 5).

Brachionus calyciflorus reached a highest density in the second diatom bloom with a maximum value of 5850 ind l^{-1} in the 5-m depth and exhibited an aggregated distribution with higher densities in the upper layers (Fig. 5). During the investigation, two peaks of *B. calyciflorus* were recorded: the first one began on 20 March and lasted for about 1 week; the second one began on 14 April and lasted for 4 days (Fig. 5).

The diatom blooms had significant impacts on densities of total rotifers, dominant species, Shannon–Wiener, Margalef's indices and evenness (Table 3). Following the diatom blooms, densities of total rotifers, *S. tremula*, *P. vulgaris*, *B. calyciflorus*, Shannon–Wiener and Margalef's diversities increased significantly, while the evenness displayed opposite trend (Table 3). NMDS revealed that the samples in the non-bloom phase were well separated from those in the bloom phase, which indicated the diatom blooms had significantly impacted rotifer community structure (Fig. 6).

Discussion

It was evident that phytoplankton and rotifers in the Xiangxi Bay exhibited spatial heterogeneity in the

Table 2 Species list of rotifers in the Xiangxi Bay

	Non-bloom		Bloom	
	Rank	Mean (ind l^{-1})	Rank	Mean (ind l^{-1})
Anuraeopsis fissa (Gosse, 1852)			35	0.06
Ascomorpha ovalis Carlin, 1944	29	0.05		
Asplanchna sp.	15	0.49	15	2.33
Bdelloidea	11	1.14	20	0.74
B. angularis Gosse, 1852	24	0.10	10	3.58
B. calyciflorus Pallas, 1767	3	96.24	3	258.66
B. quadridentatus Hermann, 1783			38	0.06
B. urceus (Linnaeus, 1759)	34	0.05	25	0.17
Cephalodella exigua (Gosse, 1887)			31	0.10
C. licina Wulfert, 1961	31	0.05	37	0.06
Collotheca sp.	16	0.45	23	0.44
Colurella adriatica (Ehrenberg, 1832)			40	0.06
Conochilus unicornis Rousselet, 1893	10	1.34	14	2.61
Euchlanis pyriformis Gosse, 1852			36	0.06
Filinia terminalis (Plate, 1887)	9	1.84	12	3.25
Keratella cochlearis (Gosse, 1852)	4	36.11	4	159.00
K. quadrata (Müller, 1786)	7	11.73	7	22.34
K. trapezoida Zhuge & Huang, 1999	8	6.45	9	10.65
K. valga (Ehrenberg, 1835)	5	15.34	5	137.08
Keratella sp.	20	0.21	32	0.09
Lecane aculeata (Jalubski, 1912)	19	0.24	24	0.17
L. curvicornis (Murry, 1913)	28	0.05	33	0.06
L. inermis (Bryce, 1892)	30	0.05		
L. unguitata (Fadeev, 1926)			27	0.11
Lepadella patella patella (Müller, 1773)			28	0.11
Monommata grandis Tessin, 1890	32	0.05	29	0.11
Monommata longiseta (Müller, 1786)	22	0.13	26	0.16
Notholca labis Gosse, 1888	13	0.64	18	1.02
Ploesoma hudsoni (Imhof, 1892)			17	1.29
P. truncatum (Levander, 1895)	14	0.54	11	3.27
P. vulgaris (Carlin, 1944)	2	126.43	2	458.47
Pompholyx sulcata Hudson, 1886	35	0.05		
S. oblonga Ehrenberg, 1833	25	0.05	21	0.55
S. pectinata Ehrenberg, 1833	6	13.56	6	50.32
S. stylata Wierzejski, 1894	17	0.45	8	15.97
S. tremula (Müller, 1787)	1	231.33	1	575.53
Taphrocampa annulosa Gosse, 1852			30	0.11
Trichocerca bicristata (Gosse, 1888)	12	0.99	13	3.02
T. capucina (Wierzejski and Zacharias, 1894)	36	0.05		
T. lophoessa (Gosse, 1887)			39	0.06
T. pusilla (Lauterborn, 1899)	27	0.05	22	0.49
T. stylata (Gosse, 1852)	18	0.30	16	1.75
T. tigris (Müller,1786)	33	0.05		

Table 2 continued

	Non-bloom		Bloom	
	Rank	Mean (ind l^{-1})	Rank	Mean (ind l^{-1})
Trichocerca sp.	26	0.05		
Trichotria pocillum (Müller, 1777)	23	0.10	34	0.06
T. tetractis tetractis (Ehrenberg, 1831)	21	0.15	19	0.83

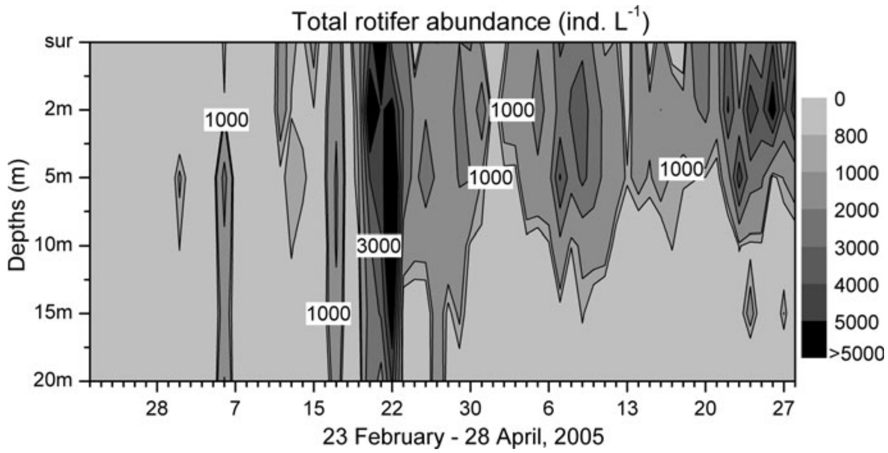

Fig. 4 Daily changes of total rotifer abundance in the Xiangxi Bay between 23 February and 28 April, 2005

vertical water column, displaying an aggregated distribution, although water temperature was almost evenly distributed. In the diel vertical research of rotifers in the Xiangxi Bay (Zhou et al., 2007), it was also found that phytoplankton and rotifers exhibited an aggregated distribution but the abiotic variables such as water temperature, oxygen content and pH values were evenly distributed. Although rotifer's distribution is related to both abiotic and biotic factors, the abiotic factors in the Xiangxi Bay were not the limiting factors for rotifer vertical distribution.

The diatom bloom in the Xiangxi Bay seemed to accelerate the densities of rotifers although with several days of lag. This indicates that phytoplankton is the primary food resource for rotifers (Guiral et al., 1994; Yoshida et al., 2003; Zhou et al., 2009). It has been reported that in spring the metabolism and production of zooplankton could be increased by the increasing food supply (Montagnes & Lessard, 1999). Additionally, all the dominant rotifer species in the Xiangxi Bay were herbivorous grazers (Kirk, 2002; Zhou et al., 2007). For instance, *S. tremula* and *P. vulgaris* were macrofilter feeders which can feed on both small and large algae (Gołdyn et al., 1997; Ooms-Wilms et al., 1999; Špoljar et al., 2005; Grzegorz et al., 2006). *B. calyciflorus* can feed on a wide size range of phytoplankton but shows a clear preference for *Cyclotella* sp. (Pagano, 2008). Hence, it was not surprising that both in the non-bloom and bloom phase densities of total rotifer and dominant rotifers had significant positive correlation with phytoplankton (Chl *a* concentration) (Table 4). However, Chl *a* concentration in April was significantly higher than that of March, but rotifers in April did not reach as high densities as in March. The possible reason was that *Cyclotella* sp., a palatable diatom species, was slowly outcompeted by another less palatable diatom species *A. formosa*, which dominated the phytoplankton community in April and accounted for more than 47% of the total phytoplankton abundance (Roche, 1995; Xu et al., 2009). *A. formosa* were on average 78 μm GALD (Greatest Axial Line Dimension) and usually formed 8-celled colonies with an average of 160 μm across. *A. formosa* can cause food limit of *Bosmina longirostris* and have a negative relation with rotifers (Balseiro et al., 1991; Wilk-Wozniak & Zurek, 2006).

Although the dominant species were the same between bloom phase and non-bloom phase, the

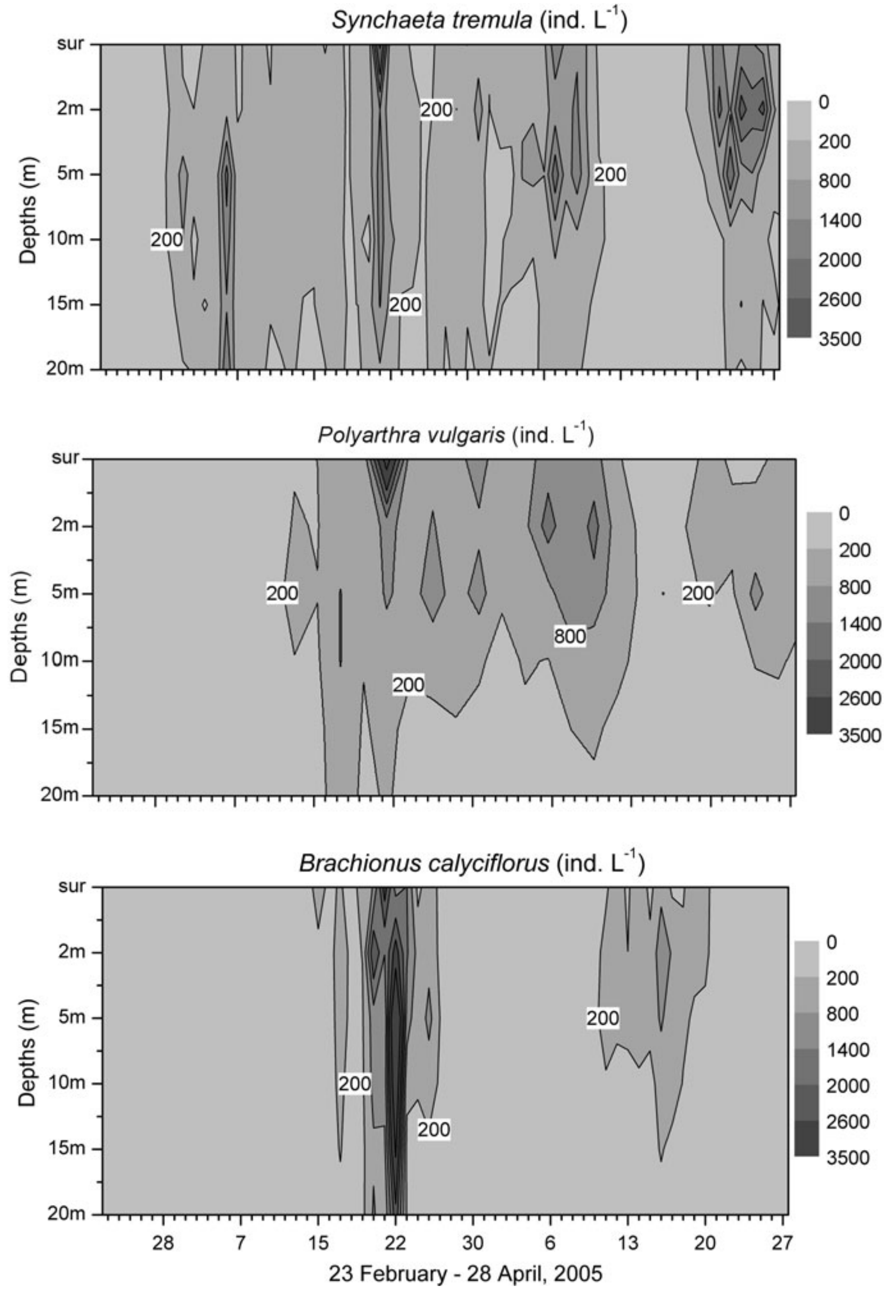

Fig. 5 The daily and vertical dynamics of dominant rotifer species in the Xiangxi Bay between 23 February and 28 April, 2005

proportion of dominant species in the rotifer community changed substantially. Furthermore, the NMDS revealed that the rotifer community in the bloom phase was significantly different from the non-bloom phase, which meant that from the non-bloom to the bloom phase rotifer community in the Xiangxi Bay changed. The community change of rotifers in the Xiangxi Bay was mainly caused by the diatom bloom because the environmental factors during this period changed little. Meanwhile, the crustaceans in the Xiangxi Bay were numerically less than rotifers, although they can effectively influence rotifer populations via predation and competition (Fussmann, 1996). During our study, crustaceans ranged from 0 to 98 ind l^{-1} with a mean of 8 ind l^{-1} (Xu et al., 2009), which was significantly lower than the maximal rotifer density (13230 ind l^{-1}) and mean density (1035 ind l^{-1}). In addition, the dominant cladoceran

Table 3 Mann–Whitney *U* test of Chl *a* concentration, total rotifers, dominant rotifers and diversity index between the non-bloom ($n = 196$) and bloom phase ($n = 168$)

	Non-bloom median (25th–75th percentiles)	Bloom median (25th–75th percentiles)	Z	*P*
Chl *a* (μg l^{-1})	5.12 (3.31–6.56)	25.39 (15.2–40.61)	−16.5	**<0.001**
Total rotifer densities (ind l^{-1})	320 (120–558)	1130 (580–2115)	−10.2	**<0.001**
S. tremula (ind l^{-1})	160 (50–298)	370 (150–708)	−6.6	**<0.001**
P. vulgaris (ind l^{-1})	30 (10–120)	240 (100–598)	−9.4	**<0.001**
B. calyciflorus (ind l^{-1})	0 (0–40)	30 (0–208)	−4.4	**<0.001**
Shannon–Wiener	1.04 (0.33–1.43)	1.34 (1.12–1.58)	−5.9	**<0.001**
Margalef's	0.46 (0.23–0.68)	0.64 (0.52–0.77)	−6.03	**<0.001**
Evenness	0.72 (0.58–0.88)	0.66 (0.56–0.77)	2.73	**0.006**

Significant differences ($P < 0.05$) are indicated in bold

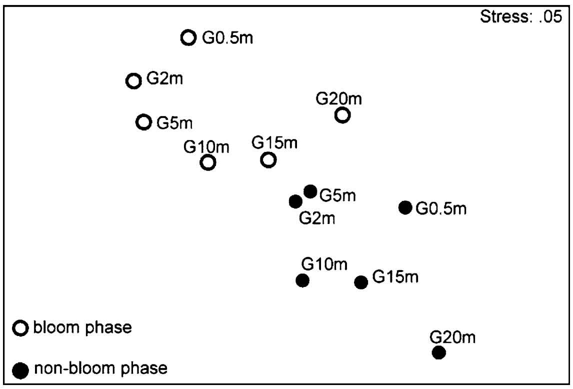

Fig. 6 Non-metric multi-dimensional scaling ordination of rotifer sampling layers in the Xiangxi Bay

Table 4 Spearman rank correlation coefficients (*R*) between Chl *a* and densities of total rotifer, dominant rotifers

	Non-bloom		Bloom	
	R	*P*	*R*	*P*
Total rotifer densities	0.37	**<0.001**	0.46	**<0.001**
S. tremula	0.24	**0.002**	0.19	**0.007**
P. vulgaris	0.36	**<0.001**	0.41	**<0.001**
B. calyciflorus	0.27	**<0.001**	0.20	**0.005**

Significant correlations ($P < 0.05$) are indicated in bold

(*Bosmina coregoni*) in the Xiangxi Bay with a maximal value of 93 ind l^{-1} (on 22 April) was also less abundant than the dominant rotifers (Han et al., 2006) and occurred latter. Other crustacean species such as cyclopoid, calanoid copepods were ephemeral species (Zhou et al., 2007). Therefore, we supposed crustaceans in the Xiangxi Bay during our investigation had little impact on rotifer community.

In conclusion, eutrophication is a worldwide water problem, which can result in the degradation of water resources and habitats, and changes in the structure and function of food webs. Rotifer densities and community structure changed significantly from the non-bloom to bloom phase in the Xiangxi Bay. This implied that the diatom bloom in the Three Gorges Reservoir can have impacts on water quality and aquatic food webs. Further investigations are needed to address the impacts of the changes of rotifer community on higher trophic levels.

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References

Andersen, V., A. Gubanova, P. Nival & T. Ruellet, 2001. Zooplankton community during the transition from spring bloom to oligotrophy in the open NW Mediterranean and effects of wind events. 2. Vertical distributions and migrations. Journal of Plankton Research 23: 243–261.

Balseiro, E. G., C. P. Queimalinos & B. E. Modenutti, 1991. Evidence of interference of *Asterionella formosa* with the feeding of *Bosmina longirostris*: a field study in a south Andes lake. Hydrobiologia 224: 111–116.

Cajander, V. R., 1983. Production of planktonic Rotatoria in Ormajärvi, an eutrophicated lake in southern Finland. Hydrobiologia 104: 329–333.

Cao, M., Q. H. Cai, R. Q. Liu, X. D. Qu & L. Ye, 2006. Comparative research on physicochemical factors between Xiangxi Bay and the front region of Three Gorges Reservoir. Acta Hydrobiologica Sinca 30: 11–20.

Cottingham, K. L., S. Glaholt & A. C. Brown, 2004. Zooplankton community structure affects how phytoplankton respond to nutrient pulses. Ecology 85: 158–171.

Fussmann, G., 1996. The importance of crustacean zooplankton in structuring rotifer and phytoplankton communities: an enclosure study. Journal of Plankton Research 18: 1897–1915.

Gołdyn, R., A. Kozak & W. Romanowicz, 1997. Food-web manipulation in the Maltański Reservoir. Hydrobiologia 342(343): 327–333.

Grzegorz, G., P. Klimaszyk & N. Kuczyńska-Kippen, 2006. Diel vertical distribution of zooplankton in Piaseczno Lake (Wdecki Landscape Park)-II. Rotifera. Oceanological and Hydrobiological Studies 20: 29–37.

Guiral, D., R. Arfi, M. Bouvy, M. Pagano & L. Saint-Jean, 1994. Ecological organization and succession during natural recolonization of a tropical pond. Hydrobiologia 294: 229–242.

Ha, K., M. H. Jang & G. J. Joo, 2003. Winter Stephanodiscus bloom development in the Nakdong River regulated by an estuary dam and tributaries. Hydrobiologia 506–509: 221–227.

Hampton, S. E., 2005. Increased niche differentiation between two conochilus species over 33 years of climate change and food web alteration. Limnology and Oceanography 50: 421–426.

Han, X. Q., J. Z. Xue & Q. H. Cai, 2006. Vertical and temporal distribution of the cladocerans during the spring bloom period in Xiangxi Bay. Sino-German Workshop on Environmental Impacts of Large-Scale Hydraulic Engineering: 35–36.

Herzig, A., 1987. The analysis of planktonic rotifer populations: a plea for long-term investigations. Hydrobiologia 147: 163–180.

Holst, H., H. Zimmermann-Timm & H. Kausch, 2002. Longitudinal and transverse distribution of plankton rotifers in the potamal of the river Elbe (Germany) during late summer. International Review of Hydrobiology 87: 267–280.

Horne, J. K. & D. C. Schneider, 1995. Spatial variance in ecology. Oikos 74: 18–26.

Iriarte, A. & D. A. Purdie, 2004. Factors controlling the timing of major spring bloom events in an UK south coast estuary. Estuarine, Coastal and Shelf Science 61: 679–690.

Jone, R. I. & R. C. Francis, 1982. Dispersion patterns of phytoplankton in lakes. Hydrobiologia 86: 21–28.

Keppeler, E. C. & E. R. Hardy, 2004. Abundance and composition of Rotifera in an abandoned meander lake (Lago Amapá) in Rio Branco, Acre, Brazil. Revista Brasileira de Zoologia 21: 233–241.

Kirk, K. L., 2002. Competition in variable environments: experiments with planktonic rotifers. Freshwater Biology 47: 1089–1096.

Lair, N. & H. O. Ali, 1990. Grazing and assimilation rates of natural populations of planktonic rotifers *Keratella cochlearis*, *Keratella quadrata* and *Kellicottia longispina* in a eutrophic lake (Aydat, France). Hydrobiologia 194: 119–131.

Martin-Smith, K. M. & A. C. J. Vincent, 2005. Seahorse declines in the Derwent estuary, Tasmania in the absence of fishing pressure. Biological Conservation 123: 533–545.

Molinero, J. C., O. Anneville, S. Souissi, G. Balvay & D. Gerdeaux, 2006. Anthropogenic and climate forcing on the long-term changes of planktonic rotifers in Lake Geneva, Europe. Journal of Plankton Research 28: 287–296.

Montagnes, D. J. S. & E. J. Lessard, 1999. Population dynamics of the marine planktonic ciliate *Strombidinopis multiauris*: its potential to control phytoplankton blooms. Aquatic Microbial Ecology 20: 167–181.

Ooms-Wilms, A. L., G. Postema & R. D. Gulati, 1999. Population dynamics of planktonic rotifers in Lake Loosdrecht, the Netherlands, in relation to their potential food and predators. Freshwater Biology 42: 77–97.

Pagano, M., 2008. Feeding of tropical cladocerans (*Moina micrura*, *Diaphanosoma excisum*) and rotifer (*Brachionus calyciflorus*) on natural phytoplankton: effect of phytoplankton size-structure. Journal of Plankton Research 30: 401–414.

Pinckney, J. L., D. F. Millie, B. T. Vinyard & H. W. Paerl, 1997. Environmental controls of phytoplankton bloom dynamics in the Neuse River Estuary, North Carolina. U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 54: 2491–2501.

Roche, K. F., 1995. Growth of the rotifer *Brachionus calyciflorus* Pallas in Dairy waste stabilization ponds. Water Research 29: 2255–2260.

Rodríguez, M. P. & T. Matsumura-Tundisi, 2000. Variation of density, species composition and dominance of rotifers at a shallow tropical Reservoir (Broa Reservoir, SP, Brazil) in a short scale time. Revista Brasileira de Biologia 60: 1–9.

Shao, M., X. He, X. Han, Z. Xie, D. Li & Q. Cai, 2008a. Seasonal patterns of sedimentation and their associations with benthic communities in Xiangxi Bay of the Three Gorges Reservoir, China. Journal of Freshwater Ecology 23: 151–160.

Shao, M., Z. Xie, X. Han, M. Cao & Q. Cai, 2008b. Macroinvertebrate community structure in Three-Gorges Reservoir, China. International Review of Hydrobiology 93: 175–187.

Simth, V. H., 2003. Eutrophication of freshwater and coastal marine ecosystems. Environmental Science and Pollution Research 10: 126–139.

Špoljar, M., I. Habdija, B. Primc-Habdija & L. Sipos, 2005. Impact of environmental variables and food availability on rotifer assemblage in the Karstic Barrage Lake Visovac (Krka River, Croatia). International Review of Hydrobiology 90: 555–579.

Thackeray, S. J., D. G. George, R. I. Jones & I. J. Winfield, 2006. Statistical quantification of the effect of thermal stratification on patterns of dispersion in a freshwater zooplankton community. Aquatic Ecology 40: 23–32.

Wasmund, N., G. Nausch & W. Matthäus, 1998. Phytoplankton spring blooms in the southern Baltic Sea-spatio-temporal development and long-term trends. Journal of Plankton Research 20: 1099–1117.

Wilk-Wozniak, E. & R. Zurek, 2006. Phytoplankton and its relationships with chemical parameters and zooplankton in the meromictic Piaseczno reservoir, Southern Poland. Aquatic Ecology 40: 165–176.

Wu, N. C., T. Tang, S. C. Zhou, X. H. Jia, D. F. Li, R. Q. Liu & Q. H. Cai, 2009. Changes in benthic algal communities following construction of a run-of-river dam. Journal of the North American Benthological Society 28: 69–79.

Xu, Y. Y., Q. H. Cai, L. Ye, S. C. Zhou & X. Q. Han, 2009. Spring diatom blooming phases in a representative eutrophic bay of the Three-Gorges Reservoir, China. Journal of Freshwater Ecology 24: 191–198.

Xu, Y. Y., Q. H. Cai, L. Ye & M. L. Shao, 2010. Asynchrony of spring phytoplankton response to temperature driver within a spatial heterogeneity bay of Three-Gorges Reservoir, China. Limnologica. doi:10.1016/j.limno.2010.10.004.

Yoshida, T., J. Urabe & J. J. Elser, 2003. Assessment of 'top-down' and 'bottom-up' force as determinants of rotifer distribution among lakes in Ontario, Canada. Ecological Research 18: 639–650.

Zhou, G. J., Q. J. Kuang, G. X. Liu, H. B. Tang & Z. Y. Hu, 2006a. Investigation on algal water-blooms in the Three-Gorge Reservoir and its toxicological study. Acta Hydrobiologica Sinca 30: 37–41. (in Chinese).

Zhou, S. C., X. F. Huang, T. Tang & Q. H. Cai, 2006b. Primary studies on plankton rotifers and water quality assessment in Xiangxi Bay of the Three Gorges Reservoir. Acta Hydrobiologia Sinica 30: 52–57. (in Chinese).

Zhou, S. C., X. F. Huang & Q. H. Cai, 2007. Vertical distribution and migration of planktonic rotifers in Xiangxi Bay of the Three Gorges Reservoir, China. Journal of Freshwater Ecology 22: 441–449.

Zhou, S. C., X. F. Huang & Q. H. Cai, 2009. Temporal and spatial distributions of rotifers in Xiangxi Bay of the Three Gorges Reservoir, China. International Review of Hydrobiology 94: 542–559.